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TOWARD A MODEL-INDEPENDENT ANALYSIS OF ELECTROWEAK DATA

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Abstract

We set the framework for a model-independent analysis of the data on electroweak precision tests. Starting from three basic observables, the mass ratio m_W/m_Z, the Z partial width and the forward-backward asymmetry for charged leptons, we define three dimensionless parameters ε_1, ε_2 and ε_3 which contain the small radiative correction effects one is interested in, with large m_t effects only appearing in ε_1. The results on the epsilons implied by the present experimental data are discussed as well as the predictions of the Standard Model, as functions of m_t and m_H, with special attention to evaluating the theoretical errors. We formulate a hierarchy of simple and general assumptions, valid in large classes of models, which are needed in order to relate the epsilons to an increasingly larger set of observables including the τ-polarisation asymmetry, the forward-backward asymmetry for the b-quark, deep inelastic neutrino scattering and atomic parity violation. Correspondingly the analysis of present data is performed in stages and the conclusions are examined at each stage. Finally the case of the Standard Model is recovered as a very relevant particular example.

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1. INTRODUCTION

With the completion of the first phase of LEP experiments, now that the 1990 data have been analyzed [1],[2], the program of precision tests of the electroweak theory has made considerable progress. The measurement at LEP of the mass and the total and partial widths of the Z and more recently the first accurate determination at the peak of the forward-backward asymmetries A_{FB} and of the τ–polarisation asymmetry A^{τ}_{pol} have added new important entries to the list of precise tests of the standard theory.

Within the framework of the standard theory some good analyses of the available data already exist (see, e.g. refs.[3]). In the Standard Model all the observables can be computed starting from the input parameters, a self-imposing set of which is given by α, α_s, G_F, m_Z, m_f, m_H. Among the fermion masses, m_f, the main unknown quantity is the top quark mass m_t. The CDF lower limit on m_t, $m_t>89$ GeV, is valid in the Standard Model [4]. The failure of direct searches at LEP imposes the bound $m_H>48$ GeV on the Higgs mass [5]. Also, the Standard Model is affected with serious pathologies for $m_H>0.6$-1TeV, when the Landau pole associated to the $\lambda(\phi^+\phi)^2$ coupling comes too close to the physical region in parameter space [6]. Finally direct measurements of $\alpha_s(m_Z)$ from the hadronic jet distributions at LEP lead to the value $\alpha_s(m_Z) = 0.118 \pm 0.008$ [7].In principle one can fit all the existent data and find the best values for $\alpha_s(m_Z)$, m_t and m_H within the above-mentioned ranges. In practice not very interesting further restrictions are obtained on $\alpha_s(m_Z)$ and m_H from these fits, while a stringent upper bound on m_t is imposed by the data. The most significant precise results that lead to the upper bound on m_t are the data on m_W/m_Z from hadron colliders, on the ratio of neutral to charged current cross-sections in neutrino-nucleus deep inelastic scattering, on the partial width Γ_l of the Z into a pair of charged leptons and on A_{FB}. Other Z widths either directly involve $\alpha_s(m_Z)$ (as is the case for the hadronic width Γ_h) or are not measured with sufficient precision (as for the invisible width, which leads to the remarkable result on the number of neutrinos $N_\nu = 2.97 \pm 0.05$ [1], or for the fraction Γ_b/Γ_h of hadronic decays involving b quarks and so on).

In the present paper we propose a different way of analysing the data which does not necessarily assume the validity of the Standard Model from the start and takes into account the recent theoretical studies on the parametrisation of possible effects of new physics on precision experiments. Given the set of input parameters as specified above, we start from the basic observables m_W/m_Z, Γ_l and A^l_{FB} (the forward-backward asymmetry for charged leptons). We assume charged lepton universality, which is supported by the data at the present level of accuracy, so that Γ_l and A^l_{FB} refer to the corresponding average data. From these three quantities we can isolate the corresponding dynamically significant corrections Δr_W, $\Delta\rho$ and $\Delta k'$, which contain the small effects one is trying to disentangle, and are defined in the following. First we introduce Δr_W as obtained from m_W/m_Z by the relation:

$$\left(1-\frac{m_W^2}{m_Z^2}\right)\frac{m_W^2}{m_Z^2} = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F m_Z^2(1-\Delta r_W)} \qquad (1)$$

Here $\alpha(m_Z) = \alpha/(1-\Delta\alpha)$ is fixed to the conventional value 1/128.8 so that the effect of the running of α due to known physics is extracted from $(1-\Delta r) = (1-\Delta\alpha)(1-\Delta r_W)$. In fact, in the Standard Model the value of $1/\alpha(m_Z)$ should be 128.8 ± 0.1 [8]. A possible departure from this value would then be included in Δr_W. In order to define $\Delta\rho$ and $\Delta k'$ we consider the effective vector and axial-vector couplings g_V and g_A of the on-shell Z to charged leptons, given by the formulae:

$$\Gamma_l = \frac{G_F m_Z^3(g_V^2 + g_A^2)}{6\pi\sqrt{2}} \qquad (2)$$

$$A^l_{FB}(\sqrt{s} = m_Z) = \frac{3\, g_V^2\, g_A^2}{(g_V^2 + g_A^2)^2} \qquad (3)$$

Note that Γ_l stands for the inclusive partial width $\Gamma(Z\to ll + \text{photons})$. We could extract from $(g_V^2 + g_A^2)$ the factor $(1 + 3\alpha/4\pi + \ldots)$ which is induced in Γ_l from final state radiation, but we prefer the simpler definition of eq.(2). The asymmetry in eq.(3) is obtained from the data after deconvolution of initial state radiation and subtraction of other pure QED effects. Contributions from box diagrams and imaginary parts of vertex functions are absorbed in the definition of g_A and g_V (of course, this can only be possible for a single channel, which we chose to be the charged lepton channel).In terms of g_V and g_A, $\Delta\rho$ and $\Delta k'$ are given by [9]:

$$g_A = -\frac{\sqrt{\rho}}{2} = -\frac{1}{2}\left(1 + \frac{\Delta\rho}{2}\right)$$
$$\frac{g_V}{g_A} = 1 - 4\,\bar{s}_W^2 = 1 - 4\,(1 + \Delta k')\, s_0^2 \qquad (4)$$

In Eq.(4) $\bar{s}_W^2$ is an effective $\sin^2\theta_W$ for on-shell Z [8-12], while s_0^2 is the corresponding quantity before non pure-QED corrections, given by:

$$s_0^2\, c_0^2 = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F m_Z^2} \qquad (5)$$

with $c_0^2 = 1 - s_0^2$ ($s_0^2 = 0.23146$ for $m_Z = 91.174$ GeV).

As is well known, in the Standard Model Δr_W, $\Delta\rho$ and $\Delta k'$, for sufficiently large m_t, are all dominated by quadratic terms in m_t of order $G_F m_t^2$ [13] and in this limit one has $\Delta r_W \sim -c_0^2/s_0^2\Delta\rho \sim (c_0^2 - s_0^2)/s_0^2\,\Delta k'$ (see, e.g. ref. [8]). As new physics can more easily be disentangled if not masked by large conventional m_t effects, it is convenient to keep $\Delta\rho$ while trading Δr_W and $\Delta k'$ for two quantities with no contributions of order $G_F m_t^2$. We thus introduce the following linear combinations [9]:

$$\varepsilon_1 = \Delta\rho$$

$$\varepsilon_2 = c_0^2 \Delta\rho + \frac{s_0^2 \Delta r_W}{(c_0^2 - s_0^2)} - 2\, s_0^2\, \Delta k' \qquad (6)$$

$$\varepsilon_3 = c_0^2 \Delta\rho + (c_0^2 - s_0^2)\, \Delta k'$$

Clearly ε_2 and ε_3 no longer contain terms of order $G_F m_t^2$ but only logarithmic terms in m_t.

The leading terms for large Higgs mass, which are logarithmic, are mainly contained in ε_1 but are also present in ε_3. In the Standard Model one has the following "large" asymptotic contributions [8], [13-15]:

$$\varepsilon_1 = \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} - \frac{3G_F m_W^2}{4\pi^2\sqrt{2}} \,tg^2\theta_W \ln(\frac{m_H}{m_Z}) + \ldots$$

$$\varepsilon_2 = -\frac{G_F m_W^2}{2\pi^2\sqrt{2}} \ln(\frac{m_t}{m_Z}) + \ldots \qquad (7)$$

$$\varepsilon_3 = \frac{G_F m_W^2}{12\pi^2\sqrt{2}} \ln(\frac{m_H}{m_Z}) - \frac{G_F m_W^2}{6\pi^2\sqrt{2}} \ln(\frac{m_t}{m_Z}) + \ldots$$

In passing, we note the following interesting alternative expression for the leptonic width in terms of $\bar{s}_W^2$, defined in eqs.(2-5) and ε_3 (valid in linear approximation in ε_1 and ε_3):

$$\Gamma_l = \frac{\alpha(m_Z) m_Z}{48 \bar{s}_W^2 \bar{c}_W^2} (1 + \frac{\varepsilon_3}{\bar{c}_W^2}) [1 + (1 - 4\bar{s}_W^2)^2] \qquad (8)$$

The definitions in eqs.(1-6) are quite general and do not commit us to any particular model. The epsilons are useful in that they provide a very efficient parametrization of the most important input data with respect to the sensitivity to new physics so that they represent a convenient starting point for a model-independent analysis of the data.One can then formulate a hierarchy of simple and rather general assumptions valid in large classes of models which are needed in order to relate the epsilons to a progressively larger set of observables.

First, very mild assumptions are required in order that all other observables related to charged leptons at the Z pole are uniquely determined by the ε_i. For example, we have in

mind, apart from Γ_l and A_{FB}^l, the τ-polarisation asymmetry A_{pol}^τ and the left-right asymmetry A_{LR}. This is true in all models where the contributions of new physics only occur either through vacuum polarisation terms [9],[11], [15-17] and/or in $Z \to l^+l^-$ vertex corrections of the form

$$\Delta V_\mu(Z \to l^+l^-) = \bar{u}\, (\Delta g_A \gamma_5 + \Delta g_V)\, \gamma_\mu u \qquad (9)$$

with Δg_V and Δg_A real form factors universal for all charged lepton flavours. These two kinds of contributions cannot be disentangled if we only consider on-shell Z properties in the charged lepton sector. Clearly in the Standard Model there are corrections to the leptonic observables at the Z pole (box diagrams, imaginary parts of vertex form factors) which violate the above assumptions. As we shall see in the following, these small corrections can be explicitly taken into account by adding a known constant, i.e. one independent of m_t and m_H.

Stronger hypotheses about possible forms of new physics are needed if one wants to relate the epsilons to observables involving quarks or neutrinos,like the hadronic widths or asymmetries, or to observables measured at low q^2, far from the Z pole (e.g. deep inelastic neutrino-nucleus scattering, ν-e scattering and atomic parity violation in atomic physics). For example, we could restrict ourselves to the case of new physics in oblique corrections with the assumption that the q^2-dependence of the relevant vacuum polarisation amplitudes is weak enough for all second and higher order derivatives in q^2 to be safely neglected [15-17].

In principle, because m_t is unknown, the observables related to the b-quark, e.g. the b-partial width and the forward-backward b asymmetry A_{FB}^b, cannot be obtained from the ε_i's even if the new physics only occurs in oblique and/or in universal Z-vertex corrections. This is because of the large m_t-dependent Standard Model corrections to the $Z \to b\bar{b}$ vertex [18]. As a consequence the relation between the previous ε_i's and Γ_b or A_{FB}^b can only be specified for a given value of m_t. However, in practice, the sensitivity to the new quadratic terms in m_t^2 from the $Z \to b\bar{b}$ vertex is only present in Γ_b, while, as we shall see, it is almost non-existent, at realistic values of m_t, for A_{FB}^b.

In the following we will discuss the results on $\varepsilon_1, \varepsilon_2$ and ε_3 that are implied by the present experimental data. Then we study the predictions of the Standard Model for the same quantities as functions of m_t and m_H. Particular attention is devoted to evaluating the theoretical errors. In fact $\varepsilon_1, \varepsilon_2$ and ε_3 are very small and sensitive to every detail of the calculation of radiative corrections (e.g. choice of parameters, renormalization scheme and so on). This study allows us to establish the connection of the epsilons, as defined in eqs.(1-6), with the other observables that we mentioned(A_{pol}^τ, A_{LR}, A_{FB}^b, neutrino scattering and atomic parity violation). Finally we discuss how the analysis of present data can be performed in stages with an increasing number of particular assumptions and we examine the conclusions that can be derived at each stage.

