DO PRESENT LEP DATA PROVIDE EVIDENCE FOR ELECTROWEAK CORRECTIONS?

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ABSTRACT

The Born approximation, based on $\bar{\alpha} \equiv \alpha(m_Z)$ instead of $\alpha$, reproduces all electroweak precision measurements within their (1σ) accuracy. The low upper limits for the genuinely electroweak corrections constitute one of the major achievements of LEP. The astonishing smallness of these corrections results from the cancellation of a large positive contribution from the heavy top quark and large negative contributions from all other virtual particles. It is precisely the non-observation of electroweak radiative corrections that places stringent upper and lower limits on the top mass.

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The precision measurements of $Z$ decays at LEP are usually considered as providing evidence for non-vanishing electroweak radiative corrections (see e.g. [1], where a representative list of references is given). The aim of this letter is to stress that present LEP data [2]-[5] are in perfect agreement [6]-[8] with the Born approximation and that no genuine electroweak corrections (involving loops with heavy virtual bosons, neutrinos and top quarks) have as yet been observed. The disagreement with statements to the contrary stems from the different definitions of the Born approximation being used. Usually it is defined in terms of electric charge at zero momentum transfer, i.e.

$$\alpha \equiv \alpha(0) = e^2/4\pi = 1/137.0359895(61) ,$$  \hspace{1cm} (1)

while we argue that the true Born approximation should be defined in terms of

$$\bar{\alpha} = \alpha(m_Z) = 1/128.87(12) , \hspace{1cm} [9],[10].$$  \hspace{1cm} (2)

By using $\bar{\alpha}$ instead of $\alpha$ one automatically takes into account the only purely electromagnetic correction (polarization of vacuum by the photon), which has not already been allowed for by the experimentalists.

While $\alpha(q^2)$ is running, the other two gauge couplings

$$\alpha_W = g^2/4\pi , \hspace{0.2cm} \alpha_Z = f^2/4\pi$$  \hspace{1cm} (3)

are “frozen” for $|q^2| \leq m_{Z,W}^2$ and start to run only for $|q^2| \gg m_{Z,W}^2$. Therefore it is natural to consider the electroweak Born approximation at the Fermi scale, i.e. at $q^2 \approx m_Z^2$. In a sense, $\alpha$, with all its accuracy, is irrelevant to electroweak physics; what is relevant is $\bar{\alpha}$. Hence, if Glashow, Weinberg and Salam [11]-[13] had thought about actually calculating electroweak radiative corrections they would have used $\bar{\alpha}$ from the beginning. Then they would have defined the weak angle $\theta$ through the equations

$$\alpha_W = \alpha_Z c^2 , \hspace{0.2cm} \bar{\alpha} = \alpha_W s^2 ,$$  \hspace{1cm} (4)

where $c \equiv \cos \theta$, $s \equiv \sin \theta$. (We do not use $\theta_W$, $s_W$, $c_W$ here, because in the literature they are associated with $\alpha$, not $\bar{\alpha}$.) Hence

$$c^2 s^2 = \bar{\alpha}/\alpha_Z .$$  \hspace{1cm} (5)

According to the Minimal Standard Model [11]-[13]:

$$m_W = g\eta/2 , \hspace{0.2cm} m_Z = f\eta/2$$  \hspace{1cm} (6)

where $\eta$ is the vacuum expectation value of the Higgs field, so that in the Born approximation:

$$m_W/m_Z = c .$$  \hspace{1cm} (7)

To obtain $\eta$ we consider, as usual, the four-fermion coupling of $\mu$-decay (see, for instance, [14])

$$G_\mu/\sqrt{2} = g^2/8m_W^2 .$$  \hspace{1cm} (8)

Then it follows from (6):

$$\eta^2 = 1/\sqrt{2}G_\mu .$$  \hspace{1cm} (9)
The value
\[ G_\mu = 1.16639(2) \times 10^{-5} \text{ GeV}^{-2} \] (10)
gives:
\[ \eta = 246.2185(21) \text{ GeV} \] (11)

In the pre-LEP era, both \( m_Z \) and \( m_W \) were poorly known. This justifies the definition \[ s_W \equiv m_W/m_Z \text{ from the historical point of view. At present, however, } m_Z \text{ is} \]

known with much higher accuracy than \( m_W \) \[ m_Z = 91.187(7) \text{ GeV} \] (12)
\[ m_W = 80.22(26) \text{ GeV} \] (13)

