FIRST EVIDENCE FOR ELECTROWEAK RADIATIVE CORRECTIONS FROM THE NEW PRECISION DATA

V.A. Novikov∗),
University of Guelph, Guelph, ON, N1G2W1, Canada
L.B. Okun∗),
Theoretical Physics Division, CERN
CH-1211 Geneva 23, Switzerland
and
A.N. Rozanov**, M.I. Vysotsky
ITEP, Moscow, 117259, Russia

Abstract
The analysis of the newest data on the leptonic Z-decays and \( m_W \) appears to reveal the first manifestations of electroweak radiative corrections. In fact, these data differ, at the level of 2\( \sigma \), from their electroweak Born values, while they agree, to within 1\( \sigma \), with the theoretical values which take the electroweak radiative corrections into account. Previous data were within 1\( \sigma \) in agreement with both sets of values.

∗) Permanent address: ITEP, Moscow 117259, Russia.
**) Present address: Particle Physics Experiments Division, CERN
CH-1211 Geneva 23, Switzerland
The traditional way of analyzing the data on electroweak radiative corrections, (see for instance [1] - [3]), is to not split off from them the large and purely electromagnetic effect of the running of the electric charge from $q^2 = 0$ to $q^2 = m_Z^2$. According to that approach, which starts from $\alpha \equiv \alpha(0) = 1/137.0359895(61)$, the “electroweak” corrections appear to be large and to have been observed for a long time. By analyzing them, many authors [4] came already several years ago to the conclusion that the mass of the top quark must be close to 130 GeV or heavier.

In a series of papers [5]-[9] we developed an approach in which the running of $\alpha(q^2)$ is explicitly excluded from the genuinely electroweak corrections and included in the electromagnetic ones. Our main argument is that the running of $\alpha(q^2)$ up to $q^2 = m_Z^2$ is a purely electromagnetic phenomenon which is totally insensitive to the existence of electroweak bosons (W, Z and higgs), and that $\alpha(0)$, with all its impressive accuracy, is wholly irrelevant to electroweak physics even at low energy [10]. Our approach starts with the most accurately known electroweak observables:

$$G_\mu = 1.16639(2) \cdot 10^{-5} \text{ GeV}^{-2}, \quad [11]$$

$$m_Z = 91.1899(44) \text{ GeV}, \quad [12]$$

$$\bar{\alpha} = \alpha(m_Z) = 1/128.87(12), \quad [13]$$

and has three free parameters: the top quark mass, $m_t$, the Higgs boson mass, $m_H$, and the QCD coupling constant $\bar{\alpha}_s \equiv \alpha_s(m_Z)$. The conventional nature of the definition on $\bar{\alpha}$ is analyzed in [14].

In terms of $G_\mu, m_Z$ and $\bar{\alpha}$ we define the electroweak angle $\theta$ ($\sin \theta \equiv s, \cos \theta \equiv c$) [5], [6], [15]:

$$s^2 c^2 = \frac{\pi \bar{\alpha}}{\sqrt{2 G_\mu m_Z^2}}, \quad (4)$$

which is analogous to, but different from, the traditional $\theta_W$ ($\sin \theta_W \equiv s_W, \cos \theta_W \equiv c_W$) defined by substituting $\alpha$ instead of $\bar{\alpha}$ in eq.(4). By solving eq.(4) one finds:

$$s^2 = 0.23118(33), \quad c = 0.87682(19) \quad (5)$$

In the $\bar{\alpha}$-Born approximation

$$m_W/m_Z = c = 0.8768(2), \quad (6)$$

$$g_A = -1/2, \quad (7)$$

$$g_V/g_A = 1 - 4s^2 = 0.0753(12). \quad (8)$$

Here $g_V$ and $g_A$ are the vector and axial couplings of the Z boson decay into a pair of charged leptons $\bar{l}l$. (Note that with the traditional angle $\theta_W$ we would
get $s_{W}^{2} = 0.2122$ and in the $\bar{\alpha}$-Born approximation $g_V/g_A = 0.1514$ which differs by $40\sigma$ (!) from the corresponding experimental value (see Table 1).

The width of the decay $Z \to ll$ is given by expression:

$$\Gamma_l = 4(1 + \frac{3\bar{\alpha}}{4\pi})(g_A^2 + g_V^2)\Gamma_0, \quad (9)$$

where

$$\Gamma_0 = \frac{\sqrt{2}G_M m_Z^2}{48\pi} = 82.948(12) \text{ MeV} \quad (10)$$

The first bracket in eq. (9) takes into account the purely electromagnetic corrections.