2. EXPERIMENTAL RESULTS

The hadron collider data on the W mass are conveniently expressed in terms of the ratio m_W/m_Z which is not affected by calibration errors. The CDF and UA2 results are [19]:

$$m_W/m_Z = 0.8768 \pm 0.0046 \quad \text{(CDF)}$$
$$= 0.8841 \pm 0.0043 \quad \text{(UA2)}$$
$$= 0.8807 \pm 0.0031 \quad \text{Average} \qquad (10)$$

By combining this last number with the LEP value for the Z mass: $m_Z = 91.174 \pm 0.021$ GeV, and using eq.(1) one obtains:

$$\Delta r_W = (-2.2 \pm 1.7)\,10^{-2} \qquad (11)$$

The LEP results on the charged lepton partial width and the forward-backward asymmetry, assuming e-μ-τ universality, are given by:

$$\Gamma_l = (83.3 \pm 0.4)\ \text{MeV} \qquad (12)$$

$$A^l_{FB}(\sqrt{s} = m_Z) = 0.0154 \pm 0.0048 \qquad (13)$$

From these values one finds:

$$g_A^2 = 0.2499 \pm 0.0013 \qquad (14)$$

$$g_V/g_A = 0.072 \pm 0.011 \quad \text{or} \quad \bar{s}_W^2 = 0.2319 \pm 0.0028 \qquad (15)$$

One can now use eqs. (4) to derive the results for $\Delta\rho$ and $\Delta k'$:

$$\varepsilon_1 = \Delta\rho = (-0.05 \pm 0.51)\,10^{-2} \qquad (16)$$

$$\Delta k' = (0.19 \pm 1.21)\,10^{-2} \qquad (17)$$

Finally the corresponding results for ε_2 and ε_3 are obtained from eqs.(6):

$$\varepsilon_2 = (-1.07 \pm 1.00)\,10^{-2} \qquad (18)$$

$$\varepsilon_3 = (0.07 \pm 0.86)\,10^{-2} \qquad (19)$$

We can make contact with the notation of refs.[15-16] by setting $\Delta\rho = \alpha T$, $\varepsilon_2 = -\alpha U/(4s_0^2)$ and $\varepsilon_3 = \alpha S/(4s_0^2)$. We then obtain:

$$S = 0.1 \pm 1.1 \quad , \quad T = -0.06 \pm 0.69 \, , \quad U = 1.4 \pm 1.3 \qquad (20)$$

Note, however, that in refs.[15-16] S and T are defined in the specific context of dominance of vacuum polarisation corrections from new physics, while the present definitions are general. Also, in refs.[15-16] S and T are defined as deviations from the theoretical predictions of the Standard Model for given values of m_t and m_H, while the values in eq.(20) are unsubtracted.

3. PREDICTIONS OF THE STANDARD MODEL

In this section we study ε_1, ε_2 and ε_3 in the Standard Model. In particular we want to estimate the theoretical errors on each of these quantities at fixed values of m_t and m_H. In fact the epsilons are small shifts from unity obtained as results of relative differences of large numbers. Thus it turns out that a considerable uncertainty is present even in the most refined existing calculations of radiative corrections.

The relevant quantities were calculated with two programme packages for evaluating electroweak libraries, one from the Dubna-Zeuten group, named DIZET [20], based on refs. [21] and another due to Hollik [22]. These packages were taken in exactly the same form as they are implemented in the KORALZ Monte Carlo programme [23], by using CALASY interface code [24]. The most reliable values of the predicted quantities are obtained from DIZET with inclusion of the corrections of order $\alpha\alpha_s$ to vacuum polarisation amplitudes [26]which have been included in the DIZET version of KORALZ (see ref. [25] for more details and additional references). These predictions will be concisely denoted as "best". However, as the corrections of order $\alpha\alpha_s$ are not available for most of the cases, for an estimate of the theoretical uncertainties we have studied the dispersion of the results from the existing codes without such refinement, also including DIZET without $\alpha\alpha_s$ corrections.For some of the calculations we also checked our results with other existing codes, such as for example EXPOSTAR [27], or with detailed published calculations [28].

We first consider m_W (which is in one-to-one relation with Δr_W and can therefore be replaced by it) together with Γ_l and A_{FB}. In Tables 1-3 the "best" results for these quantities are shown and the dependence on the computing programme is also displayed.The first column shows the "best" results. The second column is again based on DIZET but with the corrections of order $\alpha\alpha_s$ set to zero. The third column shows the results from the Hollik library. Further columns, when present, display results from additional codes, as specified in the Table caption.The "best" results for Δr_W, Γ_l and A_{FB} are shown in full detail as functions of m_t and m_H in figs.1-3 together with the corresponding experimental numbers quoted in the previous section. We see from Tables 1-3 that the differences among homogeneous programmes (i.e. those which are a priori equivalent and not including the $\alpha\alpha_s$ corrections) are, at fixed m_t and m_H, typically of order of $\pm$ a few per cent in the case of Δr_W, of less than about $\pm$ 0.1 MeV for Γ_l and of about $\pm$ 1-2 per cent for A_{FB}. A similar exercise done for A^τ_{pol} or A_{LR} leads to relative errors below $\pm$1%. Note that the present precision of experimental data is of $\pm$77% for Δr_W, of $\pm$0.48% ($\pm$0.4 MeV) for Γ_l and of $\pm$31% for A_{FB}. The ultimate precision expected is of about $\pm 3\cdot 10^{-3}$ on Δr_W (corresponding to about $\pm$50 MeV on m_W), of $\pm$ 0.2 MeV (or so) on Γ_l and of order $\pm$ 10% on A_{FB}. Thus the present theoretical uncertainties are well commensurate with the experimental possibilities.

We now consider ε_1, ε_2 and ε_3. In Tables 4 a-c we compare the results obtained from different codes for these quantities.For the determination of theoretical errors one should compare the second and third columns, or the results listed from the fifth column on. Note however that the first three columns refer to A_{FB} as the defining asymmetry, while from the fourth onwards A^{τ}_{pol} or A_{LR} are adopted to define g_A and g_V (see below). From Table 4 we see that $\varepsilon_1 = \Delta\rho$ appears to be affected by large uncertainties at small m_t, while for m_t larger than 120 GeV, $\Delta\rho$ is determined to better than $\pm 20\%$ or so, with increasing precision at larger m_t. The relative error on ε_2 is apparently smaller, of order $\pm$ 5-10%. Finally the determinations of ε_3 have variable errors, from $\pm$ a few per cent up to $\pm$ 20%, depending on the values of m_t and m_H. In general we see that one cannot expect a great precision on the epsilons, but the same remark also applies to the experimental measurements of the same quantities. In fig. 4 the best values of the epsilons are shown together on the same scale.Note that indeed ε_2 and ε_3 are much flatter than ε_1 in m_t (this is expecially true for ε_3, while some dependence is still visible in ε_2 due mainly to logarithmic terms in m_t which are three times larger for ε_2 than for ε_3, as is seen from eqs.(7). In figs.5-7 the "best" results are displayed and compared with the present experimental values.Only the comparison of $\Delta\rho$ from theory and experiment implies a strong constraint on m_t, while for ε_2 and ε_3 one observes consistency with the Standard Model with no important constraints on m_t and m_H. However, ε_2 and ε_3 impose interesting bounds on new physics, as we shall see.

The corrections of order $\alpha\alpha_s$ are only important for Δr_W and $\Delta\rho$, where they amount to a 10-15% shift.

4. OTHER OBSERVABLES AT THE Z-POLE

In the Standard Model, the knowledge of ε_1 and ε_3 allows one to determine all other observables measured at the Z pole and related to charged leptons, such as A^{τ}_{pol} and A_{LR}. As mentioned in the introduction, this is also true in a very large class of models where new physics only contributes at $q^2 = m_Z^2$ through either vacuum polarisation amplitudes and/or vertex corrections of a form as in eq.(9) It is therefore worthwhile to establish this connection in as general terms as possible.

Together with eq.(2), but in place of eq.(3), one could have used A^{τ}_{pol} to define the effective on-shell vector and axial vector Z couplings to charged leptons, via the relation:

$$A^{\tau}_{pol} = \frac{2g'_A g'_V}{g'^2_V + g'^2_A} \tag{21}$$

We have adopted different symbols for the effective couplings because g_V and g_A, defined from A_{FB}, certainly cannot be confused with g'_V and g'_A obtained from A^{τ}_{pol}, to the level of accuracy at which the LEP experiments are aiming. On the contrary A^{τ}_{pol} and A_{LR} can be considered as equivalent in this respect. In fact we have checked that the relative differences between the two asymmetries are smaller than 10^{-4} in the Standard Model.

The set of ε'_i, related to g'_A and g'_V in the same way as the set of ε_i to g_A and g_V as in eqs.(4), are also sizeably different. This is clearly visible in Tables 4 a-c, where the

two sets of epsilons are compared for given values of m_t and m_H in the Standard Model.The differences on the epsilons in the two definitions are displayed in figs.8a-c. One can easily understand the observed pattern of corrections. The same effective $\sin^2\theta_W$ would describe A_{FB} and A^{τ}_{pol} when only quadratic and logarithmic terms in m_t and m_H are included, because such terms only arise from vacuum polarisation diagrams, which affect the asymmetries in the same way. Thus the effective values of $\sin^2\theta_W$ defined from one or the other asymmetry can only differ by a constant term in m_t and m_H. In fact numerically we find:

$$(\bar{s}^2_W)_{pol} = (\bar{s}^2_W)_{FB} + \delta \quad : \quad \delta = (1.3 \pm 0.2)\ 10^{-3} \tag{22}$$

This shift on $\bar{s}^2_W$ immediately implies a difference in $\Delta k'$ by δ/s_0^2 and also a shift on $\Delta\rho$ due to the fact that the width Γ_l and hence the combination $g_A^2(1 + g_V^2/g_A^2)$ have to remain unchanged. This implies $(\Delta\rho)_{pol} = (\Delta\rho)_{FB} + 8\delta(1-4s_0^2)$. Note that while the variation of $\Delta k'$ is enhanced by $1/s_0^2$ that of $\Delta\rho = \varepsilon_1$ is suppressed by $8(1-4s_0^2)$. As Δr_W is unchanged, the corresponding changes of ε_2 and ε_3 are determined in terms of those of $\Delta k'$ and $\Delta\rho$ by eqs.(6).For $\delta = 1.3\ 10^{-3}$ one obtains $\delta\varepsilon_1 = 0.77\ 10^{-3}$, $\delta\varepsilon_2 = -2.0\ 10^{-3}$ and $\delta\varepsilon_3 = 3.6\ 10^{-3}$, where $\delta\varepsilon_i = \varepsilon'_i - \varepsilon_i$. These numbers are in good agreement with the results displayed in figs.8a-c.

Clearly, by the same argument that leads to the independence of $\delta\varepsilon_i$ from m_t and m_H, one obtains that the same shifts also apply to all cases of new physics in oblique or universal vertex corrections. Starting from the experimental value of A^{τ}_{pol} obtained by ALEPH [29] (see also fig.9):

$$A^{\tau}_{pol} = 0.152 \pm 0.045 \tag{23}$$

which corresponds to (from eq.21 using $g'_V/g'_A = 1 - 4(\bar{s}^2_W)_{pol}$)

$$(\bar{s}^2_W)_{pol} = 0.2309 \pm 0.0057 \tag{24}$$

we can apply the correction in eq.(22) and obtain $(\bar{s}^2_W)_{FB} = 0.2296 \pm 0.0057$ and hence a new value for $\Delta k'$:

$$\Delta k' = (-0.80 \pm 2.5)\ 10^{-2} \tag{25}$$

We now proceed to consider quantities that involve quarks and are measured at the Z pole. In the Standard Model, to obtain a prediction for these quantities a range of values for $\alpha_s(m_Z)$has to be assumed. Also, the large quadratic terms in m_t from the $Z \to b\bar{b}$

vertex are to be taken into account. Beyond the Standard Model, it is obvious that a stronger form of universality must be assumed in order to directly transfer into the quark sector the information embodied by the ε_i's measured in the charged lepton sector. Quark-lepton universality is automatic in the case of oblique corrections, while it is in general violated if vertex corrections are important.

Particularly important quantities, independent of $\alpha_s(m_Z)$, are Γ_b/Γ_h and A^b_{FB}. Similar quantities for charm or light quarks are not equally interesting both in terms of experimental precision and because of the large m_t terms [18] in the $Z \to b\bar{b}$ vertex corrections. For example, the data on Γ_b/Γ_h in principle allow us to set a bound on m_t which is independent of assumptions on the absence of exotic contributions to ε_1. However, such a limit is not very interesting at the moment because a comparatively large error is introduced by ambiguities associated with the semileptonic branching ratio or by other uncertainties in the case of DELPHI that uses a purely hadronic b-selection criterium. On the contrary, A^b_{FB} is almost unaffected by the presence of large m_t-dependent vertex corrections. Schematically the reason is that $A^b_{FB} = 3\eta_e\eta_b$ with $\eta = g_V g_A/(g_V^2 + g_A^2)$, so that $\delta A^b_{FB} = 3(\eta_e\delta\eta_b + \eta_b\delta\eta_e)$. We see that the sensitivity on η_b, which contains the $Z \to b\bar{b}$ vertex correction, is strongly suppressed by the small factor η_e. This is confirmed by an accurate numerical calculation of A^b_{FB}. If we define a new quantity $(\bar{s}^2_W)_b$ by the identity:

$$A^b_{FB} = 3\,\frac{1-4(\bar{s}^2_W)_b}{1+(1-4(\bar{s}^2_W)_b)^2}\;\frac{\beta(1-\frac{4}{3}(\bar{s}^2_W)_b)}{\frac{3-\beta^2}{2}+\beta^2(1-\frac{4}{3}(\bar{s}^2_W)_b)^2} \qquad (26)$$

where $\beta=\sqrt{1-4m_b^2/m_Z^2}$, we can explicitly evaluate the relation, as a function of m_t and m_H, between $(\bar{s}^2_W)_b$ and the similar quantity $(\bar{s}^2_W)_{FB}$ previously defined from the charged lepton asymmetry A^l_{FB}. We obtain the result which is displayed in fig.10, which can be summarised by the statement:

$$(\bar{s}^2_W)_b = (\bar{s}^2_W)_{FB} + \delta_b\ ,\ \delta_b = (0.9 \pm 0.15)\ 10^{-3} \qquad (27)$$

(valid for m_t = 90-300 GeV, m_H = 50-1000 GeV).