It is reasonable therefore to express \( s \) and \( c \) in terms of \( m_Z \):
\[
f^2 = 4m_Z^2/\eta^2 = 4\sqrt{2}G_\mu m_Z^2 = 0.548636(84)
\] (14)
\[ \alpha_Z = \frac{\sqrt{2}}{\pi} \cdot G_\mu m_Z^2 = 1/22.9047(35) = 0.0436592(66)
\] (15)
\[ \frac{1}{4} \sin^2 2\theta = c^2 s^2 = \frac{\pi\tilde{\alpha}}{\sqrt{2}G_\mu m_Z^2} = 0.177735(16)
\] (16)
\[
s = 0.48081(33) , \quad c = 0.87682(19)
\] (17)
\[
s^2 = 0.23118(33) , \quad c^2 = 0.76881(33)
\] (18)

Now we are ready to derive the electroweak Born predictions for various observables. We first compare Eq. (7) with the experimental ratio

\[ m_W/m_Z = 0.8797(29) \] (19)

The agreement is within 1\( \sigma \). Next we consider decays of the Z-boson. The amplitude of the decay into pairs of charged leptons, \( e^+e^- , \mu^+\mu^- , \tau^+\tau^- \), has the form:
\[
M_l = \frac{1}{2}f\bar{f}[g_A\gamma_\alpha\gamma_5 + g_V\gamma_\alpha]lZ_\alpha ,
\] (20)

where \( l \) and \( Z_\alpha \) are the wave functions of lepton and Z-boson.

The corresponding width \( \Gamma_l \) is given by the expression:
\[
\Gamma_l = \left(1 + \frac{3\tilde{\alpha}}{4\pi}\right) \times 4(g_A^2 + g_V^2)\Gamma_0 ,
\] (21)

where
\[
\Gamma_0 = \frac{f^2m_Z}{196\pi} = \frac{\sqrt{2}G_\mu m_Z^3}{48\pi} = 82.941(19) \text{ MeV} .
\] (22)

The forward-backward asymmetry in the channel \( f\bar{f} \) is
\[
A_{FB} = \frac{3}{4}A_e A_f ,
\] (23)

where
\[
A_i = 2g_i^A g_i^V/(g_A^2 + g_V^2) , \quad (i = e, \mu \ldots)
\] (24)
and the longitudinal polarization of the \(\tau\)-leptons

\[ P_\tau = -A_\tau. \] (25)

As is well known, the Born aproximation gives, for charged leptons

\[ g_A = T_3 = -1/2 = -0.5000, \] (26)

\[ g_V/g_A = 1 - 4s^2 = 0.0753(12), \] (27)

which should be compared with corresponding experimental values [3]-[6]:

\[ g_A^{exp} = -0.4999(9) \] (28)

and

\[ (g_V/g_A)^{exp} = 0.0728(28), \] (29)

(the latter was obtained from the measurements of \(A_{FB}\) for leptons and hadrons, and from \(\tau\)-polarization). Again we see agreement to within \(1\sigma\).

The decays into hadrons may be considered as decays into quark + antiquark pairs. In this case, as before,

\[ g_A = T_3, \] (30)

but the fractional charges and the colour degrees of freedom of the quarks must be taken into account:

\[ g_V/g_A = 1 - 4|Q|s^2, \] (31)

\[ \Gamma_q = 12 \left( 1 + \frac{3}{4\pi} Q^2 \tilde{\alpha} \right) G \Gamma_0 \times (g_A^2 + g_V^2), \] (32)

where the factor \(G\) describes the final state exchange and emission of gluons [17]-[19]

\[ G = 1 + \tilde{\alpha}_s/\pi + 1.4(\tilde{\alpha}_s/\pi)^2 - 13(\tilde{\alpha}_s/\pi)^3 + ... \] (33)

Here \(\tilde{\alpha}_s \equiv \alpha_s(m_Z)\) is the gluonic coupling constant at the Fermi scale. For further estimates we will assume that

\[ \tilde{\alpha}_s = 0.12 \pm 0.01, \] (34)

which agrees with the global analysis of all pertinent data: \(\tilde{\alpha}_s = 0.118 \pm 0.007\) [20], [21]. Then

\[ G(\tilde{\alpha}_s = 0.12 \pm 0.01) = 1.0395(33) \] (35)

LEP data are compared with the Minimal Standard Model predictions in the Table.