In a similar manner, the width of $Z$ decaying into a pair of quarks $q\bar{q}$ with charge $Q$ and the isospin projection $T_3$ is given by

$$\Gamma_q = 12(1 + \frac{3Q^2\bar{\alpha}}{4\pi})(g_A^2 + g_V^2)\Gamma_0 G \quad (11)$$

where

$$g_{Aq} = T_3, \quad (12)$$

$$g_{Vq}/g_A = 1 - 4|Q|s^2. \quad (13)$$

The extra factor of 3, as compared with eq.(9), comes from the colour and the factor $G$ takes into account the emission and exchange of gluons [16]:

$$G = 1 + \frac{\bar{\alpha}_s}{\pi} + 1.4(\frac{\bar{\alpha}_s}{\pi})^2 - 13(\frac{\bar{\alpha}_s}{\pi})^3 + \ldots \quad (14)$$

We thus define the $\bar{\alpha}$-Born approximation for $\Gamma_l$ by eqs.(7)-(10) and for $\Gamma_h$ by summing eq. (11) over all quarks, thereby taking into account the QED and QCD loop corrections. Beyond the $\bar{\alpha}$-Born approximation, one has to include in $g_A, g_V, g_{Aq}, g_{Vq}$ the contributions of electroweak loops proportional to $\bar{\alpha}/\pi$ (with gluonic corrections in some of them).

In ref. [8] we concluded that the data of four LEP detectors, announced at the 1993 La Thuile [17] and Moriond [18] conferences, were, within $1\sigma$, described by the electroweak $\bar{\alpha}$-Born approximation as well as by the standard model expressions including the one-loop electroweak corrections. This means that the genuine electroweak corrections were not visible experimentally at that time.

The non-observation of deviations from the electroweak $\bar{\alpha}$-Born approximation, with due allowance for QED and QCD effects, enabled us to predict the values of $\bar{\alpha}_s$ and $m_t$ within the framework of the Minimal Standard Model, while $m_H$ remained practically non-constrained. In this respect our results did not differ from those of the traditional approach. In our approach the possibility of constraining $m_t$ arises from the mutual compensation of the
contributions of the top quark and all other virtual particles for \( m_t \) in the range of \( 160 \pm 20 \) GeV \( ^8 \).

The experimental data changed somewhat by the time of the Marseille Conference \( ^9 \),\( ^4 \), so that the maximal deviation from the corresponding \( \bar{\alpha} \)-Born value became \( 1.3\sigma \) (for \( g_V/g_A \) \( ^4 \). Obviously, the situation did not change qualitatively.

According to the fit of ref. \( ^8 \), the values of the LEP observables were equally well described within \( 1\sigma \) by the \( \bar{\alpha} \)-Born approximation and by the Minimal Standard Model amplitudes including the electroweak radiative corrections. The only exception was the value of \( R_b \) for a heavy higgs where discrepancy with the MSM prediction reached \( 1.7\sigma \). (See Table 1 from \( ^9 \).)

At the 1994 La Thuile and Moriond conferences \( ^12 \) new, more accurate data were presented by CDF, ADLO and SLD. In the present note we compare these data with our theoretical expressions, which have been combined into a computer code called LEPTOP \( ^7 \).

Let us start by considering the data of CDF and ADLO. From Table 1 we see that the new experimental values of \( m_W/m_Z, \Gamma_l \) and \( g_V/g_A \) deviate from their \( \bar{\alpha} \)-Born value by \( 2\sigma \). These are the so-called “gluon-free” observables \( ^{20} \) which depend on \( \bar{\alpha}_s \) only very weakly, i.e., only through terms of the order of \( \bar{\alpha}\bar{\alpha}_s \). At the same time the data agree within \( 1\sigma \) with those theoretical predictions which take the electroweak radiative corrections into account. We consider this as a first indication that the genuine electroweak corrections have become observable. This conclusion is strengthened by the fact that the experimental errors in \( m_W/m_Z, \Gamma_l \) and \( g_V/g_A \) are practically uncorrelated. Note the difference between our statement and that of Ref. \( ^{21} \) where the departure of the MSM predicted (fitted) values from the \( \bar{\alpha} \)-Born ones is being stressed.