As a consequence, if quark-lepton universality is assumed, one can use the present combined LEP result on A^b_{FB} [30] (after correction for B-$\bar{B}$ mixing):

$$A^b_{FB} = 0.125 \pm 0.024 \qquad (28)$$

(see also fig.11) which is equivalent, by eq.(26), to

$$(\bar{s}^2_W)_b = 0.2275 \pm 0.0044 \qquad (29)$$

and obtain an independent input on $\Delta k'$. In fact we derive from eqs.(27) and (29) that $(\bar{s}^2_W)_{FB} = 0.2266 \pm 0.0044$, and then, from eq.4, the result:

$$\Delta k' = (-2.1 \pm 1.9)\ 10^{-2} \qquad (30)$$

5. LOW q^2 MEASUREMENTS

While flavour universality of new physics is the crucial assumption that is needed to relate different measured quantities at the Z pole, some hypotheses on the absence of new sources of substantial q^2 dependence have to be formulated in order to add low energy measurements to the picture. Actually, in most of the relevant cases both flavour universality and q^2 independence have to be combined in order to make contact with important experiments, such as ν (or $\bar{\nu}$)-N deep inelastic scattering and atomic parity violation. In models where oblique corrections, which directly possess flavour universality are dominant, sizeable q^2-dependent effects from new physics are absent if terms involving second and higher derivatives with respect to q^2 can be neglected in vacuum polarisation form factors. This is a good approximation in models with no decoupling, where first-order derivatives lead to effects of order 1 in the limit when the scale Λ of new physics becomes very large. On the other hand, in models with decoupling, like those considered in ref.[31], first order derivatives are of order v^2/Λ^2, where v is a parameter of the order of the electroweak scale (typically the Higgs vacuum expectation value). In this case the effect of second-order derivatives, of order m_Z^2/Λ^2, is not relatively negligible. Note, however, that in these models both effects are quite small unless the scale Λ of the new physics is very close to the domain of energies of present experiments.

If one assumes flavour and lepton-quark universality and no additional q^2-dependence, the available data on neutrino-nucleus deep inelastic scattering and on parity violation in Cs atoms lead to further constraints on ε_1 and ε_3, while they have no direct effect on ε_2. The present data [32] on R_ν and $R_{\bar{\nu}}$, the ratios of neutral to charged current processes in deep inelastic neutrino or antineutrino scattering on nuclei, imply the following constraints [33-34]:

$$R_\nu:\ \varepsilon_1 - 0.34\,\varepsilon_3 = (-0.07 \pm 0.45)\ 10^{-2}$$

$$R_{\bar{\nu}}:\ \varepsilon_1 - 0.02\,\varepsilon_3 = (1.34 \pm 0.95)\ 10^{-2} \qquad (31)$$

with our definition of the epsilons (for comparison, we also report the result from the ratio of neutrino to antineutrino scattering on electrons [35], which gives [33-34] $\varepsilon_3 - 0.74\,\varepsilon_1 = (0.13 \pm 2.12)\ 10^{-2}$)

Similarly, the results on parity violation in Cs lead to a value of ε_3, while the sensitivity to ε_1 is accidentally almost exactly cancelled due to the particular ratio of protons to neutrons in Cs [33]. Neglecting the ε_1 contribution,one finds in this case the general result [33]:

$$Q_W = -72.84 \pm 0.13 - 102\varepsilon_3 \quad (32)$$

The present experimental value [36-37]

$$(Q_W)_{exp} = -71.04 \pm 1.81 \quad (33)$$

implies the result:

$$\varepsilon_3 = (-1.8 \pm 1.8)\ 10^{-2} \quad (34)$$

Note that in eqs.(31,34) the quoted values for ε_1 and ε_3 are inclusive of all standard and possibly non-standard effects.

6. DIFFERENT FORMS OF NEW PHYSICS AND THEIR EFFECTS

In a large variety of different models the epsilon parameters are suitable for a discussion of the possible effects of new physics on the various observables. There is an extensive and still rapidly growing literature on the subject. Obviously it is impossible to give a full account of all possibilities of new physics. Thus, in the following we outline the main features of a number of significant examples.

Supersymmetry. In the Minimal Supersymmetric Standard Model (MSSM) [38] the corrections to the ε_i's vanish as inverse powers of the mass when all the new degrees of freedom, with respect to the Standard Model, become infinitely heavy (decoupling). If all s-partners are outside the mass range accessible at LEP200, all significant corrections are concentrated in vacuum polarisation amplitudes. Their effects for on-shell Z observables are then conveniently described by the epsilons. Some small residual contributions to scaling violations could be induced in observables measured at low q^2, arising from second derivatives of vacuum polarisation form-factors. The case of the MSSM, where the property of decoupling is valid, is one to which the analysis of ref.[31], based on an operator product expansion, can be applied.

As a matter of fact, in the MSSM, when all the s-partners are outside the range accessible at LEP200, for whatever spectrum of the enlarged Higgs sector, the radiative corrections reproduce to a good accuracy those of the Standard Model with a relatively light Higgs [39]. In particular in the MSSM we expect $\varepsilon_3 \simeq (0.3\text{-}0.4)\ 10^{-2}$. The only possible exception would be the case of a large and positive contribution of the $\tilde{t}$ - $\tilde{b}$ doublet of s-quarks to ε_1, if the $\tilde{t}$ - $\tilde{b}$ mass splitting were comparable to their mean mass [40]. On the other hand, with s-partners just outside the LEP1 kinematical domain, small non-universal contributions could arise [41] which would complicate the relations among the different observables that we have considered.

Technicolour. With some uncertainty, it is possible to estimate the contribution to ε_3 from a full technicolour generation with the same $SU(2)\otimes U(1)$ quantum numbers of a standard quark-lepton family and an SU(4) technicolour group. Using a dispersive approach, ε_3 can be expressed in terms of the spectral functions of the vector and axial vector isospin currents [16]. For an actual estimate, specific hypotheses about the actual dynamics have to be made, like fixing the masses and couplings of the technipions and of the vector and axial resonances. In a variety of models [16-17], [42-43] one gets

$$\varepsilon_3(1\ \text{technifamily}) = (1.3 - 2.0)\ 10^{-2} \quad (35)$$

where we have also included all the Standard Model effects. In models with a strongly interacting electroweak symmetry-breaking sector, lower values of ε_3 can also be obtained [42], but that appears to require a departure from a QCD-like technicolour dynamics.

Unlike the case for ε_3, in technicolour models it is difficult to make a definite statement about the isospin breaking parameter ε_1, since the source of the large top-bottom mass splitting is not clearly identified. On the other hand, the parameter ε_2 is generally believed to be close to the Standard Model value.

Heavy elementary fermions. The contributions in vacuum polarization amplitudes of heavy elementary fermions decouple in the large mass limit only if their mass terms are $SU(2)\otimes U(1)$ symmetric. If they are not, they can contribute to all ε_i's with terms of either sign, depending on the $SU(2)\otimes U(1)$ quantum numbers of the different helicity components and the values of the Yukawa couplings [44-45]. In general, several (often more than 10) $SU(2)\otimes U(1)$ multiplets are needed to get effects to the epsilons of about 1%. As a well-known example, a heavy degenerate lepton doublet with the usual quantum numbers contributes with a term $\Delta\varepsilon_3 = 0.4\ 10^{-3}$ [44].

Anomalous WWγ and WWZ couplings. In a phenomenological approach, if the trilinear couplings of the W to the photon and the Z deviate from the Standard Model ones [46-47] divergent contributions to the epsilons arise which, although cut-off in an ad hoc way and therefore uncertain, can be large. For example, in the case of non-zero quadrupole moment type couplings of the W to the photon and the Z, the dominant effects arise in ε_2 and ε_3 with terms that can be of either sign [9].

New U(1) gauge bosons. The case of extended gauge models [48-50 provides a particularly interesting example. Our approach being completely general, it is straightforward to evaluate the effect on the epsilons induced both by the Z-Z' mixing and by the couplings to charged leptons of the new Z', denoted by v' and a'. In fact, on the peak of the light physical Z, the effective couplings g_V and g_A are given by (see, for example, ref.[50]):

$$g_V = -\frac{1}{2}\sqrt{\rho_{SM}}\left(1 + \frac{\Delta\rho_M}{2}\right)[\cos\xi\,(1-4\,\bar{s}_W^2) - 2\sin\xi\ v']$$

$$g_A = -\frac{1}{2}\sqrt{\rho_{SM}}\left(1 + \frac{\Delta\rho_M}{2}\right)[\cos\xi\ - 2\sin\xi\ a'] \quad (36)$$

where ξ is the mixing angle and ρ_{SM} is the Standard Model quantity, while $\Delta\rho_M$ is the additional shift due to the mixing (at tree level $m_{Z_S}^2 = (1 + \Delta\rho_M)\, m_Z^2$ with Z_S and Z being the unmixed standard and the physical neutral vector boson state, respectively) and one has

$$\left(1 - \frac{m_W^2}{m_Z^2}\right)\frac{m_W^2}{m_Z^2} = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F m_Z^2(1-\Delta r_W)}\ \frac{1}{1 + \dfrac{\bar{c}_W^2\Delta\rho_M}{\bar{s}_W^2}} \quad (37)$$

$\bar{\bar{s}}_W^2$ is the effective $\sin^2\theta_W$ modified by the mixing with respect to the ordinary one according to:

$$\bar{\bar{s}}_W^2 = \bar{s}_W^2 - \frac{\bar{s}_W^2 \bar{c}_W^2}{\bar{c}_W^2 - \bar{s}_W^2} \Delta\rho_M \qquad (38)$$

At first order in $\Delta\rho_M$ and $\tan\xi$ one obtains:

$$\Delta\varepsilon_1 = \Delta\rho_M - 4\, a' \tan\xi$$

$$\Delta\varepsilon_2 = \tan\xi \left[\frac{-v'}{1-4\bar{s}_W^2} + (1-4\bar{c}_W^2)\, a' \right] \qquad (39)$$

$$\Delta\varepsilon_3 = \tan\xi \left[\frac{v'(\bar{c}_W^2 - \bar{s}_W^2)}{2(1-4\bar{s}_W^2)\bar{s}_W^2} - \frac{a'(\bar{c}_W^2 - \bar{s}_W^2 + 8\, \bar{c}_W^2\, \bar{s}_W^2)}{2\bar{s}_W^2} \right]$$

Note the enhancement factor $(1-4\bar{s}_W^2)^{-1}$ that multiplies the vector coupling v'. When v' is not suppressed with respect to a', the v' terms are largely dominant.

Thus, on the one hand, one can express the shifts of the epsilons in terms of $\Delta\rho_M$, $\tan\xi$, v' and a' and obtain from the measured value of the ε_i's general constraints on these parameters. On the other hand, if the extended gauge model is not completely specified, one cannot relate the charged lepton sector to the quark sector or go from the experiments at the Z peak to those at low q^2. In fact, the Z' couplings usually break flavour universality and moreover the diagrams with the heavy Z exchange introduce a possibly sizeable additional q^2 dependence.

7. DISCUSSION OF RESULTS AND CONCLUSION

We now start from the model-independent determination of the epsilons given in sect.2 and progressively make various stages of assumptions that allow us to combine an increasing large set of data. We first assume that there are no new physics effects that can invalidate the connection with A^{τ}_{pol} (e.g. peculiar four-fermion interactions which could affect A^{l}_{FB} but not A^{τ}_{pol}). As a second step we assume flavour and lepton-quark universality and we include hadronic quantities measured at the Z-peak. In particular we consider A^{b}_{FB} which is precisely measured and relatively unaffected by $\alpha_s(m_Z)$. Then, in addition, we assume the absence of additional sources of q^2 dependence beyond the Standard Model and include neutrino-nucleus deep inelastic scattering and parity violation in Cs atoms. Finally, we can recover the case of the Standard Model as a very important particular case.

The inclusion of the data on A^{τ}_{pol} allows us to combine the values of $\Delta k'$ given in eqs.(17) and (25), thus obtaining:

$$\Delta k' = (0.0 \pm 1.1)\ 10^{-2} \qquad (40)$$

We can then evaluate ε_1, ε_2 and ε_3 by using the values of Δr_W and Γ_l given in eqs. (11) and (12) and the above value of $\Delta k'$. This gives:

$$\varepsilon_1 = \Delta\rho = (-0.07 \pm 0.50)\ 10^{-2}$$

$$\varepsilon_2 = (-1.0 \pm 0.97)\ 10^{-2}$$

$$\varepsilon_3 = (-0.05 \pm 0.79)\ 10^{-2} \qquad (41)$$

This stage is permissible in all models discussed in the previous section, including the case of a new Z' from an extra U(1) (provided the universality of charged leptons is maintained).

We now add hadronic quantities measured at the Z pole. The b-asymmetry A^{b}_{FB} leads to the determination of $\Delta k'$ given in eq.(30) which can be combined with those leading to eq.(40). The resulting value is:

$$\Delta k' = (-0.52 \pm 0.94)\ 10^{-2} \qquad (42)$$

At this stage one could also include the hadronic width Γ_h and/or the total width Γ_Z, for $\alpha_s(m_Z)$ varying in a specified interval, for example in the range measured at LEP, as given in the introduction. The presence of large vertex corrections in the $Z \to b\bar{b}$ vertex makes the relation with the epsilons strongly m_t dependent (as is also the case for Γ_b/Γ_h). For these reasons we restrict our attention to A^{b}_{FB} at this stage. For the epsilons we then obtain:

$$\varepsilon_1 = \Delta\rho = (-0.14 \pm 0.50)\ 10^{-2}$$

$$\varepsilon_2 = (-0.82 \pm 0.93)\ 10^{-2}$$

$$\varepsilon_3 = (-0.39 \pm 0.71)\ 10^{-2} \qquad (43)$$

The next step, valid if the effects of a large q^2 difference can be described as in the Standard Model, is to include the low energy data, in particular neutrino-nucleus deep inelastic scattering and parity violation in Cs atoms. By combining the low energy results given in eqs.(31) to (34) with the rest of the data one finds:

$$\varepsilon_1 = \Delta\rho = (-0.02 \pm 0.37)\ 10^{-2}$$

$$\varepsilon_2 = (-0.71 \pm 0.89)\ 10^{-2}$$

$$\varepsilon_3 = (-0.31 \pm 0.62)\ 10^{-2} \qquad (44)$$

At each stage, in the ε_1-ε_3 plane, the experimental result is compared in figs.12 a to d with the predictions of the Standard Model for different values of m_t and m_H. It is well known that the data on atomic parity violation in Cs push the value of ε_3 on the negative side [see eq.(34)]. We see that this tendency toward negative values of ε_3 is also supported by the very recent data on A^b_{FB} (see eq.43). The effect of A^b_{FB} can be appreciated from fig.12e which is a fit to the same data as fig.12d but with A^b_{FB} removed. As seen from the overall summary in fig.12d, the central value of ε_3 is negative and about 1σ away from the Standard Model prediction. Clearly, models where an additional positive contribution to ε_3 is predicted are a fortiori discouraged, as is the case for the class of technicolour models leading to eq.(35). The values of ε_2 are consistent with the Standard Model, with a still rather large error (fig.13).

