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Non Standard Analysis of Electroweak Precision Data

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Abstract

A model independent analysis of the electroweak precision data is performed which extends previous work along the same lines by including, together with the leptonic observables at the Z pole, the hadronic observables as well, Γ_T , Γ_h and Γ_b . This is done by adding to the previously defined ϵ_1 , ϵ_2 and ϵ_3 a new parameter ϵ_b which describes the top mass dependence of the $Z \rightarrow b\bar{b}$ vertex. The data are then analysed by formulating a hierarchy of simple and general assumptions, without ever having to specify the value of the top mass m_t . In particular, by allowing arbitrary new physics effects in vacuum polarization functions (possibly distorting, e.g., the m_t -dependence of the ρ -parameter) but assuming negligible modifications of all vertices, we obtain the limit $m_t < 207$ GeV at 95% c.l. for $\alpha_s(m_Z) = 0.118 \pm 0.007$. As a very relevant particular example, the comparison of the data with the Standard Model is illustrated: all the epsilons are consistent with the Standard Model predictions, with the central values of ϵ_3 and ϵ_b being respectively slightly lower and slightly higher than expected.

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1. Introduction

Recently much attention has been devoted to develop a strategy for a model independent analysis of precision electroweak data [1-6]. The general framework consists in defining a set of variables describing possible deviations from the Standard Model. These variables are chosen in such a way as to minimise the negative impact of our ignorance of the top quark mass m_t and to be as much as possible sensitive to new physics in particularly problematic sectors of the theory, such as the Higgs sector. A very common approach [1-3], in terms of the variables S, T and U , is based on the assumption that the dominant effects of new physics only appear through vacuum polarisation diagrams [7]. Alternative assumptions, formulated in the language of effective lagrangians [4] or of dominance of lowest dimension terms in an operator expansion [5] or in physical terms [8], lead to the same or to similar sets of variables.

In a previous work [6], with S. Jadach, we have advocated a more pragmatic approach where no specific assumptions are a priori formulated. Rather, in ref.6 the variables ϵ_1, ϵ_2 and ϵ_3 were defined in general from the basic observables $m_W/m_Z, \Gamma_1$ and A_{FB}^l (the forward-backward asymmetry at the Z-peak for charged leptons). We always assume charged lepton universality, which is supported by the data at the present level of accuracy, so that Γ_1 and A_{FB}^l refer to the corresponding average data. These observables were chosen because they are particularly simple, are all defined at the intermediate gauge boson scale of mass, are precisely measured, do not involve important hadronic effects (like $\alpha_s(m_Z)$ or the Z->b $\bar{b}$ vertex [9]) and each of them carries a qualitatively different information. In terms of these observables ϵ_1, ϵ_2 and ϵ_3 were defined in ref.6 in a way that, if the assumption of vacuum polarisation dominance is made, then ϵ_1 would be linearly related to T, ϵ_2 to U and ϵ_3 to S . But one virtue of this approach is that the most interesting physical results are already obtained at a completely model independent level, without assumptions like the dominance of vacuum polarisation diagrams. One example is the result that present data favour models of new physics that lead to negative corrections to ϵ_3 with respect to the Standard Model, like suitable versions of extended gauge models [10] or the Minimal Supersymmetric Standard Model [11,12], while simple technicolour models [13,14] are disfavoured.

Of course some assumptions are needed when additional observables other than $m_W/m_Z, \Gamma_1$ and A_{FB}^l are introduced and one wants to relate them to the same set of epsilons in order to make their determination from the data more precise. One can 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 connected to charged leptons at the Z pole, e.g. the τ -polarisation asymmetry A_{pol}^τ and the left-right asymmetry A_{LR} , are uniquely determined by the ϵ_i . This is true in all models where the contributions of new physics only occur either through vacuum polarisation terms and/or in Z->H $^\pm$ vertex corrections of the form $\Delta V_H(Z \rightarrow H^\pm) = \bar{u}(\Delta G_A \gamma_5 + \Delta G_V) \gamma_\mu u$ 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. Stronger hypotheses about possible forms of new physics are needed if one wants to relate the epsilons to observables involving quarks, 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 [15,16], ν -e scattering [17] and atomic parity violation in atomic physics [18,19]). 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 [1-3]. However, 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 , in principle 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->b $\bar{b}$ vertex [9]. 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 . In practice, the sensitivity to the new quadratic terms in m_t^2 from the Z->b $\bar{b}$ vertex is only present in Γ_b , and consequently in the hadronic and total widths Γ_h and Γ_T , while it is almost non-existent, at realistic values of m_t , for A_{FB}^b . For this reason and because of the dependence on $\alpha_s(m_Z)$, the precise measurements of Γ_T, Γ_h and Γ_b were not included in the previous analysis [6] (while A_{FB}^b was included).

In the present paper we overcome the above limitation by adding a new parameter, ϵ_b , which describes the m_t dependent part of the Z->b $\bar{b}$ vertex, and by correspondingly enlarging the set of basic observables with the inclusion of Γ_b . From the quantities $m_W/m_Z, \Gamma_1, A_{FB}^l$ and Γ_b the four epsilons can be defined without need of specifying m_t . The important point is that, in the Standard Model, for all observables at the Z pole, the whole dependence on m_t arising from one-loop diagrams only enters through the epsilons. Furthermore, the same is obviously true for any extension of the Standard Model such that all possible deviations only occur through vacuum polarisation diagrams and/or the Z->b $\bar{b}$ vertex. At the same time we improve the previous analysis [6] by slightly modifying the original definition of the epsilons in order to achieve a number of advantages: the modified variables are exactly zero in the Standard Model in the limit of neglecting all pure electroweak loop corrections (i.e. when only the predictions from the tree level Standard Model plus pure QED corrections are taken into account), are more directly related to the forward-backward asymmetry at the peak as by now precisely specified by the LEP experiments [20] and some small top quark mass dependences are better taken into account. Finally we update the whole analysis by using the most complete set of available data [20,21].