There are two small clouds on this blue sky. First, the new measurements of \( A_{LR} \) at SLD give \( \sin^2 \theta_{\text{eff}} = 0.2290(10) \) or \( g_V/g_A = 0.0840(40) \), which differs by \( 3\sigma \) from the LEP value \( g_V/g_A = 0.0711(20) \) and from the theoretical prediction (see Table 1). This discrepancy is probably of purely experimental origin. Note that the SLD value for \( g_V/g_A \) lies \( 2\sigma \) above the \( \bar{\alpha} \)-Born value, while the LEP value lies \( 2\sigma \) below. Their average is compatible with \( \bar{\alpha} \)-Born.

Second, the value of \( R_b \) measured at LEP coincides with the \( \bar{\alpha} \)-Born value and is \( 2.5\sigma \) away from its theoretically fitted value \( R_b = 0.2161(4) + \delta m_t \) (with the central value corresponding to \( m_H = 300 \) GeV, the shifts + (–) 6 to \( m_H = 60(1000) \) GeV, and the uncertainty \( \pm 4 \) to \( \delta m_t = \pm 11 \) GeV. This discrepancy may, if not caused by a systematic error, indicate the existence of new physics \( ^{14} \).

Let us note that the figures presented in the Table correspond to the

\(^{1} \)One can obtain the FORTRAN code of LEPTOP from rozanov@cernvm.cern.ch
fitted values of $m_t$ and $\bar{\alpha}_s$ derived from the new LEP and CDF data:

\begin{align*}
m_t &= 171(11)^{+15}_{-21}(5), \\
\bar{\alpha}_s &\equiv \alpha_s(m_Z) = 0.125 \pm 0.005 \pm 0.002, \\
\chi^2 &= 14/10.
\end{align*}

Here the central values correspond again to $m_H = 300$ GeV, with the first uncertainties being experimental, the second corresponding to $m_H = 300^{+700}_{-240}$ GeV, and the third (for $m_t$) corresponding to the uncertainty in $1/\bar{\alpha} = 128.87 \pm 0.12$.

Comparing this with the fit [9] of the earlier data:

\begin{align*}
m_t &= 162^{+14+16}_{-15-22}, \\
\bar{\alpha}_s &= 0.119 \pm 0.006^{+0.002}_{-0.003}, \\
\chi^2 &= 3.5/10,
\end{align*}

we observe that central values of $m_t$ and $\bar{\alpha}_s$ have increased, their uncertainties decreased, while the $\chi^2$ became more palatable. The individual contributions to the average value of $m_t$ show more variations than previously (see Fig. 1).

Our new fitted values for $m_t$ and $\bar{\alpha}_s$ are in good agreement with these of the LEP Electroweak Working Group as obtained in the traditional approach and presented at the Moriond Conference [12].

The numbers of the fit (15)–(17) and of Table 1 include a recently estimated QCD correction [22], which increases $m_t$ by about 4 GeV.

With reference to Table 1, we would like to stress two points:

(1) The shifts caused by changing $m_H$ are, as a rule, small compared to the uncertainties (in brackets) in column 5. This “$m_H$ independence” is characteristic for the global fit which predicts $m_t$ for a given $m_H$.

(2) The situation is different when $m_t$ is fixed (e.g., measured). For $m_t = 170$ GeV, the shifts of $g/V/g_A$ from its central value 0.0711 are $-0.0024$ and $+0.0035$ for $m_H = 1000$ GeV and 60 GeV, respectively (see Table 2 of Ref. [6]), which is larger than the current experimental uncertainty in $g/V/g_A(\pm 0.0020)$. Thus a further improvement of the accuracy in $g/V/g_A$ could place serious bounds on $m_H$. Two other “gluon-free” observables, $m_W/m_Z$ and $g_A$, are less sensitive: their higgs shifts are half as large as their present experimental uncertainties.
To conclude: Within the framework of the traditional approach, which starts with $\alpha(0)$, the latest precision data do not herald anything qualitatively new; one merely gets a slightly heavier top mass, and a slightly larger strong coupling constant. In strong contrast, these same data open, with our approach – which starts with $\alpha(m_Z)$ – a new window, one through which the non-vanishing electroweak radiative corrections become visible.