Finally, if we come back to the Standard Model, the strong upper limit on m_t which follows from the value of ε_1 in eq.(44) is already evident from fig.12d. A precise determination of the limit on m_t is obtained by re-evaluating ε_1 with ε_3 fixed at its Standard Model value, given by ε_3=0.30 10^{-2} (0.55 10^{-2}) for m_H= 50 GeV (1TeV). One obtains m_t = 130 ± 35 GeV, with the central value near m_t = 115 (150)GeV for light (heavy) Higgs. At the 1.64σ level we find m_t < 165 (195) GeV for m_H =50-100 GeV (1TeV), where the data on Γ_T and Γ_h were also included in this case (with the value of $\alpha_s(m_Z)$ measured at LEP, as given in the Introduction). Light values of m_H are preferred because they correspond to smaller values of ε_3.

Summarising, we have shown that it is possible and indeed useful to introduce the parameters ε_1, ε_2 and ε_3 (or equivalently S, T and U) following a general definition independent on assumptions like the dominance of oblique corrections as were made in previous discussions. The presence of three parameters is related to the fact that m_W/m_Z, Γ_l and A^l_{FB} carry qualitatively different information and are the most precisely measured observables defined at the W/Z mass scale (beyond the input parameter m_Z). ε_2 and ε_3 are good indicators for the presence of new physics effects, because the uncertainties due to our ignorance of m_t are concentrated in ε_1. The epsilons have been studied in the Standard Model as functions of m_t and m_H and the associated theoretical errors were extimated. ε_3 turns out to be particularly interesting, being independent of m_t with very good accuracy, sensitive to the Higgs sector and likely to collect large contributions in models with no decoupling. Present data on A^b_{FB} and on parity violation in atomic Cesium favour values of ε_3 smaller than in the Standard Model (although compatible with it).

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REFERENCES

[1] G.J. Bobbink, Proceedings of the XXVI Rencontre de Moriond, Les Arcs, France, 1991.

[2] P. Ratoff, ibidem.

[3] P. Langacker, M. Luo, Univ. of Pennsylvania preprint UPR-04465 (1991).

[4] CDF Collaboration, F. Abe et al., FERMILAB-PUB 90-1373 (1990).

[5] ALEPH Collaboration, D. Decamp et al., CERN preprint PPE/91-019 (1991).

[6] For reviews, see, e.g., M. Sher, Phys. Rep. 179 (1989) 275;
L. Maiani, Proceedings of the Cargèse Summer School, 1990, Rome Univ. preprint N. 775 (1991).

[7] See, for a review, S. Bethke, CERN preprint PPE/91-36 (1991).

[8] M. Consoli et al., in "Z Physics at LEP1", eds. G. Altarelli et al., CERN89-08 (1989).

[9] G. Altarelli and R. Barbieri, Phys. Lett. B253 (1990) 161.

[10] M.Consoli,S.Lopresti and L.Maiani, Nucl. Phys. B223 (1983) 472

[11] D.C. Kennedy and B.W. Lynn, Nucl. Phys. B322 (1989) 1;
D.C. Kennedy et al., Nucl. Phys. B231 (1989) 83;
B.W. Lynn, SU-ITP-867 (1989).

[12] A. Sirlin, CERN preprint TH.5506/89 (1989).

[13] M. Veltman, Nucl. Phys. B123 (1977) 89;
M.S. Chanowitz et al., Phys. Lett. 78B (1978) 285.

[14] G. Passarino and M. Veltman, Nucl. Phys. B160 (1979) 151.

[15] D.C. Kennedy and P. Langacker, Phys. Rev. Lett. 65 (1990) 2967 and preprint UPR-0467T;
A Ali and G. Degrassi, DESY preprint DESY 91-035 (1991).

[16] M.E. Peskin and T. Takeuchi, Phys. Rev. Lett. 65 (1990) 964.

[17] B. Holdom and J. Terning, Phys. Lett. B247 (1990) 88;
M. Golden and L. Randall, Fermilab-Pub 90-83-T (1990);
A. Dobado et al., Phys. Lett. B255 (1991) 405;
R.D. Peccei and S. Peris, UCLA preprint UCLA/TEP/91/13 (1991).

[18] A.A. Akundov et al., Nucl. Phys. B276 (1988) 1;
F. Diakonov and W. Wetzel, HD-THEP-88-4 (1998);
W. Beenakker and H. Hollik, Z. Phys. C40 (1988) 569;
J. Bernabeu, A. Pich and A. Santamaria, Phys. Lett. B200 (1988) 569; CERN preprint CERN_TH.5931/90 (1990);
B.W. Lynn and R.G. Stuart, CERN preprint TH.5786/90 (1990).

[19] CDF Collaboration, F. Abe et al., Phys. Rev. Lett. 65 (1990) 2243;
UA2 Collaboration, G. Unal, Proceedings of the XXVI Rencontre de Moriond, Les Arcs, France (1991).

[20] D. Bardin et al., Comp. Phys. Commun. 59 (1990) 303.

[21] A. Akhundov et al., Nucl. Phys. B276 (1986) 1;
D. Bardin et al., Z. Phys. C44 (1989) 493.

[22] W. Hollik, Fortsch. f. Physik 38 (1990) 65.

[23] S. Jadach, B.F.L. Ward and Z. Was, CERN preprint TH.5994/91 (1991), to be published in Comp. Phys. Comm.

[24] S. Jadach and Z. Was, in "Z Physics at LEP1", eds. G. Altarelli, R. Kleiss and C. Verzegnassi, CERN-89/08, Vol. 3, p. 58 (1989).

[25] T. Riemann, M. Sachwitz and Z. Was, CERN preprint TH.5964/90 (1990).

[26] A. Djouadi and C. Verzegnassi, Phys. Lett. B195 (1987) 265;
B.A. Kniehl, J.H. Kühn and R.G. Stuart, Phys. Lett. B214 (1988) 621;
B.A. Kniehl, Nucl. Phys. B347 (1990) 89;
F. Halzen and B.A. Kniehl, Nucl. Phys. B353 (1991) 567.

[27] D.C. Kennedy et al., Nucl. Phys. B321 (1989) 83.

[28] S. Fanchiotti and A. Sirlin, Preprint NYU-Th-91/02/04 (1991);
C. Degrassi and A. Sirlin, preprint MPI-PAE/P5448/90 (1990).

[29] ALEPH Collaboration, private communication by V.L. Rolandi.

[30] R. Clare, Proceedings of the XXVI Rencontre de Moriond, Les Arcs, France, (1991).

[31] B. Grinstein and M. Wise, HUTP-91/A015 (1991).

[32] U.Amaldi et al., Phys. Rev. D26 (1987) 1385;
A. Blondel et al., CDHSW Collaboration, Z. Phys. C45 (1990) 361;
J.V. Allaby et al., CHARM Collaboration, Z. Phys. C36 (1987) 611;
P.G. Reutens et al., CCFRR Collaboration, Z. Phys. C45 (1990) 539;
T.S. Mattison et al., FMM Collaboration, Phys. Rev. D42 (1990) 1311.

[33] W.J. Marciano and J.L. Rosner, Phys. Rev. Lett. 65 (1990) 2963.

[34] W.J. Marciano, BNL-45999 (1991).

[35] D. Geigerat et al., CHARMII Collaboration, Phys. Lett. B232 (1989) 539.

[36] M.C. Noecker et al., Phys. Rev. Lett. 61 (1988) 310;
M. Bouchiat, M.A. Proceedings of the 12th International Atomic Physics Conference (1990).

[37] S.A. Blundell et al., Phys. Rev. Lett. 65 (1990) 1411;
V. Dzuba et al., Phys. Lett. A141 (1989) 147.

[38] H.P. Nilles, Phys. Rep. C110 (1984) 1;
H.E. Haber and G.L. Kane, Phys. Rep. C117 (1985) 75;
R. Barbieri, Riv. N. Cim. 11 (1988) 1.

[39] R. Barbieri et al., Nucl. Phys. B341 (1990) 309.

[40] R. Barbieri and L. Maiani, Nucl. Phys. B224 (1983) 32;
L. Alvarez-Gaumé et al., Nucl. Phys. B221 (1983) 495.

[41] S. Lim et al., Phys. Rev. D29 (1984) 1488;
J. Grifols and J. Sola, Nucl. Phys. B253 (1985) 47;
R. Barbieri et al., Phys. Lett. B156 (1985) 348; Nucl. Phys. B269 (1986) 253;
B. Lynn et al., in "Physics at LEP", eds. J. Ellis and R. Peccei, CERN 86-02 (1986), vol. 1;
P. Gosdzinsky and J. Sola, UAB-FT-247/90 (1990).

[42] R. Casalbuoni et al., Phys. Lett. B258 (1991) 161.

[43] R.N. Cahn and M. Suzuki, LBL-30351 (1991).

[44] M. Veltman, Nucl. Phys. B123 (1977) 589;
S. Bertolini and A. Sirlin, Nucl. Phys. B248 (1984) 589.

[45] S. Bertolini and A. Sirlin, Phys. Lett. B257 (1991) 179;
E. Gates and J. Terning, YCTP-P17-91 (1991).

[46] J.A. Grifols et al., Int. Journ. of Mod. Phys. Lett. A3 (1988) 225;
G.K. Kane et al., Phys. Rev. D39 (1989(2617.

[47] M. Kuroda et al., Nucl. Phys. B284 (1987) 271; Phys. Lett. B183 (1987) 366; Phys. Lett. B190 (1987) 217; Nucl. Phys. B299 (1988) 7.

[48] E. Witten, Nucl. Phys. B258 (1985) 75;
M. Dine, V. Kaplunovsky, M. Mangano, C. Nappi and N. Seiberg, Nucl. Phys. B259 (1985) 519;
S. Cecotti, J.-P. Derendinger, S. Ferrara, L. Girardello and M. Roncadelli, Phys. Lett. B156 (1985) 318;
J.D. Breit, B.A. Ovrut and G. Segrè, Phys. Lett. B158 (1985) 33;
E. Cohen, J. Ellis, K. Enqvist and D.V. Nanopoulos, Phys. Lett. B165 (1985) 76;
J. Ellis, K. Enqvist, D.V. Nanopoulos and F. Zwirner, Nucl. Phys. B276 (1986) 14; Mod. Phys. Lett. A1 (1986) 57;
F. Del Aguila, G. Blair, M. Daniel and G.G. Ross, Nucl. Phys. B272 (1986) 413;
L. Ibanez and J. Mas, Nucl. Phys. B286 (1987) 107;
J.C. Pati and A. Salam, Phys. Rev. D10 (1974) 275;
R.N. Mohapatra and J.C. Pati, Phys. Rev. D11 (1975) 566, 2559;
G. Senjanovic and R.N. Mohaptra, Phys. Rev. D12 (1975) 152;
G. Senjanovic, Nucl. Phys. B153 (1979) 334;
M.C. Gonzales-Garcia and J.W.F. Valle, preprint FTUV/90-15 (1990);
F. Del Aguila, J.M. Moreno and M. Quiros, CERN preprint TH. 5646 (1990);
S.L. Glashow and U. Sarid, Phys. Rev. Lett. 64 (1990) 725;
A.E. Farraggi and D.V. Nanopoulos, preprint CTP-TAMU-69/89 (1989).

[49] G. Altarelli, R. Casalbuoni, D. Dominici, F. Feruglio and R. Gatto, Mod. Phys. Lett. A5 (1990) 495 and Nucl. Phys. B342 (1990) 15;
G. Altarelli, R. Casalbuoni, F. Feruglio and R. Gatto, Phys. Lett. B245 (1990) 669;
J. Layssac, F.M. Renard and C. Verzegnassi, LAPP preprint LAPP-TH-290/90 (1990).

[50] G. Altarelli et al., CERN preprint TH.6051/91 (1991).

Table 1

The quantity $\Delta r_W \times 10^2$, defined in Eq. (1), as obtained by a number of available calculations. A^{best} is from DIZET [20] and also includes $0(\alpha\alpha_s)$ corrections. These are the results that are used in the text. A', A'', FS1 and FS2 are based on DIZET [20], Hollik [22], and Fanchiotti-Sirlin [28] respectively. Corrections of order $\alpha\alpha_s$ are not included. Their comparison gives an indication of theoretical errors. (m_Z = 91.174 GeV).

$\frac{m_H}{m_t}$(GeV)	A^{best}	A'	A''	FS1	FS2
$\frac{50}{90}$	-0.044	-0.15	-0.19	-0.12	-0.20
$\frac{50}{120}$	-1.00	-1.17	-1.19	-1.14	-1.15
$\frac{50}{150}$	-2.06	-2.31	-2.32		
$\frac{50}{180}$	-3.28	-3.67	-3.64	-3.60	-3.4
$\frac{50}{210}$	-4.72	-5.27	-5.21		
$\frac{50}{300}$	-10.47	-11.91	-11.92	-11.22	-11.32
$\frac{1000}{90}$	+1.10	+ 1.00	+0.95	1.02	
$\frac{1000}{120}$	+1.88	+0.029	-0.021	0.034	
$\frac{1000}{150}$	-0.81	-1.06	-1.11		
$\frac{1000}{180}$	-1.97	-2.34	-2.39	-2.36	
$\frac{1000}{210}$	-3.34	-3.86	-3.92		
$\frac{1000}{300}$	-8.79	-10.15	-10.43	-9.82	

Table 2

Results on Γ_ℓ (MeV) obtained by various available calculations. A^{best} is based on DIZET [20] with corrections of order $\alpha\alpha_s$ included. It is the value which is used in the text. A', A'', Expostar, DS1-3 are based on DIZET [20], Hollik [22], Expostar [27], Degrassi-Sirlin [28], without $0(\alpha\alpha_s)$ corrections. Their comparison gives an indication of theoretical errors. ($m_Z = 91.174$ GeV).