2. Basic Definitions

In the Standard Model all the observables can be computed starting from the input parameters, a self-imposing set of which is given by $\alpha, \alpha_s, G_F, m_Z, m_t, m_H$. In the following we use the values $\alpha^{-1} = 137.036, G_F = 1.166372 \cdot 10^{-5} \text{ GeV}^2, m_Z = 91.187 \text{ GeV}$. Among the fermion masses, m_t , the main unknown quantity is the top quark mass m_t . The

CDF lower limit on m_t , $m_t > 91$ GeV, is valid in the Standard Model [22]. The failure of direct searches at LEP imposes the bound $m_H > 60$ GeV on the Higgs mass [23]. Also, the Standard Model is affected with serious pathologies for $m_H > 0.6-1$ TeV, when the Landau pole associated to the $\lambda(\phi^4)^2$ coupling comes too close to the physical region in parameter space [24]. Thus in evaluating the Standard Model predictions we vary m_H in the range 60 GeV- 1 TeV. Finally direct measurements of $\alpha_s(m_Z)$ from many different experiments lead to a relatively precise value of $\alpha_s(m_Z)$ [25]. In the present paper we use $\alpha_s(m_Z) = 0.118 \pm 0.007$ [25].

We start from the basic observables m_W/m_Z , Γ_1 and A_{FB}^1 and Γ_b . From these four quantities one can isolate the corresponding dynamically significant corrections Δr_W , $\Delta \rho_N$, Δk_N and ϵ_b , 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:

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

Here $\alpha(m_Z) = \alpha/(1 - \Delta\alpha)$ is fixed to the conventional value $1/128.87$ 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 128.87 ± 0.12 [26]. A possible departure from this value would then be included in Δr_W . The present definition of Δr_W is unchanged with respect to ref.6. In order to define $\Delta \rho_N$ and Δk_N 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:

$$\Gamma_1 = \frac{G_F m_Z^3}{6\pi\sqrt{2}} (g_V^2 + g_A^2) \left(1 + \frac{3\alpha}{4\pi}\right) \quad (2)$$

$$A_{FB}^1(\sqrt{s} = m_Z) = \frac{3}{2} \frac{g_V^2 g_A^2}{(g_V^2 + g_A^2)^2} = \frac{3x^2}{(1+x^2)^2} \quad (3)$$

Note that Γ_1 stands for the inclusive partial width $\Gamma(Z \rightarrow ll + \text{photons})$. With respect to the definition of g_V and g_A in ref.[6] we stress the following differences. First, we have extracted from $(g_V^2 + g_A^2)$ the factor $(1 + 3\alpha/4\pi)$ which is induced in Γ_1 from final state radiation. Second, by the asymmetry at the peak in eq.(3) we mean the quantity which is now commonly referred to by the LEP experiments (denoted as A_{FB}^0 in ref.20), which is corrected for all QED effects, including initial and final state radiation and also for the effect of the imaginary part of the γ vacuum polarisation diagram. The last effect was instead not corrected for in ref.6. In terms of g_A and $x = g_V/g_A$, $\Delta \rho_N$ and Δk_N are given by [6]:

$$g_A = -\frac{\sqrt{\Delta \rho_N}}{2} = -\frac{1}{2} \left(1 + \frac{\Delta \rho_N}{2}\right)$$

$$x = \frac{g_V}{g_A} = 1 - 4 \frac{s_W^2}{s_0^2} = 1 - 4(1 + \Delta k_N) \frac{s_0^2}{s_W^2} \quad (4)$$

The index N for "new" is there to remind that the corresponding definition was changed with respect to ref.6. In fact the formal relations with the couplings are identical but the definition of g_V and g_A has been modified (it is only for simplicity that we do not append the index N to them too). In Eq.(4) $\tilde{s}_W^2$ is an effective $\sin^2 \theta_W$ for on-shell Z , defined by this very equation, while s_0^2 is the corresponding quantity before non pure-QED corrections, given by:

$$s_0^2 \tilde{c}_0^2 = \frac{\pi\alpha(m_Z)}{\sqrt{2}G_F m_Z^2} \quad (5)$$

with $\tilde{c}_0^2 = 1 - s_0^2$ ($s_0^2 = 0.231184$ for $m_Z = 91.187$ GeV).