ACKNOWLEDGEMENTS

We are grateful to D.Yu.Bardin, A.Sirlin, V.L.Telegdi and M.B.Voloshin for helpful remarks. VN, LO, and MV are grateful to the Russian Foundation for Fundamental Research for grant 93-02-14431. LO, MV and AR are grateful to CERN TH and PPE Divisions, respectively, for their warm hospitality.
Table 1

Results of fitting the Moriond 1994 data from LEP and $p\bar{p}$ colliders. Observables (first column), their '94 and '93 experimental values (second and third columns) and their predicted values: (a) in the electroweak tree (Born) approximation based on $\bar{\alpha}$ (fourth column) and (b) in the electroweak tree plus one loop approximation (fifth column). Both in columns 4 and 5 the QED and QCD loops were taken into account.

The predicted values have been obtained for three fixed values of $m_H = 300^{+700}_{-240}$ GeV; for each of them the fitted values of $m_t \pm \delta m_t$ and $\alpha_s \pm \delta \alpha_s$ were used. The central values correspond to $m_H = 300$ GeV. The upper (lower) numbers give the shifts of these central values corresponding to $m_H = 1000$ (60) GeV.

The numbers in brackets correspond to experimental uncertainties (columns 2 and 3), and predicted uncertainties (columns 4 and 5), arising in column 4 from $\delta \bar{\alpha}$ for $m_W/m_Z$, $g_V/g_A$ and $\Gamma_l$ and from $\delta \alpha_s$ for the five other observables. The errors in brackets in column 5 come from $\delta \bar{\alpha}$ (for $g_V/g_A$ only). Note that the $\bar{\alpha}$-Born values of hadronic observables depend on $m_H$. This is caused by their dependence on $\alpha_s$, the fitted values of which depend on $m_H$.

| Observable | Exp. '94 | Exp. '93 | $\bar{\alpha}$-Born | MSM prediction |
|------------|----------|----------|----------------------|---------------|
| $m_W/m_Z$  | 0.8814(21) | 0.8798(28) | 0.8768(2) | 0.8803(8)_{+0}^{+2} |
| $g_V/g_A$  | 0.0711(20) | 0.0716(28) | 0.0753(12) | 0.0711(19)_{+7}^{+9} |
| $\Gamma_l$ (MeV) | 83.98(18) | 83.82(27) | 83.57(2) | 83.87(11)_{+6}^{+2} |
| $\Gamma_b$ (GeV) | 1.7460(40) | 1.7403(59) | 1.7445(26)_{+11}^{+9} | 1.7435(27)_{+5}^{+3} |
| $\Gamma_Z$ (GeV) | 2.4971(38) | 2.4890(70) | 2.4930(26)_{+10}^{+9} | 2.4962(32)_{+12}^{+3} |
| $\sigma_{had}$ (nb) | 41.51(12) | 41.56(14) | 41.41(3)_{+9}^{+9} | 41.43(3)_{+6}^{+2} |
| $R_l$ | 20.790(40) | 20.763(49) | 20.874(31)_{+13}^{+11} | 20.788(32)_{+10}^{+3} |
| $R_b$ | 0.2210(19) | 0.2200(27) | 0.2197(0)_{+6}^{+0} | 0.2161(4)_{+6}^{+0} |
References

[1] G. Altarelli, R. Kleiss, and C. Verzegnassi, eds., Physics at LEP1, report
CERN 89-08 (CERN, Geneva, 1989) Vol. 1.

[2] D. Bardin et al., ZFITTER, CERN Preprint TH.6443/92 (1992).

[3] The LEP Collaborations ALEPH, DELPHI, L3, OPAL and the LEP
Electroweak Working Group, CERN-PPE/93-157 (1993).

[4] J. Ellis and G. Fogli, Phys. Lett. B213 (1988) 189, 526; B232 (1989)
139; B249 (1990) 543;
J. Ellis, G. Fogli and E. Lisi, Phys. Lett. B274 (1992) 456; B292 (1992)
427;
R.D. Peccei, Mod. Phys. Lett. A5 (1990) 1001;
G. Passarino, Phys. Lett. B255 (1991) 127;
F.Del Aguila, M.Martinez and M.Quiros, Nucl. Phys. B381 (1992) 451;
D. Shaile, Z. Phys. C54 (1992) 387.