Note that in the Table the “Born” values of hadronic observables are obtained by using the gluonic factor \(G\), given by Eq. (33) for all quark flavours. The specific gluonic corrections to \(\Gamma_b\) [21]-[27] caused by the non-vanishing \(m_b = m_b(m_Z) = 2.3\) GeV and the large \(m_t\) are included in the MSM corrections. Allowing for them in the \(G\)-factor of \(b\bar{b}\) decay would give \(G_B \approx G - 0.01\); the new central Born values (\(\Gamma_b = 1799\) MeV, \(\Gamma_Z = 2487\) MeV, \(\sigma = 41.46\) nb, \(R_\ell = 20.82\) and \(R_b = 0.218\)) would still preserve the \(1\sigma\) agreement with experimental data.
The agreement between “Born” and experiment is stunning, even if one allows for the fact that not all the observables in the Table are independent: $\Gamma_\ell$ can be expressed in terms of $g_A$ and $g_V/g_A$, $R_t = \Gamma_h/\Gamma_\ell$ and

$$
\sigma_h = 12\pi\Gamma_e\Gamma_h/m_Z^2 \Gamma_Z^2.
$$

The coincidence of the central experimental and Born values is amazing: their differences are in some cases smaller than the experimental uncertainties. This fact must be considered a rare statistical fluctuation.

What is much more interesting from the physics point of view is the smallness of the electroweak radiative corrections as compared with naïve estimates ($\sim \alpha_W/\pi \sim \bar{\alpha}$). This originates from the compensation of two large contributions: a positive one from the heavy top quark ($m_t \sim 150$ GeV), and a negative one from all other virtual particles (light quarks, higgs, $W$, $Z$-bosons).

Were the top quark much lighter, the agreement with the Born approximation would be destroyed. This is shown in detail in [7],[8]. It may seem paradoxical, but it is precisely the non-observation of electroweak radiative corrections that places stringent upper and lower limits on the top’s mass. (Note that in the usual approach based on $\alpha$, not $\bar{\alpha}$, the same limits appear as a result of precision measurements of non-vanishing radiative corrections, some of which are very large.)

The results of the “low-energy” electroweak experiments complement the above picture of “Born”–experiment agreement. From $\nu_\mu e$ scattering experiment [28]:

$$
g_A^{\nu\mu} = -0.5030(180), \quad g_V^{\nu\mu}/g_A^{\nu\mu} = 0.0500(380),
$$

which should be compared with $-0.5000$ and $0.0753(12)$, respectively [29]. The three experiments on deep inelastic neutrino scattering (CHARM, CDHS, CCFR) give for $m_W/m_Z = 0.8785(30)$ (see [14]), where the uncertainty seems to be less reliable than in the case of direct $m_W$ measurement (UA2, CDF). Still, it would be interesting to check whether the electroweak Born approximation (with due allowance for strong interactions) would describe deep inelastic scattering also to within 1$\sigma$. The most promising seems to be the experiment on atomic parity violation in $^{133}\text{Cs}$. The experimental value of the weak charge $Q_W^{(133}\text{Cs})=-71.04(1.81)$ is 1.5$\sigma$ away from its “Born” value: $-73.9$.

The reduction of the one-loop corrections by a factor 3 to 5 (through partial cancelation) is important in the light of the experimental uncertainties. Even if these were reduced by, say, a factor of 3, this would still not make the electroweak two-loop contribution essential. Hence one can safely limit oneself to the one-loop electroweak approximation.

The fact that one can confine oneself from the beginning to the one-loop approximation not only makes the calculations quite simple but also extremely transparent. It is convenient to organize them in five steps:

**Step 1.** Start with a Lagrangian, which contains only bare couplings ($e_0$, $f_0$, $g_0$) and bare masses ($m_{W0}, m_{Z0}$...). Substitute $m_t, m_b$ and $m_H$ for $m_{t0}, m_{b0}$, and $m_{H0}$, since two loops are neglected.