We now define ϵ_b from Γ_b , the inclusive partial width for $Z \rightarrow b\bar{b}$ according to the relation

$$\Gamma_b = \frac{G_F m_Z^3}{6\pi\sqrt{2}} \beta \left(\frac{3}{2} \beta_{bV}^2 + \beta_{bA}^2 \right) N_C R_{QCD} \left(1 + \frac{\alpha}{12\pi}\right) \quad (6)$$

where $N_C=3$ is the number of colours, $\beta = \sqrt{1 - 4m_b^2/m_Z^2}$, with $m_b=4.8$ GeV, R_{QCD} is the QCD correction factor given by

$$R_{QCD} = 1 + 1.2a - 1.1a^2 - 1.3a^3; \quad a = \frac{\alpha_s(m_Z)}{\pi} \quad (7)$$

(for $\alpha_s(m_Z)=0.118$, $R_{QCD}=1.0428$) and g_{bV} , g_{bA} are specified as follows

$$g_{bA} = -\frac{1}{2} \left(1 + \frac{\Delta \rho_N}{2}\right) (1 + \epsilon_b)$$

$$\frac{g_{bV}}{g_{bA}} = \frac{1 - 4/3 \tilde{s}_W^2 + \epsilon_b}{1 + \epsilon_b} = \frac{1 - 4/3 (1 + \Delta k_N) \frac{s_0^2}{s_W^2} + \epsilon_b}{1 + \epsilon_b} \quad (8)$$

with $\Delta \rho_N$, Δk_N , $\tilde{s}_W^2$ and s_0^2 as defined in eqs.(2-5). The parameter ϵ_b in the Standard Model is closely related to the quantity $-\text{Re}\{\delta_b\text{-vertex}\}$ defined in the last of refs.9.

As is well known [27], in the Standard Model Δr_W , $\Delta \rho_N$ and Δk_N and ϵ_b , for sufficiently large m_t , are all dominated by quadratic terms in m_t of order $G_F m_t^2$. As new physics can more easily be disentangled if not masked by large conventional m_t effects, it

is convenient to keep $\Delta\rho_N$ and ϵ_b while trading $\Delta\Gamma_W$ and $\Delta\kappa_N$ for two quantities with no contributions of order $G_F m_t^2$. We thus introduce the following linear combinations [2,6]:

$$\begin{aligned}\epsilon_{N1} &= \Delta\rho_N \\ \epsilon_{N2} &= c_0^2 \Delta\rho_N + \frac{s_0^2 \Delta\Gamma_W}{(c_0^2 - s_0^2)} - 2 s_0^2 \Delta\kappa_N \\ \epsilon_{N3} &= c_0^2 \Delta\rho_N + (c_0^2 - s_0^2) \Delta\kappa_N\end{aligned}\quad (9)$$

In analogy with $\Delta\rho_N$ and $\Delta\kappa_N$ the new epsilons are labeled by ϵ_N . Clearly ϵ_{N2} and ϵ_{N3} 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_{N1} but are also present in ϵ_{N3} . In the Standard Model one has the following "large" asymptotic contributions [9,28,29]:

$$\begin{aligned}\epsilon_{N1} &= \frac{3G_F m_t^2}{8\pi^2\sqrt{2}} - \frac{3G_F m_W^2}{4\pi^2\sqrt{2}} \lg 2\theta_W \ln\left(\frac{m_H}{m_Z}\right) + \dots \\ \epsilon_{N2} &= -\frac{G_F m_W^2}{2\pi^2\sqrt{2}} \ln\left(\frac{m_t}{m_Z}\right) + \dots \\ \epsilon_{N3} &= \frac{G_F m_W^2}{12\pi^2\sqrt{2}} \ln\left(\frac{m_H}{m_Z}\right) - \frac{G_F m_W^2}{6\pi^2\sqrt{2}} \ln\left(\frac{m_t}{m_Z}\right) + \dots \\ \epsilon_b &= -\frac{G_F m_t^2}{4\pi^2\sqrt{2}} + \dots\end{aligned}\quad (10)$$

The relations between the basic observables and the epsilons can be linearised and inverted, leading to the formulae

$$\begin{aligned}\epsilon_{N1} &= -0.9882 + 0.011963 \Gamma_W/\text{Mev} - 0.1511 x \\ \epsilon_{N3} &= -0.7146 + 0.009181 \Gamma_W/\text{Mev} - 0.69735 x \\ \epsilon_b &= -0.62 \epsilon_{N1} + 0.24 \epsilon_{N3} + 0.436 \left[\frac{\Gamma_b}{\Gamma_{b0}} - 1 \right] \\ \epsilon_{N2} &= \frac{1}{c_0^2 s_0^2} [c_0^2 \epsilon_{N1} - 2 s_0^2 \epsilon_{N3} + s_0^2 \Delta\Gamma_W] = \\ &= 1.43 \epsilon_{N1} - 0.86 \epsilon_{N3} + 0.43 \Delta\Gamma_W\end{aligned}\quad (11)$$

where $x = g_V/g_A$ is defined in eq.3 from A_{FB}^l . The quantity Γ_{b0} is the value of Γ_b in the limit when all epsilons are neglected. With $\alpha_s(m_Z)=0.118$, $\Gamma_{b0} = 379.4$ MeV (more in general its value is given by eqs.6-8 and 27).

Eqs (11) are also used to obtain, by definition, the behaviour of the epsilons in the Standard Model as functions of m_t and m_H : by means of the latest version of the programme ZFITTER [30] we compute Γ_b , x and $\Delta\Gamma_W$ as functions of m_t and m_H and we obtain the results for ϵ_{N1} , ϵ_{N2} and ϵ_{N3} given in Table 1 and shown in fig.1, while the result for ϵ_b , which is practically independent of m_H , is given in Table 2 and plotted in fig.2 for $\alpha_s(m_Z)=0.118$. The above results were also checked by using the new code TOPAZ0 [31]. As already mentioned, in the Standard Model the dependence on m_t and m_H of all observables at the Z pole only enters through the epsilons (see sect.3). This is also true in any extension which deviates from the Standard Model in vacuum polarizations and/or in the Z- $b\bar{b}$ vertex. This is an exact statement if one loop corrections are only considered. At two loops, some residual dependence on m_t is induced in the various observables from terms of order α_s^2 [32] which can be reabsorbed in the epsilons only in an approximate but sufficiently accurate way.