[5] V.A. Novikov, L.B. Okun and M.I. Vysotsky, CERN Preprint TH
6053/91 (1991), unpublished;
M.I. Vysotsky, V.A. Novikov and L.B. Okun, JETP 76 (1993) 725; Zh. 
Exp. Teor. Fiz. 103 (1993) 1489 (in Russian).

[6] V.A. Novikov, L.B. Okun, and M.I. Vysotsky, Nucl. Phys. B397 (1993)
35.

[7] N.A. Nekrasov, V.A. Novikov, L.B. Okun, and M.I. Vysotsky, to be
published in Yad. Fiz. 57 (1994) No. 5, CERN Preprint TH 6696/92
(1992).

[8] V.A. Novikov, L.B. Okun and M.I. Vysotsky, Mod. Phys. Lett. A8
(1993) 2529, Err 8 (1993) 3301; Phys. Lett. B320 (1994) 388.

[9] V.A. Novikov, L.B. Okun, A.N. Rozanov, M.I. Vysotsky and V.P. Yurov,
CERN Preprint TH.7137/94 (1994).

[10] V.A. Novikov, L.B. Okun and M.I. Vysotsky, Phys.Lett. B298
(1993) 453; CERN preprint TH.7153/94 (1994), to be published in
Mod.Phys.Lett.A.

[11] Review of Particle Properties, Phys. Rev. D45 (1992) No. 11, part II.

[12] P. Clarke, Y.K. Kim, B. Pietrzyk, P. Siegrist and M. Woods, Talks
at 1994 Moriond Conference on “Electroweak Interactions and Unified 
Theories”.
[13] H. Burkhardt, F. Jegerlehner, G. Penzo and C. Verzegnassi, *Z.Phys.* **C43** (1989) 497;
J. Jegerlehner, in Proceedings of the 1990 Theoretical Advanced Study Institute in Elementary Particle Physics, eds. P.Langacker and M. Cvetič (World Scientific, Singapore, 1991), p.476.

[14] V.A. Novikov, L.B. Okun and M.I. Vysotsky, CERN Preprint TH.7071/93 (1993).

[15] B.W. Lynn and M.E. Peskin, report SLAC-PUB-3724 (1985), unpublished;
B.W. Lynn, M.E. Peskin and R.G. Stuart, in: Physics at LEP, report CERN 86-02 (CERN Geneva, 1986), Vol. 1, p. 90;
M. Peskin, SLAC-PUB-5210 (1990). Lectures at 17th SLAC Summer Institute, Stanford, July 1989.

[16] S.G. Gorishny, A.L. Kataev and S.A. Larin, *Phys. Lett.* **B259** (1991) 144;
L.R. Surguladze and M.A. Samuel, *Phys. Rev. Lett.* **66** (1991) 560.

[17] M. Pepe-Altararelli, Talk at the 1993 La Thuile Conference, preprint LNF-93/019 (F).

[18] C. de Clercq, Proceedings of the 28th Rencontre de Moriond on “93 
Electroweak Interactions and Unified Theories”, edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, 1993).

[19] G. Altarelli, Talk at the 1993 Marseilles EPS-HEP Conference (1993).

[20] V.A. Novikov, L.B. Okun, M.I. Vysotsky and V.P. Yurov, *Phys. Lett.* **B308** (1993) 123;
V.A. Novikov, L.B. Okun and M.I. Vysotsky, *Phys. Lett.* **B299** (1993) 329, Err. **B304** (1993) 386.

[21] A. Sirlin, New York University preprint NYU-TH-93/11/01.

[22] B.H. Smith and M.B. Voloshin, TPI-MINN-94/5-T (1994), UMN-TH-1241/94 (1994).
Figure Captions

Fig. 1: The fitted values of $m_t$ from the specified observables measured at LEP and $p\bar{p}$ colliders, assuming $m_H = 300$ GeV and $\bar{\alpha}_s = 0.125$. The region $m_t < m_Z$, is definitely excluded by the direct searches. The central values of $m_t$ from $R_b$, $A_{\tau}$ and $R_l$ lie in this excluded region.

Fig. 2: Allowed region of $m_t$ and $m_H$ with $\bar{\alpha}_s = 0.125$. The lines represent the $s$-standard "ellipses" ($s=1,2,3,4,5$) corresponding to the constant values of $\chi^2$ ($\chi^2 = \chi^2_{min} + s^2$).
Figure 1:
