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Electroweak Physics at LEP[1]

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ABSTRACT

We have examined the evidence for the electroweak radiative corrections in the LEP precision data sets of 1993 and 1994 along with the intriguing possibility that the QED corrections only may be sufficient to fit the data within the framework of the minimal standard model. We find that the situation is very sensitive to the precise value of M_W. The current world average value of M_W and the improved 1994 LEP data strongly favor nonvanishing electroweak radiative corrections, and are consistent with a heavy m_t as reported by CDF but with a heavy Higgs scalar of about 400 GeV. We discuss how future precision measurements of M_W and m_t can provide a decisive test for the standard model with radiative corrections.

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Recently much interests have been paid to the electroweak radiative corrections (EWRC) and precision tests of the standard model (SM) thanks to the accurate data obtained at LEP [1,2]. Numerous articles have appeared on the subject as has been documented in [1 - 3]. The LEP data are generally regarded as the success of the SM and as the evidence for the nonvanishing EWRC [4].

There have been new experimental developments since last year that warrant a renewed examination of the precision tests of the SM, namely, the new measurements of M_W [5], the improved LEP precision data [2], and the evidence of m_t from CDF [6]. We would like to report on the results of the new precision tests of the SM based on these new experimental informations and implication on the Higgs mass range. At the same time we reexamine the intriguing claim made by Novikov, Okun, and Vysotsky [7] based on the 1993 experimental data from LEP that the electroweak parameters as defined in the SM could be explained by the QED Born approximation (QBA) in which $\alpha(M_Z^2)$ is used instead of $\alpha(0)$ and the corresponding redefinition of the weak mixing angle $\sin^2\theta$ instead of $\sin^2\theta_W$ in the tree-level SM within 1 σ level.

The full one-loop EWRC are calculated with the aid of the ZFITTER program [8] modified by the improved QCD correction factor and the χ^2 minimization to the fit. In order to achieve QBA, we neglect the terms of non-photonic and pure weak interaction origin systematically in the program.

Since the basic lagrangian contains the bare electric charge e_0, the renormalized physical charge e is fixed by a counter term δe; $e_0 = e + \delta e$. The counter term δe is determined by the condition of the on-shell charge renormalization in the $\overline{MS}$ or on-shell scheme. It is well known that the charge renormalization in the conventional QED fixes the counter term by the renormalized vacuum polarization $\hat{\Pi}^\gamma(0)$ and one can evaluate $\hat{\Pi}^\gamma(q^2) = \hat{\Sigma}^{\gamma\gamma}(q^2)/q^2$ from the photon self energy $\hat{\Sigma}^{\gamma\gamma}(q^2)$, for example, by the dimensional regularization method. This gives at $q^2 = M_Z^2$,

$$\hat{\Pi}^\gamma(M_Z^2) = \sum_f Q_f^2 \frac{\alpha}{3\pi}\left(\frac{5}{3} - \ln\frac{M_Z^2}{m_f^2} + i\pi\right), \tag{1}$$

where Q_f is the charge of the fermion f in the unit of e and α is the hyperfine structure constant $\alpha = \frac{e^2}{4\pi} = 1/137.0359895(61)$.

This gives the total fermionic contribution of $m_f \leq M_Z$ to the real part, $Re\hat{\Pi}^\gamma(M_Z^2) = -0.0602(9)$, so that the "running" charge defined as $e^2(q^2) = \frac{e^2}{1+Re\hat{\Pi}^\gamma(q^2)}$ gives $\alpha(M_Z^2) = 1/128.786$ in the on-shell scheme. The concept of the running charge is, however, scheme dependent [9]: the $\overline{MS}$ fine structure constant at the Z mass scale is given by

$$\hat{\alpha}(M_Z) = \alpha/[1 - \Pi^\gamma(0)|_{\overline{MS}} + 2\tan\theta_W(\Sigma^{\gamma Z}(0)/M_Z^2)_{\overline{MS}}]. \tag{2}$$

so that one can show $\hat{\alpha}(M_Z) = (127.9 \pm 0.1)^{-1}$, which differs by some 0.8 % from the on-shell $\alpha(M_Z^2)$.

The electroweak parameters are evaluated numerically with the hyperfine structure constant α, the four-fermion coupling constant of μ-decay, $G_\mu = 1.16639(2) \times 10^{-5}$ GeV^{-2}, and Z-mass, i.e., $M_Z = 91.187(7)$ GeV for the 1993 data fit and 91.1899(44) GeV for the 1994 data fit. Numerical estimate of the full EWRC requires the mass values of the leptons, quarks, Higgs scalar and W-boson besides these quantities. While Z-mass is known to an incredible accuracy from the LEP experiments largely due to the resonant depolarization method, the situation with respect to the W-mass is desired to be improved, i.e., $M_W = 80.22(26)$ GeV [10] and 80.21(16) GeV [5] vs. the CDF measurement $M_W = 79.91(39)$ GeV [11] and 80.38(23) GeV [5].

One has, in the standard model, the on-shell relation $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$, and the four-fermion coupling constant G_μ

$$G_\mu = \frac{\pi\alpha}{\sqrt{2} M_W^2} \left(1 - \frac{M_W^2}{M_Z^2}\right)^{-1} (1 - \Delta r)^{-1} \tag{3}$$

so that Δr, representing the radiative corrections, is given by

$$\Delta r = 1 - \left(\frac{37.28}{M_W}\right)^2 \frac{1}{1 - M_W^2/M_Z^2}. \tag{4}$$

Notice that the radiative correction Δr is very sensitive to the value of M_W: Mere change in M_W by 0.59% results as much as a 75% change in Δr. Also precise determination of the on-shell value of $\sin^2\theta_W$ can constrain the needed radiative correction and the value of M_W, thus providing another crucial test for the evidence of the EWRC in the standard model.

We have made χ^2-fits to both 1993 and 1994 data sets of the Z-decay parameters measured at LEP and M_W as shown in Tables 1 - 4. In each set, the fit is carried out for both the CDF and world average values of M_W. Details of the analysis can be found elsewhere [12].

The Z-decay parameters are calculated with a modified ZFITTER program, in which the best χ^2 fit search is made with the gluonic coupling constant $\bar{\alpha}_s(M_Z^2) = 0.123 \pm 0.006$ in the improved QCD correction factor [13] $R_{\rm QCD} = 1 + 1.05\frac{\bar{\alpha}_s}{\pi} + 0.9(\pm 0.1)\left(\frac{\bar{\alpha}_s}{\pi}\right)^2 - 13.0\left(\frac{\bar{\alpha}_s}{\pi}\right)^3$ for all quarks. The partial width for $Z \to f\bar{f}$ is given by

$$\Gamma_f = \frac{G_\mu}{\sqrt{2}} \frac{M_Z^3}{24\pi} \beta R_{\rm QED} c_f R_{\rm QCD}(M_Z^2) \left\{ [(\bar{v}_f^Z)^2 + (\bar{a}_f^Z)^2] \times \left(1 + 2\frac{m_f^2}{M_Z^2}\right) - 6(\bar{a}_f^Z)^2 \frac{m_f^2}{M_Z^2} \right\} \tag{5}$$

where $\beta = \beta(s) = \sqrt{1 - 4m_f^2/s}$ at $s = M_Z^2$, $R_{\rm QED} = 1 + \frac{3}{4}\frac{\alpha}{\pi} Q_f^2$ and the color factor $c_f = 3$ for quarks and 1 for leptons. Here the renormalized vector and axial-vector couplings are

	Experiment	QBA	Full EW	Full EW	Full EW
m_t (GeV)	150		120	138	158
m_H (GeV)	$60 \leq m_H \leq 1000$		60	300	1000
M_W (GeV)	79.91 ± 0.39	79.95	80.10	80.10	80.13
Γ_Z (MeV)	2488.0 ± 7.0	2488.4	2489.0	2488.9	2488.8
$\Gamma_{b\bar{b}}$ (MeV)	383.0 ± 6.0	379.4	377.4	376.5	375.4
$\Gamma_{l\bar{l}}$ (MeV)	83.52 ± 0.28	83.47	83.53	83.53	83.63
Γ_{had} (MeV)	1739.9 ± 6.3	1740.3	1738.8	1738.2	1737.7
$R(\Gamma_{b\bar{b}}/\Gamma_{had})$	0.220 ± 0.003	0.218	0.217	0.217	0.216
$R(\Gamma_{had}/\Gamma_{l\bar{l}})$	20.83 ± 0.06	20.85	20.82	20.81	20.78
$\sigma_h^P(nb)$	41.45 ± 0.17	41.41	41.37	41.38	41.40
g_V	-0.0372 ± 0.0024	-0.0372	-0.0341	-0.0334	-0.0334
g_A	-0.4999 ± 0.0009	-0.5000	-0.5003	-0.5005	-0.5006
χ^2		0.9621	4.2664	6.0802	7.7723
$\sin^2\theta_W$	0.2321	0.2314	0.2284	0.2283	0.2278
Δr	0.0623	0.06022	0.05162	0.05131	0.04967

Table 1: Numerical results including full EWRC for nine experimental parameters of the Z-decay and M_W. The results of QBA are shown also for comparison. Each pair of m_t and m_H represents the case of the best χ^2 -fit to the 1993 LEP data and $M_W = 79.91(39)$ GeV.

defined by $\bar{a}_f^Z = \sqrt{\rho_f^Z} 2a_f^Z = \sqrt{\rho_f^Z} 2I_3^f$ and $\bar{v}_f^Z = \bar{a}_f^Z[1 - 4|Q_f|\sin^2\theta_W\kappa_f^Z]$ in terms of the familiar notations [8,9,14]. Note that $\Delta\alpha$ is contained in the couplings through G_μ and all other non-photonic and pure weak loop corrections are grouped in ρ_f^Z and κ_f^Z. Thus the case of the QBA can be achieved simply by setting ρ_f^Z and κ_f^Z to 1 in the vector and axial-vector couplings.

Numerical results for the best χ^2 fit to the 1993 LEP experimental parameters of Z-decay are shown in Tables 1 and 2 for $M_W = 79.91(39)$ GeV and $M_W = 80.22(26)$ GeV respectively as experimental inputs. The results for the best χ^2-fit to the improved 1994 LEP data and M_W are given in Tables 3 and 4 for $M_W = 80.38(23)$ GeV and $M_W = 80.21(16)$ GeV respectively. Also included in the Tables are the results of QBA as well as the output $\sin^2\theta_W$ and Δr for comparison. We see that the contributions of the weak corrections are generally small and in particular for the 1993 data the QBA is close to the experimental values within the uncertainty of the measurements.

The near absence of the pure weak loop contributions to the radiative corrections for the 1993 data is more impressive for $M_W = 79.91$ GeV than for $M_W = 80.22$ GeV. At closer examination, however, the QBA in the latter case over-estimates the radiative corrections and the full one-loop EWRC fair better.

	Experiment	QBA	Full EW	Full EW	Full EW
m_t (GeV)	150		126	142	160
m_H (GeV)	$60 \leq m_H \leq 1000$		60	300	1000
M_W (GeV)	80.22 ± 0.26	79.95	80.13	80.13	80.15
Γ_Z (MeV)	2488.0 ± 7.0	2488.4	2490.2	2489.7	2489.3
$\Gamma_{b\bar{b}}$ (MeV)	383.0 ± 6.0	379.4	377.3	376.4	375.3
$\Gamma_{l\bar{l}}$ (MeV)	83.52 ± 0.28	83.47	83.53	83.63	83.63
Γ_{had} (MeV)	1739.9 ± 6.3	1740.3	1739.6	1738.8	1738.1
$R(\Gamma_{b\bar{b}}/\Gamma_{had})$	0.220 ± 0.003	0.218	0.217	0.216	0.216
$R(\Gamma_{had}/\Gamma_{l\bar{l}})$	20.83 ± 0.06	20.85	20.83	20.79	20.78
$\sigma_h^P(nb)$	41.45 ± 0.17	41.41	41.38	41.39	41.40
g_V	-0.0372 ± 0.0024	-0.0372	-0.0344	-0.0337	-0.0335
g_A	-0.4999 ± 0.0009	-0.5000	-0.5004	-0.5006	-0.5007
χ^2		2.0545	4.1346	5.9538	7.5517
$\sin^2\theta_W$	0.2261	0.2314	0.2278	0.2279	0.2275
Δr	0.0448	0.06022	0.04975	0.04991	0.04895

Table 2: The same as Table 1 but for the experimental $M_W = 80.22 \pm 0.26$ GeV.

	Experiment	QBA	Full EW	Full EW	Full EW
m_t (GeV)	$174 \pm 10^{+13}_{-12}$		187	172	155
m_H (GeV)	$60 \leq m_H \leq 1000$		1000	300	60
M_W (GeV)	80.38 ± 0.23	79.95	80.33	80.32	80.30
Γ_Z (MeV)	2497.1 ± 3.8	2488.7	2496.8	2497.3	2496.7
$\Gamma_{l\bar{l}}$ (MeV)	83.98 ± 0.18	83.49	83.90	83.87	83.80
Γ_{had} (MeV)	1746.0 ± 4.0	1740.5	1743.4	1744.1	1744.2
$R(\Gamma_{b\bar{b}}/\Gamma_{had})$	0.2210 ± 0.0019	0.2180	0.2149	0.2155	0.2160
$R(\Gamma_{had}/\Gamma_{l\bar{l}})$	20.790 ± 0.04	20.847	20.778	20.794	20.813
$\sigma_h^P(nb)$	41.51 ± 0.12	41.41	41.41	41.40	41.39
g_V/g_A	0.0711 ± 0.002	0.0745	0.0711	0.0714	0.0723
χ^2		25.8	11.6	9.99	9.86
$\sin^2\theta_W$	0.2231	0.2314	0.2240	0.2242	0.2245
Δr	0.0355	0.06022	0.03841	0.03913	0.03998

Table 3: Numerical results including full EWRC for seven experimental parameters of the Z-decay and M_W. The case of QBA is shown also for comparison. Each pair of m_t and m_H represents the case of the best χ^2- fit to the 1994 LEP data and $M_W = 80.38(23)$ GeV.

	Experiment	QBA	Full EW	Full EW	Full EW
m_t (GeV)	$174 \pm 10^{+13}_{-12}$		185	174	153
m_H (GeV)	$60 \leq m_H \leq 1000$		1000	400	60
M_W (GeV)	80.21 ± 0.16	79.95	80.32	80.31	80.29
Γ_Z (MeV)	2497.1 ± 3.8	2488.7	2496.3	2496.8	2496.2
$\Gamma_{l\bar{l}}$ (MeV)	83.98 ± 0.18	83.49	83.88	83.87	83.79
Γ_{had} (MeV)	1746.0 ± 4.0	1740.5	1743.0	1743.6	1743.9
$R(\Gamma_{b\bar{b}}/\Gamma_{had})$	0.2210 ± 0.0019	0.2180	0.2150	0.2154	0.2161
$R(\Gamma_{had}/\Gamma_{l\bar{l}})$	20.790 ± 0.04	20.847	20.779	20.791	20.813
$\sigma_h^P(nb)$	41.51 ± 0.12	41.41	41.41	41.40	41.38
g_V/g_A	0.0711 ± 0.002	0.0745	0.0707	0.0711	0.0720
χ^2		25.8	12.1	10.6	10.1
$\sin^2\theta_W$	0.2263	0.2314	0.2243	0.2244	0.2247
Δr	0.0455	0.06022	0.03925	0.03957	0.04070

Table 4: The same as Table 3 but for the experimental $M_W = 80.21 \pm 0.16$ GeV.

From the global fit to the data with two variables m_t and m_H in the range $60 - 1000$ GeV, we find the best fits to the 1993 data is obtained by $m_t = 142^{-16}_{+18}$ GeV, the central value being the best χ^2 case of $m_H = 300$ GeV in Table 2. The best global fits to the 1993 data give a rather stable output $M_W = 80.13 \pm 0.03$ GeV if the full EWRC are taken into account, which is to be contrasted to the output $M_W = 79.95$ GeV from the QBA, for either experimental M_W value. Also $\sin^2\theta_W = 0.2279 \pm 0.0005$ in the case of the full EWRC is to be compared to $\sin^2\theta_W = 0.2314$ in the case of QBA. While the 1993 world average value of M_W supports strongly for the evidence of the full EWRC in the LEP data, the QBA appears to be in statistically comparable agreement, i.e., within 2σ, with the precisions of the 1993 data. If M_W were to be definitely at around 79.95 GeV with the uncertainty of the 1993 LEP data, then the QED correction would have been all that was observed at LEP and one would have been cultivating the null result of the weak correction to produce the range of t-quark mass as pointed out in [7].

The situation with the χ^2-fit to the improved 1994 LEP data and M_W is significantly different from the case of the 1993 data as one can see from Tables 3 and 4. Not only there is clear evidence for the full EWRC in each of the seven LEP data but also the QBA gives distinctively inferior χ^2 in either case of new M_W. From the best fits to the 1994 data, one gets again a stable output $M_W = 80.31 \pm 0.02$ GeV for m_H in the range of 60 - 1000 GeV. In particular, the CDF m_t value 174 GeV is a possible output solution (in the case $M_W = 80.21(16)$ GeV) but with a m_H about 400 GeV among the many possible combinations of (m_t, m_H) given by the 'Best.fit' curve in Fig. 1. In general the

χ^2-value tends to prefer lower m_t and accordingly smaller m_H combination of the curve but any pair of (m_t, m_H) on this curve is statistically comparable to each other. We see from Fig. 1 that the best global fits to the 1994 data are obtained by $m_t = 153 - 185$ GeV for $m_H = 60 - 1000$ GeV.

Fig.2 shows how M_W changes with m_t for fixed m_H from full EWRC where the new world average M_W and CDF m_t are also shown. The central values of the world average M_W and CDF m_t are consistent with a Higgs scalar mass somewhat heavier than 1000 GeV, though $m_H = 200$ GeV is only less than 1.5 σ away. Clearly a better precision measurement of M_W is desired to distinguish different m_H. For example, a change of m_H by 200 GeV, i.e., from 400 GeV to 200 GeV, requires from the best χ^2-fits a change of 9 GeV in m_t, i.e., from 174 GeV to 165 GeV, as one can see from Fig. 1. This in turn requires a precision of 20 MeV or better in M_W from Fig. 2.

In short, we find that the QBA is in agreement with the 1993 data within 2σ level of accuracy but the new world average value of M_W and the improved 1994 LEP data disfavor the QBA and definitely support for the evidence of the nonvanishing weak-loop correction. Furthermore, the CDF m_t is a solution of the minimal χ^2-fit to the 1994 data but then the Higgs scalar mass is *about* 400 GeV. Further precision measurement of M_W can provide a real test of the standard model as it will give a tight constraint for the needed amount of the EWRC and provide a profound implication to the mass of t-quark and Higgs scalar in the context of the standard model. If M_W is determined within 20 MeV uncertainty, Δr within the context of the standard model can distinguish the mass range of the t-quark and Higgs scalar and provide a crucial test for and even the need of new physics beyond the standard model.

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Figure Captions

: The mass ranges of m_t and m_H from the minimal χ^2-fit to the 1994 LEP data and M_W = 80.21 GeV.

: M_W versus m_t for fixed values of m_H from the full radiative correction in the standard model. The case of the minimal χ^2-fit to the 1994 LEP data corresponding to the full EWRC in Table 4 are indicated by .