Table1

	$m_t(\text{GeV})$	$m_H=50 \text{ GeV}$	100	500	1000
$\epsilon_{N1} \cdot 10^3$	100	0.09	0.05	-0.87	-1.59
	125	1.63	1.71	0.56	-0.05
	150	3.58	3.55	2.41	1.80
	175	5.83	5.80	4.67	3.94
	200	8.59	8.45	7.10	6.39
	225	11.6	11.5	9.95	9.12
	250	15.1	14.9	13.1	12.0
	275	19.0	18.8	16.5	15.4
	300	23.3	23.0	20.2	18.9
	$m_t(\text{GeV})$	$m_H=50 \text{ GeV}$	100	500	1000
$\epsilon_{N2} \cdot 10^3$	100	-5.30	-5.13	-4.82	-4.81
	125	-6.31	-6.04	-5.82	-5.69
	150	-7.15	-6.90	-6.59	-6.40
	175	-8.00	-7.70	-7.23	-7.07
	200	-8.83	-8.57	-8.03	-7.82
	225	-9.89	-9.55	-8.89	-8.61
	250	-11.2	-10.7	-9.90	-9.64
	275	-12.7	-12.1	-11.1	-10.7
	300	-14.6	-13.9	-12.6	-12.0

$$g_A^2 = 0.2494 \pm 0.0009 \quad (13)$$

$$x = g_V/g_A = 0.0720 \pm 0.0063 \quad \text{or} \quad s_W^2 = 0.2320 \pm 0.0016 \quad (14)$$

Table 3

$m_Z(\text{GeV})$	91.187 ± 0.007
m_W/m_Z [33]	0.8807 ± 0.0031
$\Gamma_T(\text{MeV})$	2492 ± 7
$R = \Gamma_W/\Gamma_T$	20.85 ± 0.07
$\sigma_{\text{th}} = 12\pi\Gamma_e\Gamma_W/m_Z^2\Gamma_T^2$ (nb)	41.16 ± 0.18
$\Gamma_T(\text{MeV})$	83.33 ± 0.30
$\Gamma_W(\text{MeV})$	1737.1 ± 6.7
$\Gamma_b(\text{MeV})$	373 ± 9
$R_{\text{th}} = \Gamma_W/\Gamma_h$	0.2147 ± 0.0052
A_{FB}^l	0.0154 ± 0.0027
A_{pol}^+	0.140 ± 0.018
A_e^e	0.122 ± 0.031
A_{FB}^b	0.098 ± 0.012

Table 3. List of experimental values used in the text. LEP data are from ref.20.

One can now use eqs. (4) to derive the results for $\Delta\rho_N$ and $\Delta\kappa_N$:

$$\epsilon_{N1} = \Delta\rho_N = (-2.2 \pm 3.7) \cdot 10^{-3} \quad (15)$$

$$\Delta\kappa_N = (3.5 \pm 6.8) \cdot 10^{-3} \quad (16)$$

The corresponding results for ϵ_{N2} and ϵ_{N3} are obtained from eqs.9 or 11:

$$\epsilon_{N2} = (-12.5 \pm 8.0) \cdot 10^{-3} \quad (17)$$

$$\epsilon_{N3} = (0.2 \pm 5.25) \cdot 10^{-3} \quad (18)$$

Finally from the value of Γ_b listed in Table 3 one finds, by using eqs.6-8 or 11:

$$\epsilon_b = (-6.0 \pm 10.6) \cdot 10^{-3} \quad (19)$$

To proceed further, and include other measured observables in the analysis we need to make some dynamical assumptions. The minimum amount of model dependence is

$\epsilon_{N3} \cdot 10^3$	$m_t(\text{GeV})$	$m_H=50 \text{ GeV}$	100	500	1000
	100	4.75	5.49	6.78	7.12
	125	4.51	5.34	6.47	6.88
	150	4.31	5.08	6.24	6.65
	175	4.07	4.85	6.07	6.42
	200	3.93	4.65	5.79	6.19
	225	3.69	4.45	5.59	5.92
	250	3.42	4.22	5.32	5.57
	275	3.16	3.94	4.98	5.27
	300	2.78	3.57	4.57	4.88

Table 1. Values of $\epsilon_{N1} \cdot 10^3$ obtained from eqs.11 and the programme ZFITTER [30].

Table2

$m_t(\text{GeV})$	$\epsilon_b \cdot 10^3$
100	-1.12
125	-2.82
150	-4.88
175	-7.13
200	-9.79
225	-12.8
250	-16.1
275	-19.9
300	-23.9

Table 1. Values of $\epsilon_b \cdot 10^3$ obtained from eqs.11 and the programme ZFITTER [30] with $\alpha_s(m_Z)=0.118$.

3. Determination of the epsilons from the data

The experimental results that will be used in the present analysis are collected in Table 3. We start by deriving from the data on the input observables the values of the epsilons that follow by directly applying their definition, with no dynamical assumptions.