$\frac{m_H}{m_t}$(GeV)	A^{best}	A'	A''	Expostar	DS1	DS2	DS3
$\frac{50}{90}$	83.35	83.38	83.50	83.29			
$\frac{50}{120}$	83.54	83.58	83.695	83.50			
$\frac{50}{150}$	83.77	83.84	83.94	83.76			
$\frac{50}{180}$	84.06	84.155	84.25	84.07			
$\frac{50}{210}$	84.39	84.53	84.61	84.46			
$\frac{50}{300}$	85.69	85.99	86.09	86.01			
$\frac{1000}{90}$	83.13	83.16	83.28	83.07	83.2	83.1	83.2
$\frac{1000}{120}$	83.315	83.36	83.475	83.27	83.4	83.4	83.4
$\frac{1000}{150}$	83.545	83.61	83.72	83.53	83.6	83.6	83.6
$\frac{1000}{180}$	83.83	83.92	84.03	83.84			
$\frac{1000}{210}$	84.16	84.29	84.39	84.22			
$\frac{1000}{300}$	85.45	85.74	85.86	85.77			

Table 3

Results on $A^{\ell}_{FB} \times 10^2$ (MeV) obtained by various available calculations. A^{best} is based on DIZET [20] with corrections of order $\alpha\alpha_s$ included. It is the value which is used in the text. A', A'', DS1-3 are based on DIZET [20], Hollik [22], Degrassi-Sirlin [28], without $0(\alpha\alpha_s)$ corrections. Their comparison gives an indication of theoretical errors. ($m_Z = 91.174$ GeV).

$\frac{m_H}{m_t}$(GeV)	A^{Best}	A'	A''	DS1	DS2	DS3
50 / 90	1.44	1.46	1.45			
50 / 120	1.56	1.59	1.56			
50 / 150	1.69	1.74	1.70			
50 / 180	1.86	1.93	1.87			
50 / 210	2.06	2.15	2.09			
50 / 300	2.75	2.94	3.02			
1000 / 90	1.18	1.20	1.22	1.17	1.16	1.22
1000 / 120	1.29	1.32	1.32	1.28	1.28	1.32
1000 / 150	1.42	1.47	1.45	1.42	1.42	1.45
1000 / 180	1.57	1.64	1.62			
1000 / 210	1.76	1.85	1.82			
1000 / 300	2.40	2.60	2.71			

Table 4a

Values of $\epsilon_i \times 10^2$ obtained in various available calculations (a,b,c refer to $\epsilon_1, \epsilon_2, \epsilon_3$ respectively). A^{best}, A' and A'' are based on DIZET [20] with (A^{best}) or without (A') corrections of order $\alpha\alpha_s$ and on Hollik [22] (A''). The columns labelled FB and pol differ in that A^{ℓ}_{FB} or A^{τ}_{pol} are used in the two cases to define g_V and g_A. ($m_Z = 91.174$ GeV).

$\frac{m_H}{m_t}$(GeV)	A^{best}	A'	A''	A^{best}_{pol}	A'_{pol}	A''_{pol}
50 / 90	0.053	0.083	0.231	0.125	0.153	0.294
50 / 120	0.240	0.285	0.428	0.312	0.355	0.489
50 / 150	0.473	0.541	0.678	0.545	0.611	0.737
50 / 180	0.756	0.854	0.984	0.830	0.923	1.041
50 / 210	1.092	1.225	1.348	1.166	1.124	1.402
50 / 300	2.411	2.701	2.789	2.492	2.766	2.833
1000 / 90	-0.123	-0.094	0.043	-0.055	-0.027	0.107
1000 / 120	0.062	0.106	0.243	0.132	0.175	0.305
1000 / 150	0.295	0.361	0.496	0.367	0.432	0.556
1000 / 180	0.579	0.672	0.805	0.653	0.745	0.863
1000 / 210	0.915	1.043	1.172	0.991	1.117	1.223
1000 / 300	2.241	2.517	2.627	2.324	2.594	2.672

Table 4b

m_H, m_t (GeV)	A^{best}	A'	A''	A^{best}_{pol}	A'_{pol}	A''_{pol}
50, 90	-0.205	-0.202	-0.121	-0.420	-0.415	-0.312
50, 120	-0.336	-0.338	-0.274	-0.540	-0.541	-0.452
50, 150	-0.451	-0.454	-0.399	-0.644	-0.646	-0.563
50, 180	-0.577	-0.579	-0.528	-0.759	-0.759	-0.677
50, 210	-0.732	-0.730	-0.675	-0.903	-0.898	-0.810
50, 300	-1.539	-1.528	-1.382	-1.687	-1.667	-1.473
1000, 90	-0.181	-0.170	-0.055	-0.412	-0.398	-0.270
1000, 120	-0.285	-0.283	-0.198	-0.511	-0.509	-0.398
1000, 150	-0.374	-0.379	-0.313	-0.592	-0.597	-0.496
1000, 180	-0.473	-0.482	-0.429	-0.680	-0.691	-0.595
1000, 210	-0.596	-0.607	-0.562	-0.791	-0.806	0.711
1000, 300	-1.266	-1.284	-1.204	-1.433	-1.461	-1.302

Table 4c

m_H, m_t (GeV)	A^{best}_{FB}	A'_{FB}	A''_{FB}	A^{best}_{pol}	A'_{pol}	A''_{pol}
50, 90	0.304	0.294	0.427	0.673	0.649	0.744
50, 120	0.287	0.279	0.429	0.644	0.620	0.726
50, 150	0.281	0.274	0.435	0.624	0.599	0.711
50, 180	0.284	0.278	0.446	0.616	0.588	0.701
50, 210	0.302	0.295	0.462	0.624	0.589	0.695
50, 300	0.554	0.563	0.545	0.859	0.810	0.709
1000, 90	0.554	0.537	0.610	0.934	0.901	0.955
1000, 120	0.528	0.512	0.615	0.907	0.876	0.937
1000, 150	0.519	0.504	0.624	0.891	0.861	0.923
1000, 180	0.523	0.508	0.638	0.886	0.854	0.912
1000, 210	0.542	0.525	0.656	0.895	0.861	0.907
1000, 300	0.792	0.776	0.747	1.126	1.081	0.920

FIGURE CAPTIONS

Fig. 1: Δr_W as a function of m_t in the Standard Model, for different values of m_H (GeV). The present experimental value is also indicated.

Fig. 2: Γ_l as a function of m_t in the Standard Model, for different values of m_H (GeV). The present experimental value is also indicated.

Fig. 3: A^l_{FB} as a function of m_t in the Standard Model, for different values of m_H (GeV). The present experimental value is also indicated.

Fig. 4: The epsilons in the Standard Model as function of m_t. The bands correspond to m_H in the range 50-1000 GeV.

Fig. 5: $\varepsilon_1 = \Delta\rho$ computed in the Standard Model as function of m_t for different values of m_H (GeV) and compared with the experimental value obtained from Δr_W, Γ_l and A^l_{FB}.

Fig. 6: ε_2 computed in the Standard Model as function of m_t for different values of m_H (GeV) and compared with the experimental value obtained from Δr_W, Γ_l and A^l_{FB}.

Fig. 7: ε_3 computed in the Standard Model as function of m_t for different values of m_H (GeV) and compared with the experimental value obtained from Δr_W, Γ_l and A^l_{FB}.

Fig. 8: Effect of replacing A^l_{FB} with A^τ_{pol} in the definitions of ε_1 (a), ε_2 (b) and ε_3 (c).

Fig. 9: A^τ_{pol} as a function of m_t in the Standard Model, for different values of m_H (GeV). The present experimental value is also indicated.

Fig. 10: A^b_{FB} as a function of m_t in the Standard Model, for different values of m_H (GeV). The present experimental value is also indicated.

Fig. 11: The difference $\delta_b = (\bar{s}^2_W)_b - (\bar{s}^2_W)_{FB}$ defined in Eq. (27), as a function of m_t for different values of mH (mH = 50,100,500,1000 GeV).

Fig. 12: Data on ε_1 and ε_3. The 1σ ellipses and their projections on the ε_1, ε_3 axes are shown. The Standard Model prediction is also displayed for reference purposes (The four solid lines are for different values of m_H, m_H = 50, 100, 500, 1000 GeV, and the dots mark values of m_t in the range m_t = 50-270 GeV). Cases a) to e) correspond to different input data. a) is obtained from Γ_l and A^l_{FB} [Eqs. (12) and (13)]. In b) the data on A^τ_{pol} have been also taken into account [Eq. (23)]. The result in Eq. (28) for A^b_{FB} is added in c). All data, including low energy experiments, [see Eqs. (31) and (34)] are included in d). Finally e) is obtained from all data with the exception of those on A^b_{FB}.

Fig. 13: ε_3 vs. m_t in the Standard Model for different values of m_H (m_H = 50,100, 500, 1000 GeV) with the experimental result in Eq. (44), obtained from all the data which are available at present.

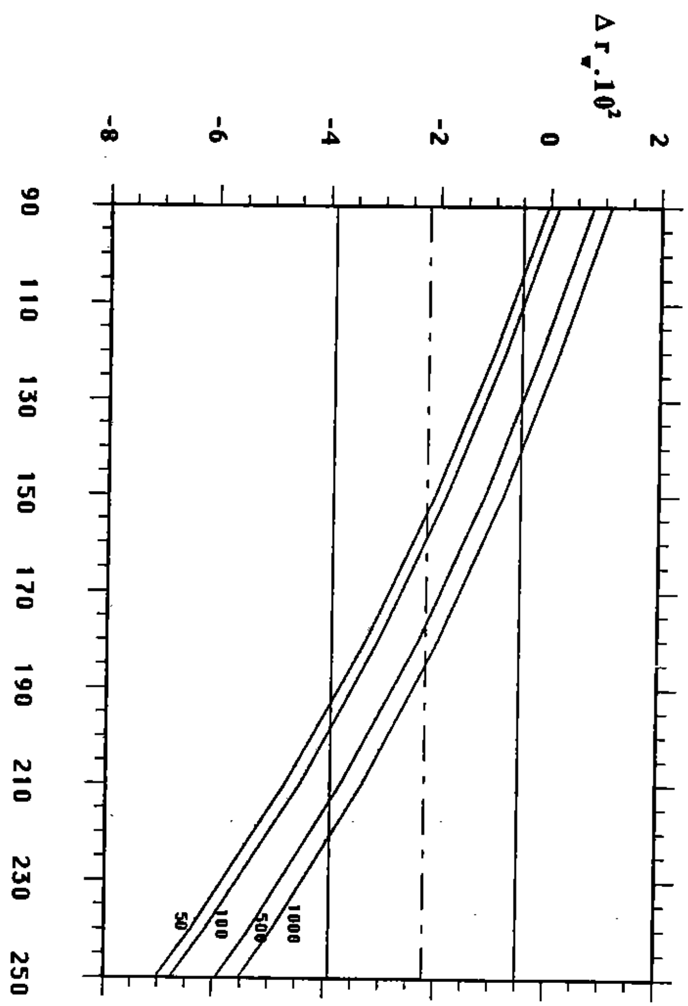


FIGURE 1

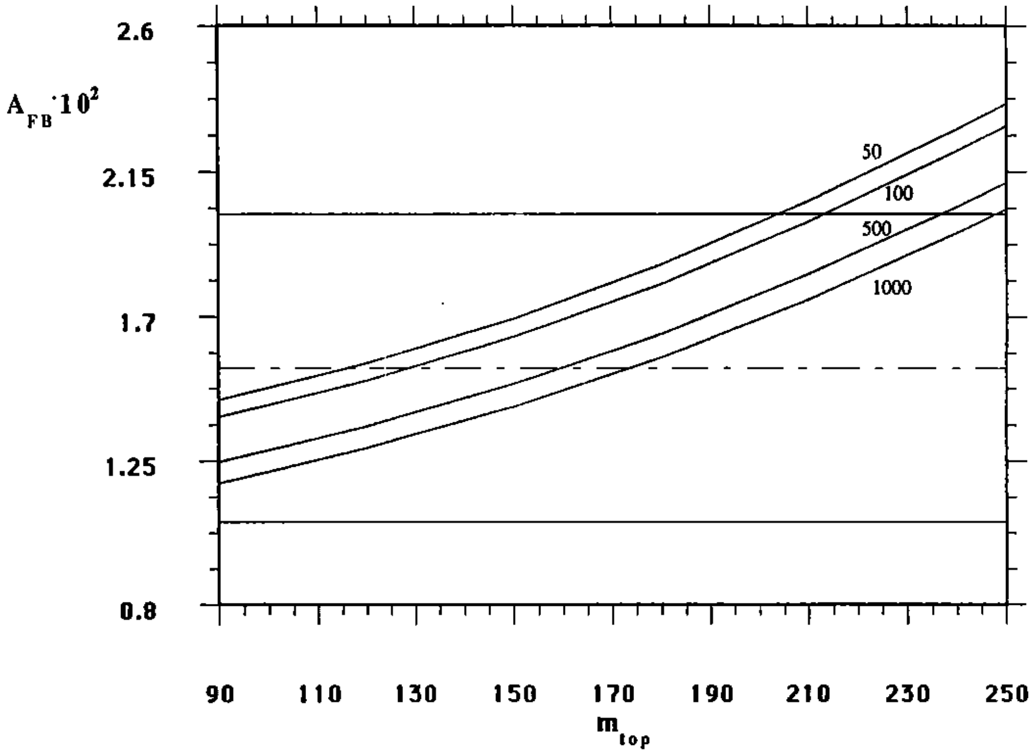


FIGURE 3

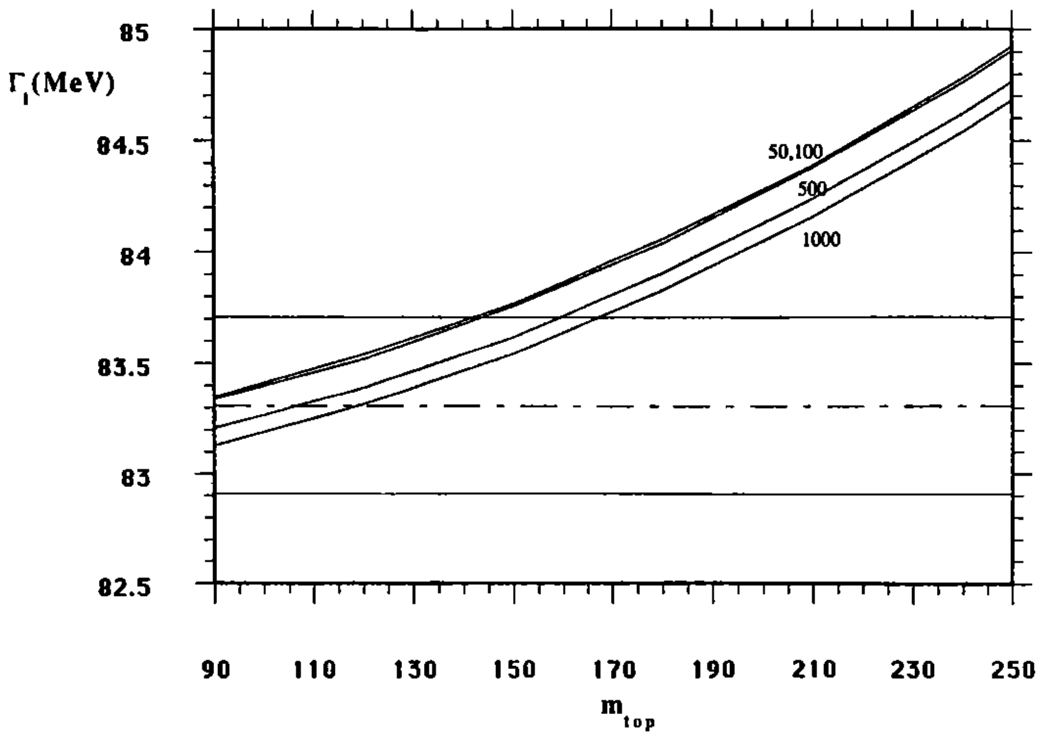


FIGURE 2

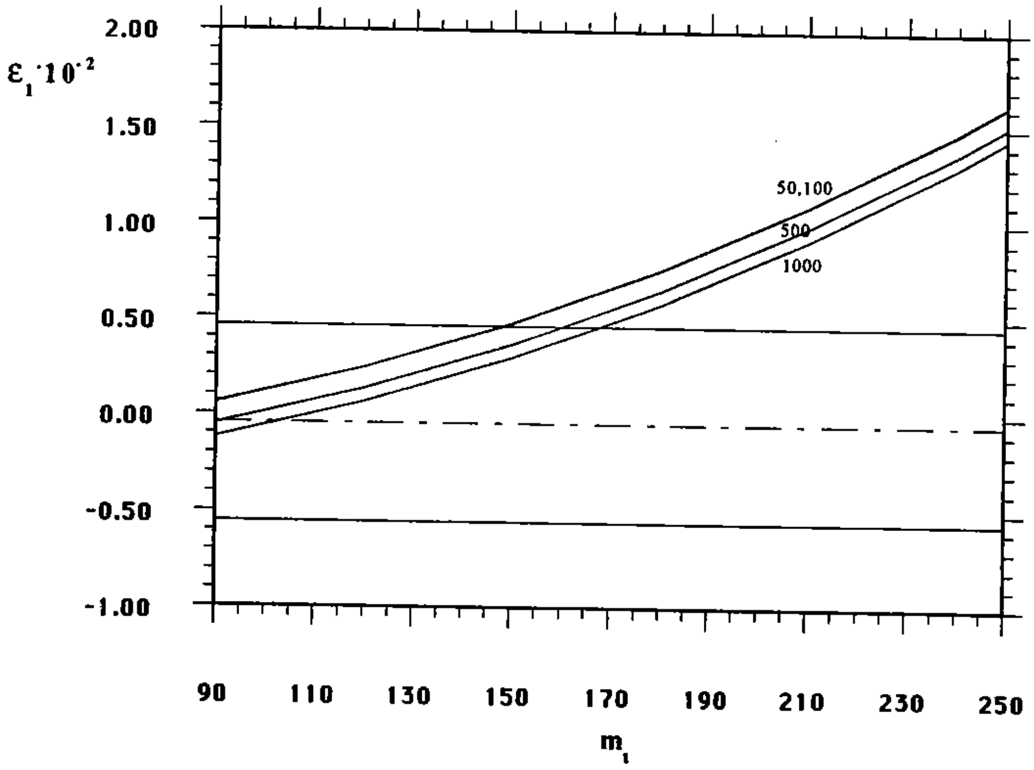


FIGURE 5

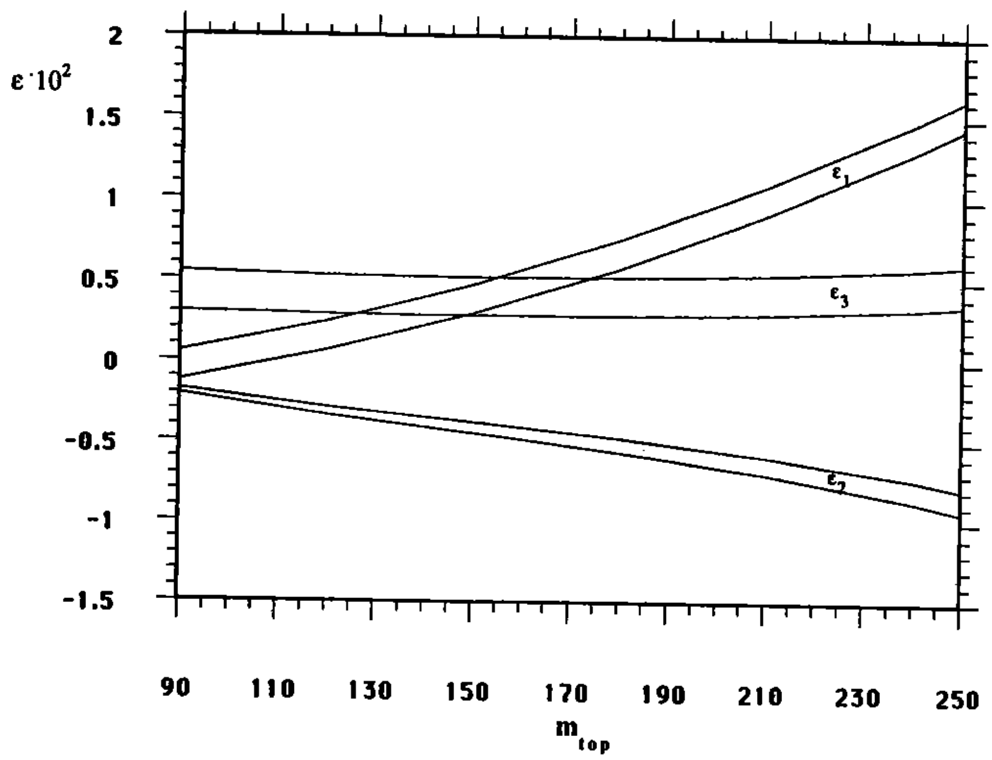