By combining the value of m_W/m_Z [33] with the LEP value for the Z mass [20], both given in Table 3, and using eq.(1) one obtains:

$$\Delta\tau_W = (-21.3 \pm 16.5) \cdot 10^{-3} \quad (12)$$

From the LEP results on the charged lepton partial width and the forward-backward asymmetry, assuming $e\text{-}\mu\text{-}\tau$ universality, given in Table 3, one finds:

introduced by including other purely leptonic quantities at the Z pole such as $A_{\text{pol}}^\tau \cdot A_e$ (measured [20] from the angular dependence of the τ polarisation) and A_{LR} . At this stage, one is simply relying on lepton universality. Indeed, with the new definition of $x = gv/g_A$ in eq.3 in terms of the peak asymmetry, defined with all pure QED effects, including the imaginary part of the photon vacuum polarisation, subtracted away, the data on $A_{\text{pol}}^\tau \cdot A_e$ and A_{LR} can be taken into account by using the simple formula

$$A_{\text{pol}}^\tau \cdot A_e \cdot A_{LR} = \frac{2x}{g_V^2 + g_A^2} \quad ; \quad (20)$$

with the same x as defined from A_{FB}^l , apart from still negligible differences. With essentially the same assumptions one can also include the data on the b-quark forward backward asymmetry A_{FB}^b . In fact it turns out that A_{FB}^b is almost unaffected by the $Z \rightarrow b\bar{b}$ vertex correction. Schematically the reason is that $A_{FB}^b = 3\eta_e\eta_b$ with $\eta = gv/g_A/(g_V^2 + g_A^2)$, so that $\delta A_{FB}^b = 3(\eta_e\delta\eta_b + \eta_b\delta\eta_e)$. We see that the sensitivity on η_b , which contains the $Z \rightarrow b\bar{b}$ vertex correction, is strongly suppressed by the small factor η_e . This is confirmed by an accurate numerical calculation of A_{FB}^b . If we define a new quantity $(\tilde{s}_W^2)_b$ by the identity:

$$A_{FB}^b = 3 \frac{1-4(\tilde{s}_W^2)_b}{1+(1-4(\tilde{s}_W^2)_b)^2} \frac{\beta(1-\frac{4}{3}(\tilde{s}_W^2)_b)}{\beta^2 + \frac{3-\beta^2}{2}(1-\frac{4}{3}(\tilde{s}_W^2)_b)^2} \quad (21)$$

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 $(\tilde{s}_W^2)_b$ and the similar quantity $(\tilde{s}_W^2)_{FB}$ previously defined from the charged lepton asymmetry A_{FB}^l and check that, with the new definition of A_{FB}^l , they indeed practically coincide.

As a result of the previous discussion, we can combine the values of $x = gv/g_A$ obtained from the whole set of asymmetries measured at LEP and we get the value:

$$x = gv/g_A = 0.0705 \pm 0.0042 \quad \text{or} \quad \tilde{s}_W^2 = 0.2324 \pm 0.0011 \quad (22)$$

which coincides with the result quoted in ref.[20]. At this stage the best values of ϵ_{N1} , ϵ_{N2} and ϵ_{N3} are modified according to

$$\begin{aligned} \epsilon_{N1} &= \Delta\rho_N = (-1.9 \pm 3.6) \cdot 10^{-3} \\ \epsilon_{N2} &= (-13.1 \pm 7.8) \cdot 10^{-3} \\ \epsilon_{N3} &= (1.3 \pm 4.0) \cdot 10^{-3} \end{aligned} \quad (23)$$

$$\epsilon_b = (-5.9 \pm 10.6) \cdot 10^{-3}$$

All observables measured on the Z peak at LEP can be included in the analysis provided that we assume that all deviations from the Standard Model are only contained in vacuum polarisation diagrams (without demanding a truncation of the q^2 dependence of the corresponding functions) and/or the $Z \rightarrow b\bar{b}$ vertex. Note that this is true for whatever partition of the new effect between g_{bV} and g_{bA} , because only one combination of them is measured in Γ_b , while, as already mentioned, A_{FB}^b is nearly independent of the $Z \rightarrow b\bar{b}$ vertex. A set of primary measurements at LEP contains Γ_Z , $R = \Gamma_b/\Gamma_l$, the hadronic peak cross section σ_h (with a 3×3 correlation matrix given in ref.21), $R_{bh} = \Gamma_b/\Gamma_h$ plus the symmetries that lead to the value of x in eq.22. The relations between these quantities and the epsilons can be written down in the following linearised form:

$$\begin{aligned} \Gamma_Z &= \Gamma_Z^0 [1 + 1.35 \epsilon_{N1} - 0.46 \epsilon_{N3} + 0.35 \epsilon_b] \\ R &= R_0 [1 + 0.28 \epsilon_{N1} - 0.36 \epsilon_{N3} + 0.50 \epsilon_b] \\ \sigma_h &= \sigma_{h0} [1 - 0.03 \epsilon_{N1} + 0.04 \epsilon_{N3} - 0.20 \epsilon_b] \end{aligned} \quad (24)$$

$$R_{bh} = R_{bh0} [1 - 0.06 \epsilon_{N1} + 0.07 \epsilon_{N3} + 1.79 \epsilon_b]$$

$$x = x_0 [1 + 17.6 \epsilon_{N1} - 22.9 \epsilon_{N3}]$$

The constant values are functions of $\alpha_s(m_Z)$ and also of $\alpha(m_Z)$. Defining

$$\delta\alpha_s = [\alpha_s(m_Z) - 0.118]/\pi ; \quad \delta\alpha = (\alpha(m_Z) - 1/128.87)/\alpha \quad (25)$$

we have, from the code of ref.30:

$$\begin{aligned} \Gamma_Z^0 &= 2488.1 [1 + 0.73 \delta\alpha_s - 0.35 \delta\alpha] \text{ MeV} \\ R_0 &= 20.812 [1 + 1.05 \delta\alpha_s - 0.28 \delta\alpha] \\ \sigma_{h0} &= 41.425 [1 - 0.41 \delta\alpha_s + 0.03 \delta\alpha] \text{ nb} \\ R_{bh0} &= 0.21818 [1 + 0.15 \delta\alpha_s + 0.06 \delta\alpha] \\ x_0 &= 0.07526 - 1.32 \delta\alpha \end{aligned} \quad (26)$$

For completeness we also report the corresponding values for Γ_b and Γ_h separately:

$$\Gamma_{b0} = 379.4 [1 + 1.2 \delta\alpha_s - 0.42 \delta\alpha] \text{ MeV} \quad (27)$$

$$\Gamma_{b0} = 1739.0[1 + 1.05\delta a_s - 0.47\delta\alpha] \text{ MeV}$$

We stress that, at the one-loop level, all the dependence on m_t and m_H of the quantities in eqs.24 enters through the epsilons and not in the various numerical coefficients. This is no longer true for those two-loop effects, unlike those computed in ref.34, which are not vacuum polarisation or $Z \rightarrow b\bar{b}$ vertex corrections. For example, the dependence on m_t in RQCD introduced by the α_s^2 terms of ref. 31, was not included in eq.7. As a consequence, their effect on Γ_b is, by definition, found in ϵ_b . Their remaining effect on all other observables we consider is numerically irrelevant.

We have made a global fit of the data on m_W/m_Z , Γ_Z , R , σ_h , $R_{b\bar{b}}$, given in Table 3 and the results on the asymmetries, summarised by the value of x in eq.22. For LEP data, we have taken the correlation matrix for Γ_Z , R and σ_h given in ref.21, while we have considered the additional information on $R_{b\bar{b}}$ and x as independent. The results of our fit are:

$$\begin{aligned} \epsilon_{N1} &= \Delta\rho_N = (0.3 \pm 3.3) 10^{-3} - 0.1 \delta a_s \\ \epsilon_{N2} &= (-11.2 \pm 7.7) 10^{-3} - 0.11 \delta a_s + 0.23 \delta a \\ \epsilon_{N3} &= (2.8 \pm 3.8) 10^{-3} - 0.04 \delta a_s - 0.77 \delta a \\ \epsilon_b &= (5.45 \pm 5.7) 10^{-3} - 1.72 \delta a_s \end{aligned} \quad (28)$$

where the dependence on the values of $\alpha_s(m_Z)$ and $\alpha(m_Z)$ has also been indicated. If we neglect possible contributions from δa and add in quadrature the effect of a ± 0.007 error on $\alpha_s(m_Z)$ around the central value 0.118, we obtain:

$$\begin{aligned} \epsilon_{N1} &= \Delta\rho_N = (0.3 \pm 3.3) 10^{-3} \\ \epsilon_{N2} &= (-11.2 \pm 7.7) 10^{-3} \\ \epsilon_{N3} &= (2.8 \pm 3.8) 10^{-3} \\ \epsilon_b &= (5.45 \pm 6.8) 10^{-3} \end{aligned} \quad (29)$$

which shows that the errors induced from $\alpha_s(m_Z)$ are entirely negligible with the exception of the error on ϵ_b .

Provided that all deviations from the Standard Model are only contained in vacuum polarizations and/or in the $Z \rightarrow b\bar{b}$ vertex, Eqs. 24 apply. For that to be true, it is important that we focus on observables at the intermediate gauge boson scale of mass. To include in the analysis lower energy observables as well, a stronger hypothesis needs to be made: only vacuum polarization diagrams are allowed to vary from the Standard Model ones and only in their constant and first derivative terms in a q^2 -expansion [1-3], a likely picture,

e.g., in technicolour theories [13,14]. In such a case, to eqs. 11 one can add the linearized expressions, in terms of the epsilons, of the ratio R_V of neutral to charged current processes in deep inelastic neutrino scattering on nuclei [15,16]

$$R_V = 0.3115 + 0.83 \epsilon_{N1} - 0.27 \epsilon_{N3} \quad (30)$$

or of the "weak charge" Q_W measured in atomic parity violation experiments on Cs [18,19]

$$Q_W = -72.72 \pm 0.13 - 102 \epsilon_{N3} \quad (31)$$

(with the error due to the theoretical uncertainties in the atomic wave functions).

It is now possible to include these low energy observables in an overall fit. Using, together with the data in Table 3, the present average value from νN scattering

$$\langle R_V \rangle = 0.312 \pm 0.003 \quad (32)$$

(which takes the recent CCFR result [16] into account) and the result from cesium data [18,19]

$$Q_W = -71.04 \pm 1.81, \quad (33)$$

one obtains the global fit

$$\begin{aligned} \epsilon_{N1} &= \Delta\rho_N = (0.3 \pm 2.8) 10^{-3} \\ \epsilon_{N2} &= (-10.8 \pm 7.5) 10^{-3} \\ \epsilon_{N3} &= (2.4 \pm 3.6) 10^{-3} \\ \epsilon_b &= (5.1 \pm 6.6) 10^{-3} \end{aligned} \quad (34)$$

Here the error induced from $\alpha_s(m_Z)$ was taken into account in the same way as in eqs. 29.