FIGURE 4

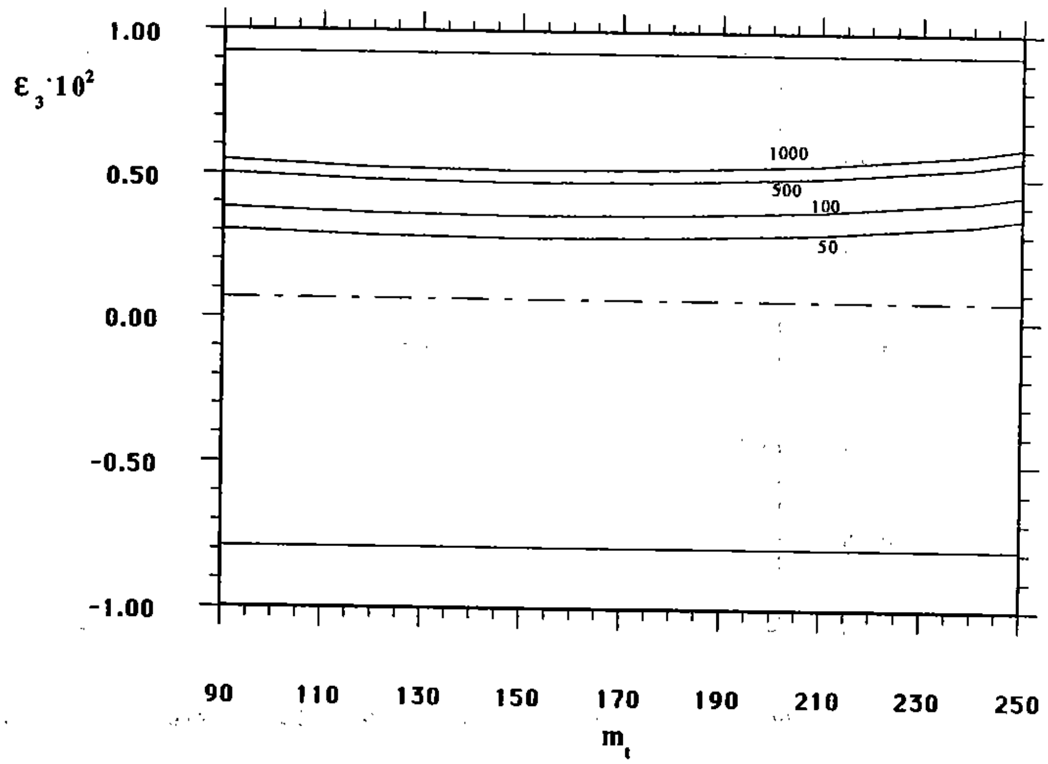


FIGURE 7

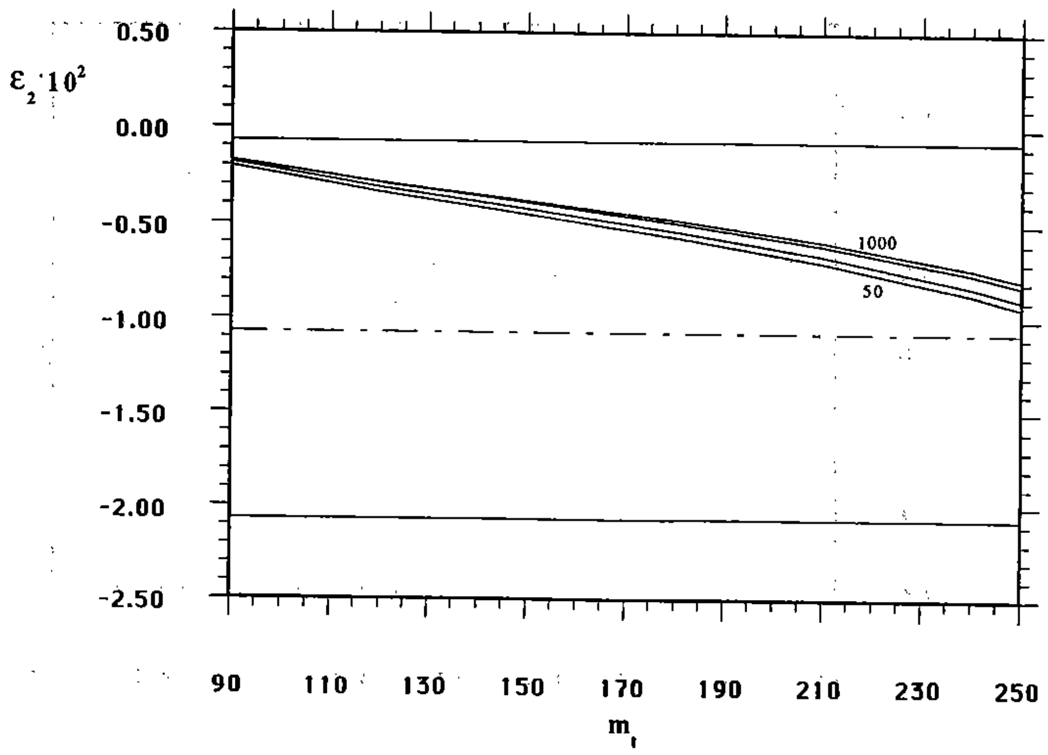


FIGURE 6

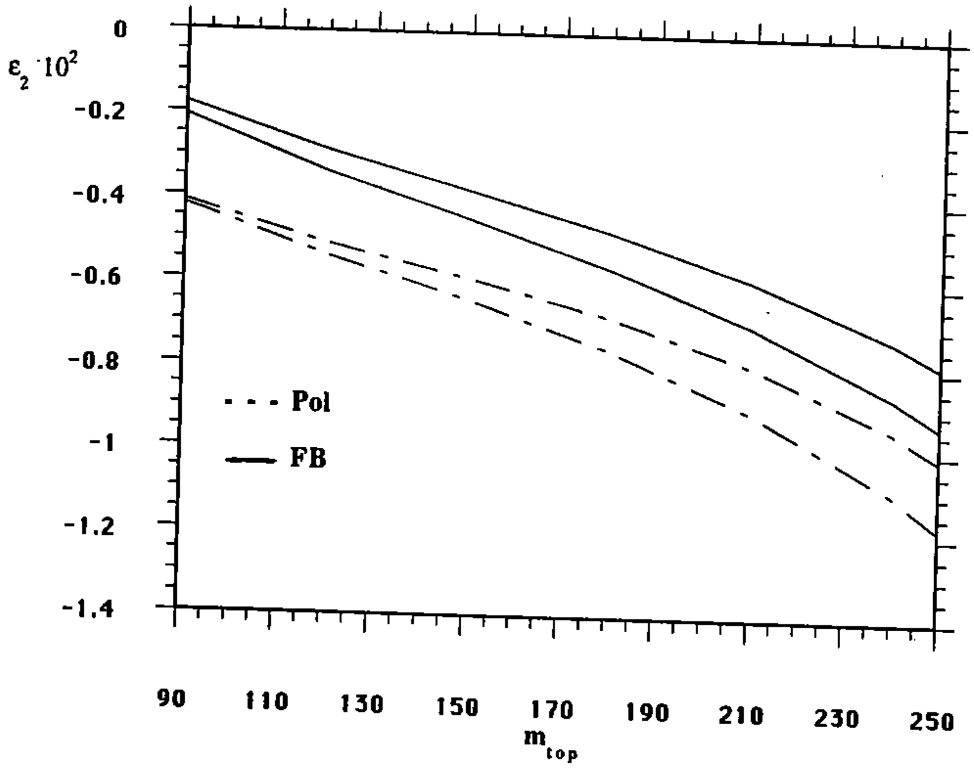


FIGURE 8b

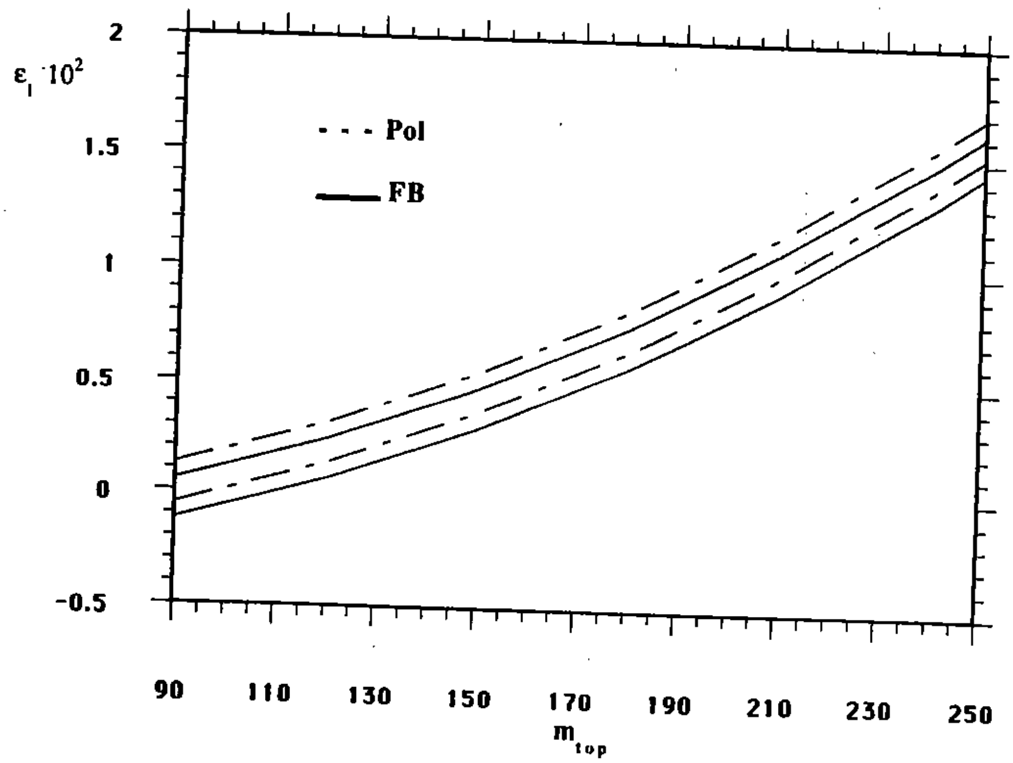
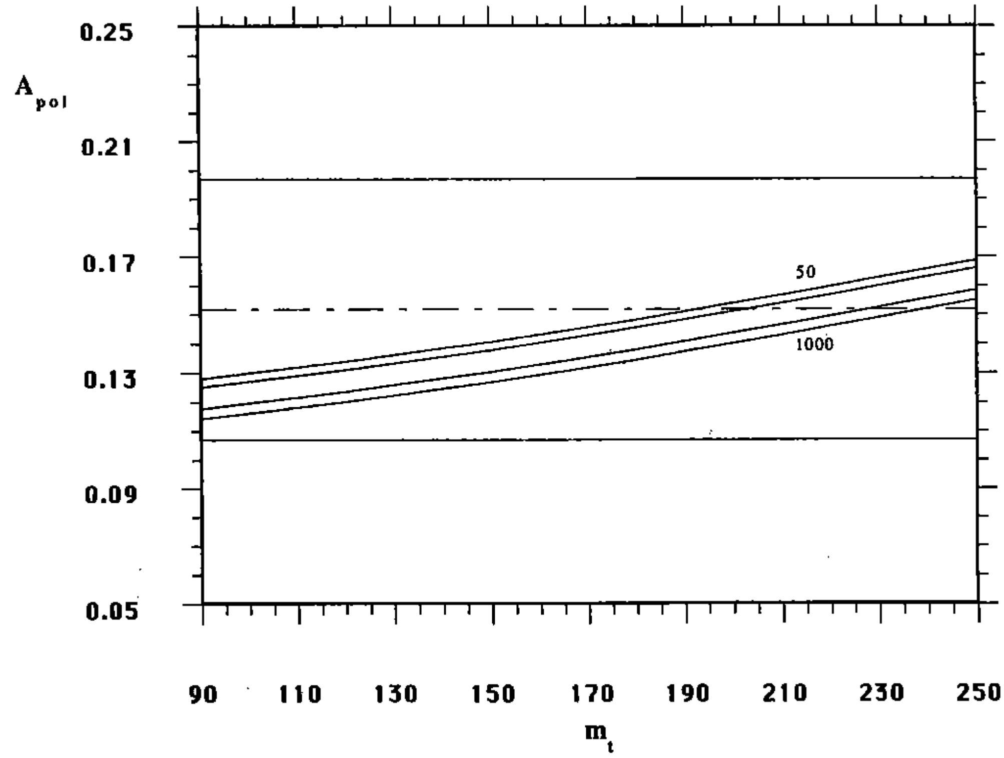


FIGURE 8a



FITURE 9

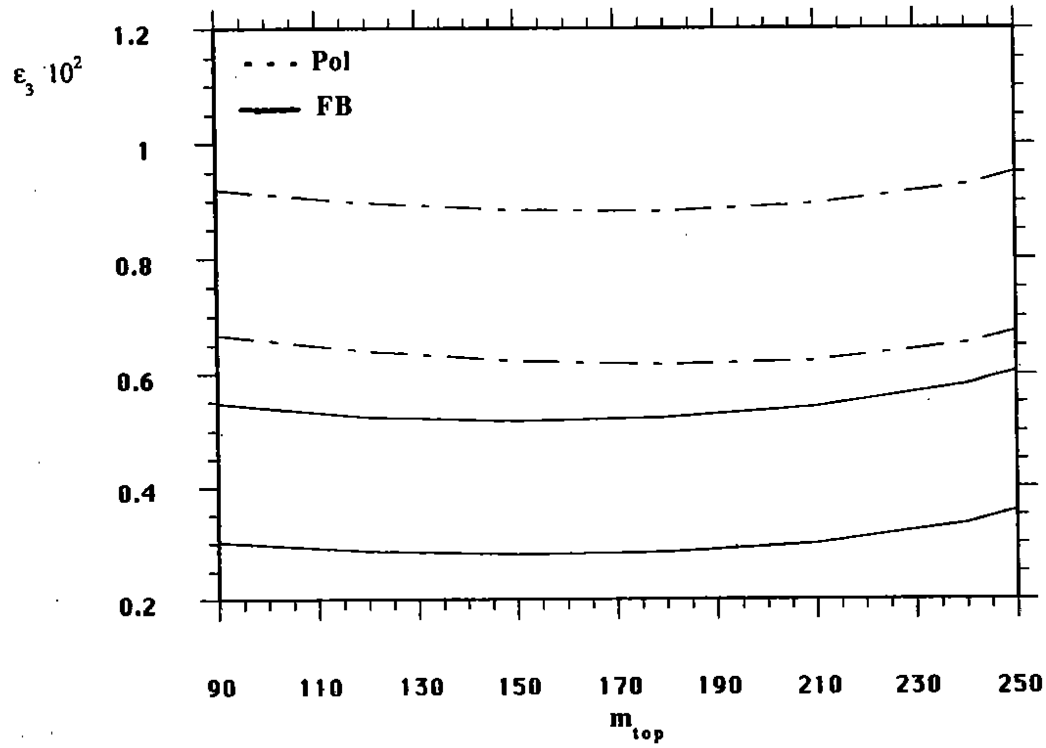


FIGURE 8c

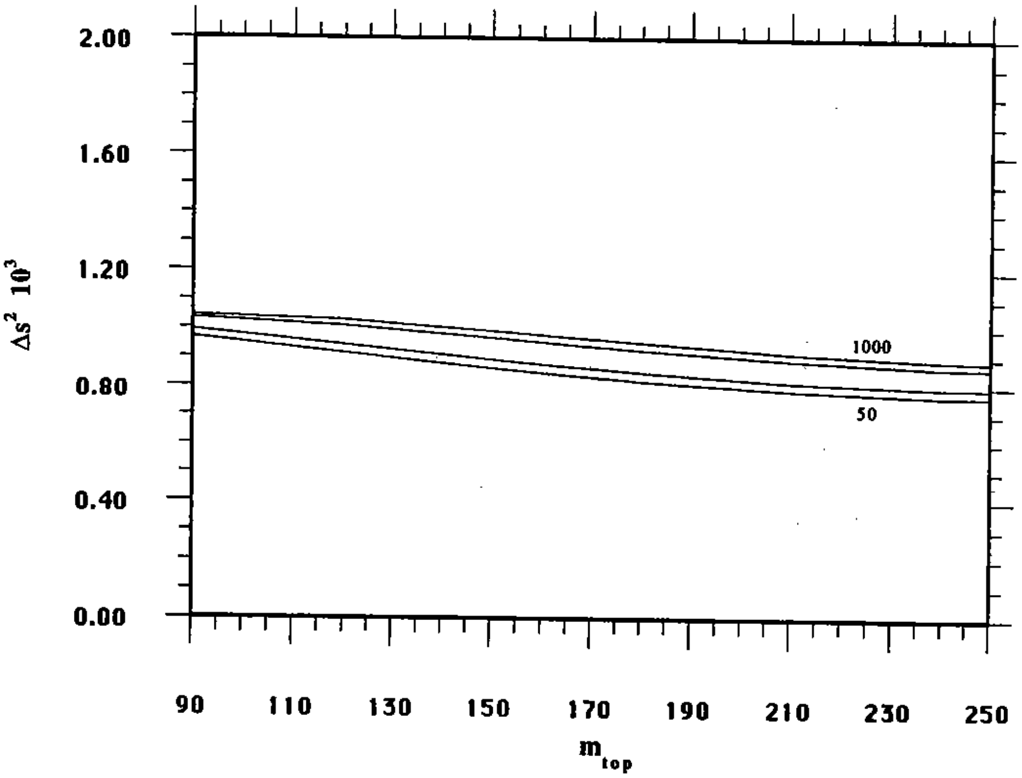


FIGURE 11

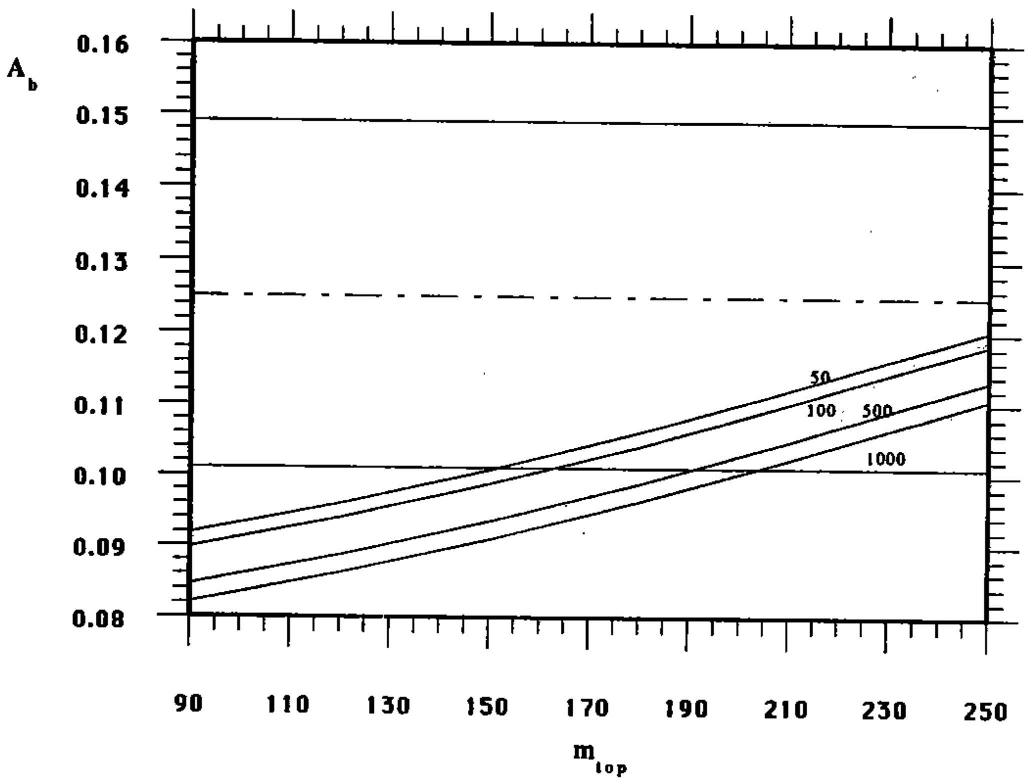


FIGURE 10

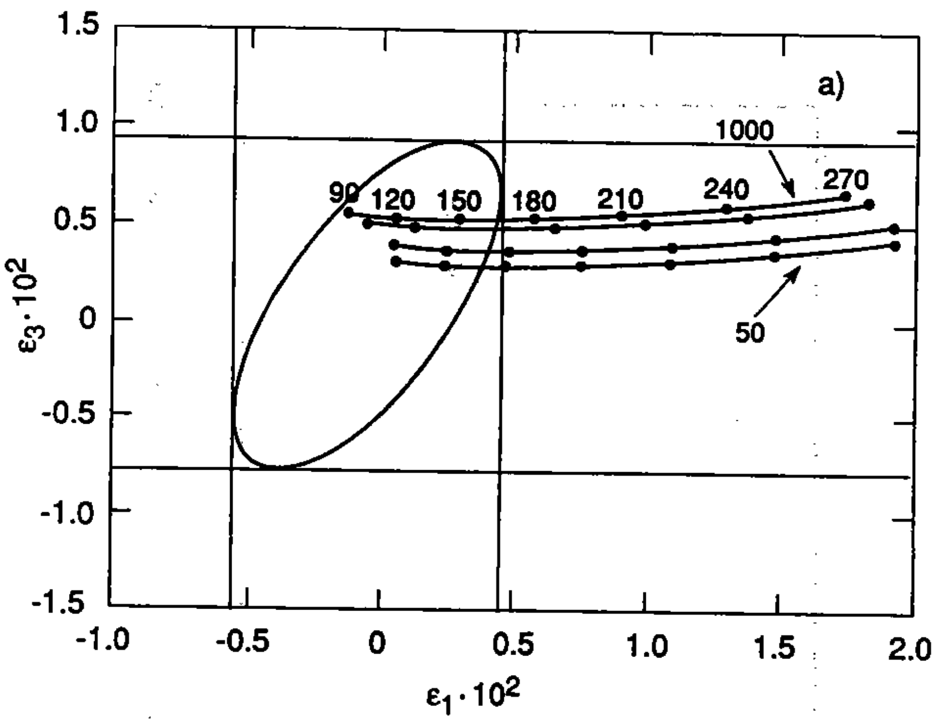


FIGURE 12a

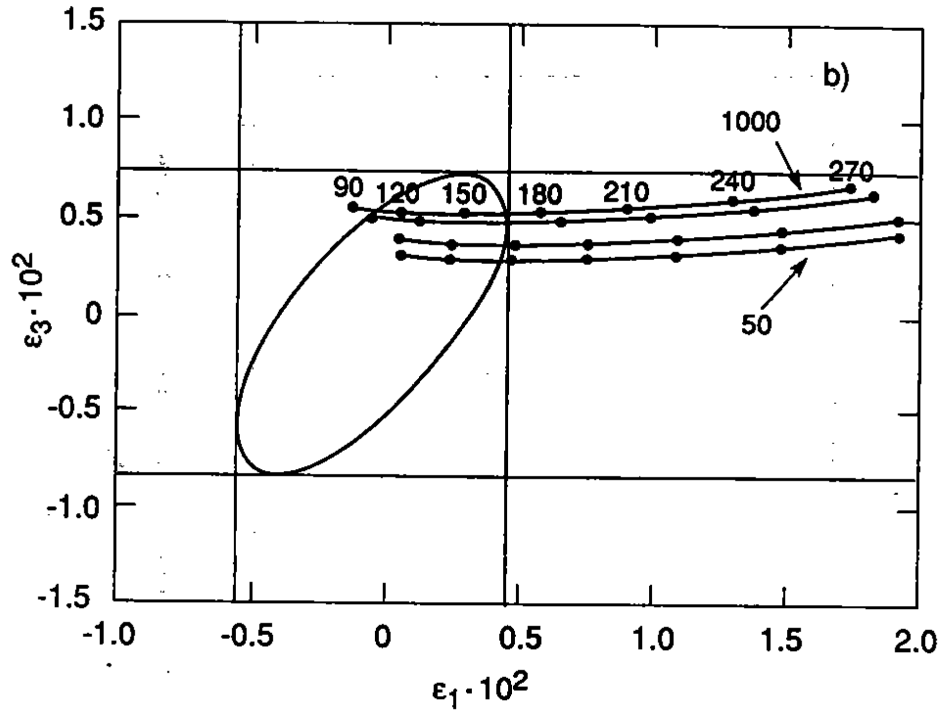


FIGURE 12b

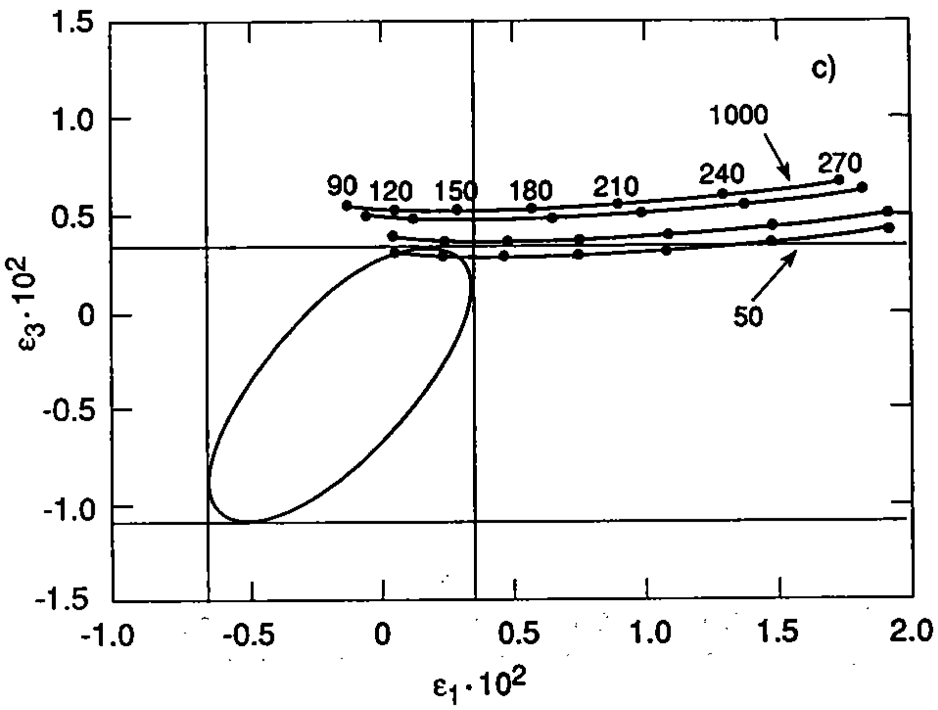


FIGURE 12c

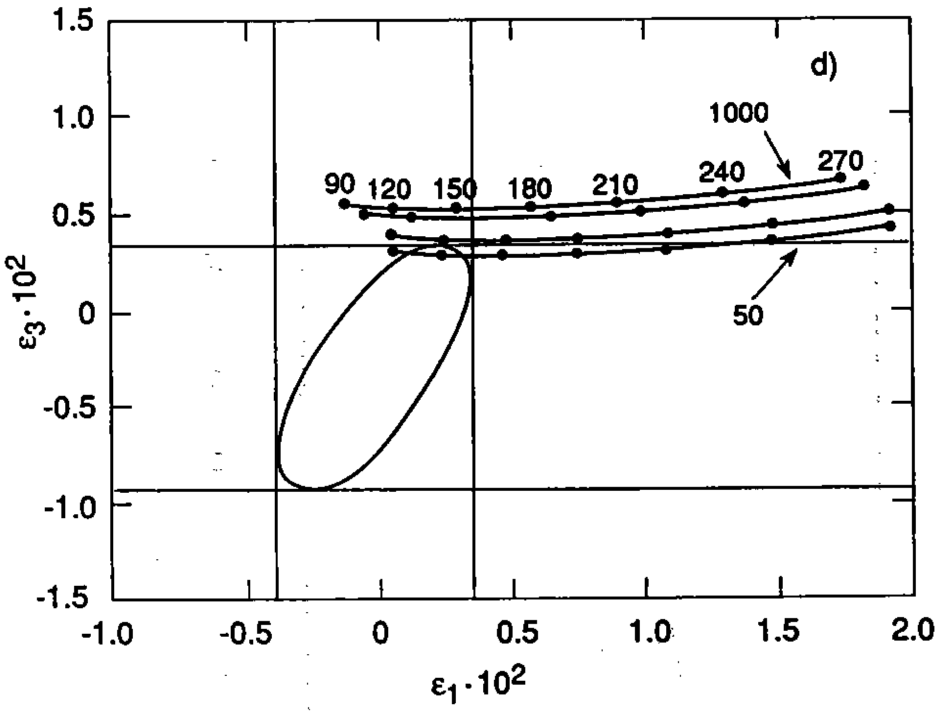


FIGURE 12d

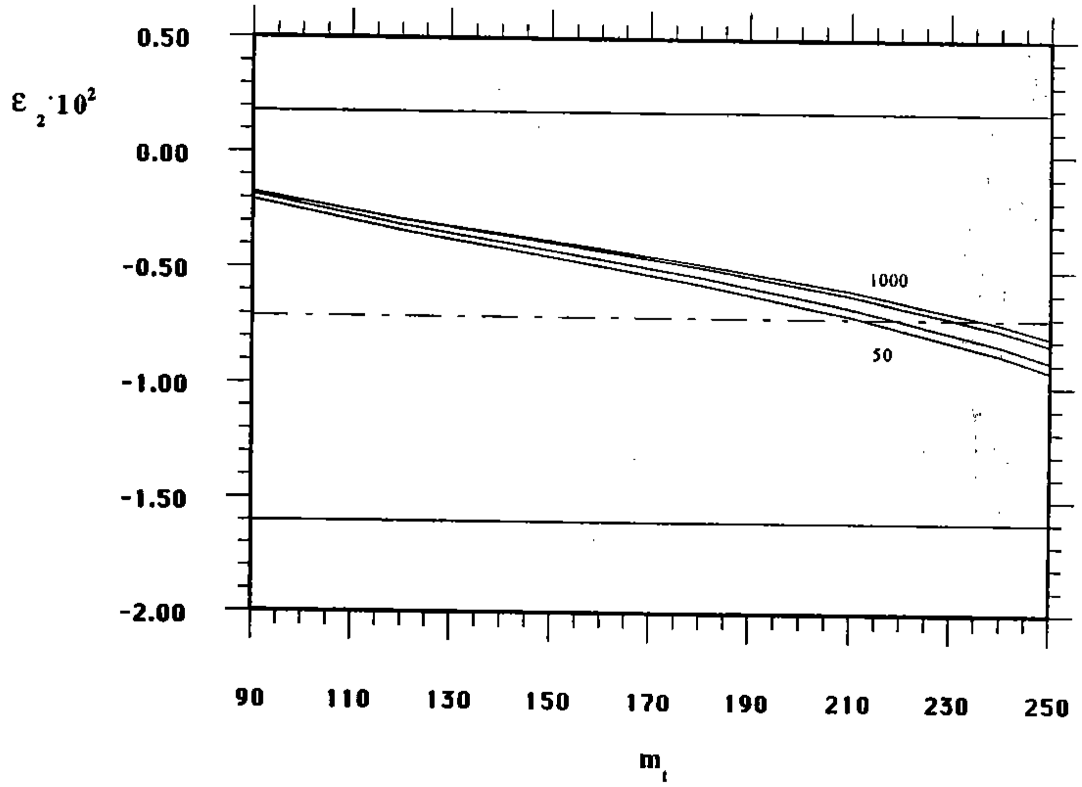


FIGURE 13

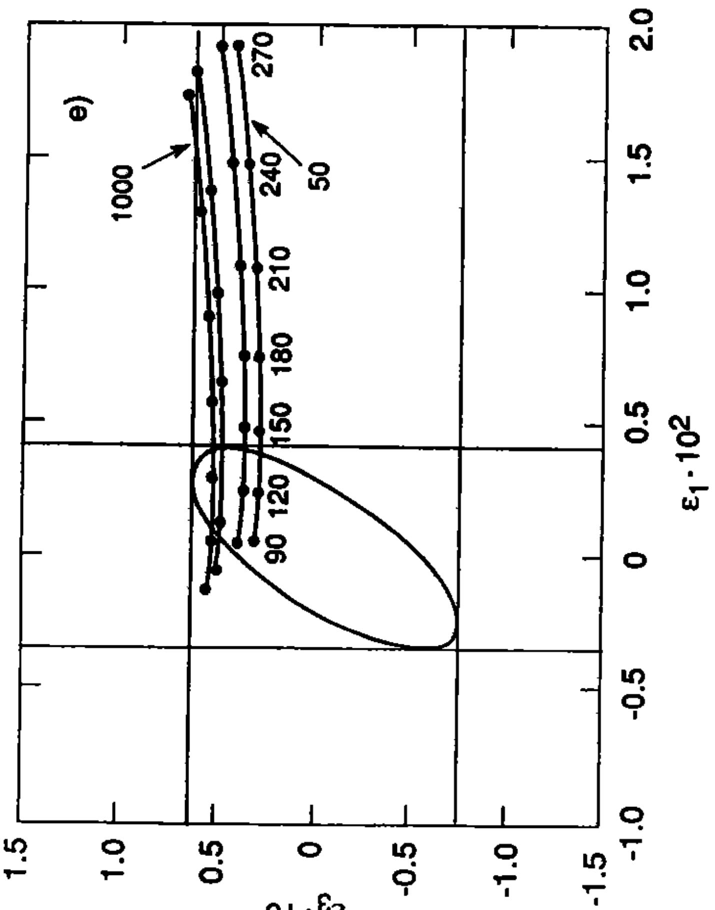


FIGURE 12e