4. Discussion and Conclusion

The results of the various fits in eqs.15-19, 23, 29, 34 are collected in Table 4. The results for ϵ_b and ϵ_{N2} are compared with the Standard Model predictions in figs. 2 and 3. We also show in figs. 4-6 the projected ellipses in the planes ϵ_{N1} - ϵ_{N3} , ϵ_{N1} - ϵ_b , ϵ_{N3} - ϵ_b for different fits together with the corresponding Standard Model predictions.

We note that, with the progress of LEP, the effect of low energy data on the epsilons is decreasing in importance. We also observe that all the epsilons are compatible with zero within 1σ (somewhat more for ϵ_{N2} , as a consequence of the fact that $\Delta\tau_W$ is

displaced from zero by more than 1σ). This means that the tree level Standard Model plus pure QED corrections is quite a good approximation and that the possibility of testing the pure weak radiative corrections is marginal within the present accuracy.

Table 4

	Only Defining Variables	Defining Variables plus all Asymmetries	All LEP data	"All data"
$\epsilon_{N1} \cdot 10^3$	-2.2 ± 3.7	-1.9 ± 3.6	0.3 ± 3.3	0.3 ± 2.8
$\epsilon_{N2} \cdot 10^3$	-12.5 ± 8.0	-13.1 ± 7.8	-11.2 ± 7.7	-10.8 ± 7.5
$\epsilon_{N3} \cdot 10^3$	0.2 ± 5.25	1.3 ± 4.0	2.8 ± 3.8	2.4 ± 3.6
$\epsilon_b \cdot 10^3$	-6.0 ± 10.6	-5.9 ± 10.6	5.45 ± 6.8	5.1 ± 6.6

Table 4. Summary of the different determinations of the epsilon parameters.

By comparing the results from the global fit given in eqs.29 (Table 4, column 3) with those in eqs.23 (Table 4, column 2) obtained from fitting m_W/m_Z , Γ_b , Γ_b and the value of x derived from all the asymmetries, we observe that the effect on ϵ_{N1} , ϵ_{N2} , and ϵ_{N3} of the additional information from Γ_Z , R and σ_h is quite modest. Their central values are displaced by less than 1σ and the gain on the errors is very limited. This a posteriori supports the procedure proposed in ref.6, where, for the determination of ϵ_{N1} , ϵ_{N2} , and ϵ_{N3} , the hadronic quantities were discarded because of the top dependence introduced by the $Z \rightarrow b\bar{b}$ vertex and of the need of specifying $\alpha_s(m_Z)$. Note, however, that the value of ϵ_{N3} , which is particularly important as a constraint for models of new physics, is somewhat displaced towards the standard value by including the hadronic quantities. It is possible to make contact with the approach in terms of the variables S , T and U [1.3] only under the assumption of dominance of new physics effects through vacuum polarisation corrections. In such a case, the precise relation with the epsilons is given by:

$$\epsilon_{N1} = \epsilon_{N10} + \alpha T; \quad \epsilon_{N2} = \epsilon_{N20} - \frac{\alpha}{4s_0^2} U; \quad \epsilon_{N3} = \epsilon_{N30} + \frac{\alpha}{4s_0^2} S \quad (35)$$

Note that S , T and U have only meaning in terms of a reference set of values for m_t and m_H , while our epsilons are defined from measurable quantities without need of specifying given values of m_t and m_H . The quantities ϵ_{N10} , ϵ_{N20} and ϵ_{N30} are the SM values at the reference point, where also ϵ_b would have to be fixed.

It is interesting to observe that, contrary to the case of ϵ_{N1} , ϵ_{N2} , and ϵ_{N3} , a very large effect is induced on ϵ_b by including Γ_Z , R and σ_h . In fact Γ_Z , R and especially σ_h all tend to displace ϵ_b in the positive direction. As a consequence, the value of ϵ_b is changed by more than 1σ , and within one standard deviation is essentially positive, while the

predictions of the Standard Model are negative for $m_t > 91$ GeV (fig.2). Thus, besides ϵ_{N3} we have identified another interesting variable for constraining models of new physics: those extensions of the Standard Model that push the prediction of ϵ_b in the positive direction are favoured. Another interesting consequence of this result is that one can obtain a rather strong limit on m_t , independent of $\Delta\rho_N$ (i.e. ϵ_{N1}). Suppose in fact that one assumes that new physics leads to arbitrary effects in vacuum polarisation functions but that all vertices are instead negligibly affected. Then our analysis would apply and, moreover, ϵ_b would be described by the Standard Model prediction as a function of m_t . For $\alpha_s(m_Z) = 0.118 \pm 0.007$, we obtain from ϵ_b the limit

$$m_t < 207 \text{ GeV} \quad (95\% \text{ c.l.}) \quad (36)$$

By a similar approach a weaker limit was obtained in ref.35 because only the data on Γ_b and R were taken into account, while also the results on Γ_Z and σ_h have a sizeable impact. There may be some question on the meaning of the confidence level assigned to this bound as the data on ϵ_b at 1σ intersect the Standard Model theoretical curve in a region of m_t which is mostly excluded by the CDF limit: we have taken the ratio of the Gaussian tail above the limit (36) and the area from 91 GeV to infinity to be 5%. If we did not know that the region below 91 GeV is forbidden, the corresponding limit would be $m_t < 160$ GeV. Note that if we perform a complete fit in the Standard Model of the same set of data, with $\alpha_s(m_Z) = 0.118 \pm 0.007$, we obtain the results $m_t = 132 \pm 22$ GeV for $m_H = 50$ GeV and $m_t = 173 \pm 21$ GeV for $m_H = 1$ TeV, with a better χ^2 for the light Higgs case (5.5 vs. 8.4).

It is important to stress that the fitted value of ϵ_b and its excess with respect to the Standard Model prediction for realistic values of m_t depend on the input range of $\alpha_s(m_Z) = 0.118 \pm 0.007$, which has been derived from all existing experiments, assuming the validity of QCD [25]. It is interesting to repeat the fit without constraining $\alpha_s(m_Z)$. By considering all LEP data (as for the results in eqs.29) one obtains in this case:

$$\begin{aligned} \epsilon_{N1} &= \Delta\rho_N = (-0.6 \pm 3.4) \cdot 10^{-3} \\ \epsilon_{N3} &= (2.4 \pm 3.8) \cdot 10^{-3} \\ \epsilon_b &= (-9.9 \pm 13.9) \cdot 10^{-3} \\ \alpha_s(m_Z) &= 0.146 \pm 0.024 \end{aligned} \quad (37)$$

(Note that a fit of the same data in the Standard Model with $\alpha_s(m_Z)$ unconstrained gives $\alpha_s(m_Z) = 0.135 \pm 0.009$ [20]). By comparison with eqs.29 we see that, while ϵ_{N1} and ϵ_{N3} change by only a small fraction of their errors, on the contrary the central value of ϵ_b becomes strongly negative and gets close to the value in eqs.23 obtained when only Γ_b is used. As a matter of fact, when $\alpha_s(m_Z)$ is a free parameter, ϵ_b is essentially determined from eqs.24 by R_b alone, which is almost α_s -independent, with ϵ_{N1} and ϵ_{N3} fixed by Γ_1 and $x = g_V/g_A$. In principle one can experimentally decide if the observed excess of ϵ_b is

due to $\alpha_s(m_Z)$ or to the $Z \rightarrow b\bar{b}$ vertex, because the pattern of deviations for the various observables is different in the two cases, as is clear from eqs. 24 and 26-27. At present the precision of the data, especially those on $R_{b\bar{b}}$, is not sufficient to really decide this issue. However, the fit in eqs. 37, goes in the direction of attributing at least part of the effect to $\alpha_s(m_Z)$.

The decrease of ϵ_{N3} with respect to the Standard Model prediction is possible in many models, for example extended gauge models [10] or the Minimal Supersymmetric Standard Model (MSSM) [11,12]. In particular, it has been shown in ref. 12, that in the MSSM a sizeable reduction of ϵ_{N3} is induced by a Z wave function renormalisation effect if electroweak gaugino-higgsinos are close to their experimental limits. While this is interesting, it is important to observe that such an effect, by itself, would reduce by the same percentage all widths. Then it would not at all affect R and σ_h , so that it would not cure the apparently high value of ϵ_b , which then should be, at least in part, cured by $\alpha_s(m_Z)$. We also note that, the vertex corrections being negligible in this case, the determination of the epsilons from all LEP data given in table 4 applies. On the contrary, due to the strong q^2 dependence of the Z wave function renormalisation in the case of gauginos and higgsinos close to threshold, the low energy data cannot be included.

In conclusion, especially in view of the envisaged accuracy that will be obtained by the electroweak tests at the end of the LEP1 phase, the study of the epsilons can provide important constraints and possibly also positive clues on new physics beyond the Standard Model. The isolation of different sectors of the theory, as allowed by the epsilons, may help to clarify the physical origin of any deviation from the Standard Model that will possibly be found or to discard theories that require some specific pattern of radiative effects on the epsilons which turns out to be incompatible with the data.

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Figure Captions.

Fig 1. The quantities ϵ_{N1} , ϵ_{N2} and ϵ_{N3} as predicted in the Standard Model [30] as functions of m_t . The bands correspond to the dependence on m_H in the range $m_H = 50-1000$ GeV.

Fig.2. The curve corresponds to the Standard Model [30] prediction of ϵ_b as function of m_t (there is no dependence on m_H). The band is the fitted value in eq.34 from all the data analysed with $\alpha_s(m_Z)=0.118\pm0.007$.

Fig.3. The theoretical prediction for ϵ_{N2} in the Standard Model [30] as function of m_t and m_H compared with the fitted values from all the data (eqs.34). The arrows indicate the limits of the band if only the defining variables are used (eq.17).

Fig.4. Plots of ϵ_{N3} versus ϵ_{N1} for different fits presented in Table 4: a) column 2; b) column 3; c) column 4. The projections on the axis of the ellipses correspond to the 1σ errors displayed in Table 4. The curves refer to the Standard Model [30] predictions for different values of m_t and m_H .

Fig.5. Plots of ϵ_b versus ϵ_{N1} for different fits presented in Table 4: a) column 3; b) column 4. The projections on the axis of the ellipses correspond to the 1σ errors displayed in Table 4. The curves refer to the Standard Model [30] predictions for different values of m_t and m_H with $\alpha_s(m_Z)=0.118\pm0.007$.

Fig.6. Plots of ϵ_{N3} versus ϵ_b for different fits presented in Table 4: a) column 3; b) column 4. The projections on the axis of the ellipses correspond to the 1σ errors displayed in Table 4. The curves refer to the Standard Model [30] predictions for different values of m_t and m_H with $\alpha_s(m_Z)=0.118\pm0.007$.

Fig.2

Fig.1

Fig. 3

Fig. 4a

Fig. 4b

Fig. 4c

Fig. 5a

Fig. 6a

Fig. 5b

Fig. 6b