**Step 2.** Calculate one-loop Feynman diagrams for the three most accurately known observables – $G_\mu, m_Z, \bar{\alpha}$ – in terms of the bare quantities $e_0, f_0$ ... and $1/\varepsilon$, where $\varepsilon$ is
the parameter used in dimensional regularization: $2\varepsilon = D - 4$ and $D$ is the dimension in which Feynman integrals are calculated.

**Step 3.** Invert the equations resulting from Step 2 by expressing all bare quantities in terms of $G_\mu, m_Z, \bar{\alpha}, m_t, m_b, m_H$ and $1/\varepsilon$.

**Step 4.** Calculate Feynman integrals for $m_W/m_Z, g_A, g_V/g_A$ or any other electroweak observable in terms of bare quantities $e_0, g_0$, etc. and $1/\varepsilon$.

**Step 5.** Express $m_W, g_A, g_V/g_A$, etc. in terms of $G_\mu, m_Z, \bar{\alpha}, m_t, m_b, m_H$. At this step all terms proportional to $1/\varepsilon$ cancel each other and the resulting relations contain no infinities in the limit $\varepsilon \to 0$.

Each of the “gluon-free” observables, $m_W/m_Z, g_A, g_V/g_A$, is conveniently presented as the sum of the Born term and the one-loop term [7]:

$$m_W/m_Z = c + \bar{\alpha} \frac{3c}{32\pi s^2(c^2 - s^2)} V_m(t, h) = 0.8768 + 0.00163 V_m,$$  (38)

$$g_A = \frac{1}{2} - \bar{\alpha} \frac{3}{64\pi s^2 c^2} V_A(t, h) = -0.5000 - 0.00065 V_A,$$  (39)

$$g_V/g_A = 1 - 4s^2 + \bar{\alpha} \frac{3}{4\pi(c^2 - s^2)} V_R(t, h) = 0.0753(12) + 0.00345 V_R,$$  (40)

where

$$t = (m_t/m_Z)^2, \quad h = (m_H/m_Z)^2.$$  (41)

All three functions $V_i$ are normalized in such a way that they behave similarly for $t \gg 1$, i.e.:

$$V_i \simeq t \text{ for } t \gg 1.$$  

By comparing Eqs. (38), (39), (40) with the corresponding experimental values (see column 1 of the Table) one obtains the experimental values of the $V_i$'s:

$$V_i^{\text{exp}} = \bar{V}_i \pm \delta V_i.$$  (42)

They are:

$$V_m^{\text{exp}} = 1.78 \pm 1.78$$  (43)

$$V_A^{\text{exp}} = -0.15 \pm 1.38$$  (44)

$$V_R^{\text{exp}} = -0.73 \pm 0.81.$$  (45)

The fact that experiments are, to within 1$\sigma$, described by the Born approximation means that

$$|\bar{V}_i| \leq |\delta V_i|.$$  (46)

The one-loop approximation leads to an important property of the functions $V_i(t, h)$, namely, they may be presented in the form [7]:

$$V_i(t, h) = t + T_i(t) + H_i(h).$$  (47)
Thus $V_i(m_t)$ for different values of $m_H$ differ only by a shift; see Fig. 1, where $V_R(m_t)$ is presented.

Simple analytical expressions and numerical tables for functions $T_i(t)$ and $H_i(h)$ are given in Ref. [7], which allows a “do-it-yourself analysis” [30] of the data. It is important to emphasize that Eqs. (38)-(40) are exact in the one-loop approximation, unlike the so-called “improved Born approximation” (see, e.g., [31]), which starts with $\alpha$ and includes terms proportional to $\Delta \alpha = \bar{\alpha} \alpha$.

The functions $V_i(t, h)$ form a surface over the plane $m_t, m_H$. The intersection with a plane orthogonal to the axis $m_H$ gives a curve describing the $m_t$-dependence of $V_i$ at given $m_H$. Examples of such curves are given in Fig. 1. Similarly, the intersection with a plane orthogonal to the axis $m_t$ gives a curve describing the $m_H$-dependence of $V_i$ at given $m_t$. Horizontal planes at $V_i = \bar{V}_i \pm \delta V_i$ give isolines corresponding to a central value $\bar{V}$ and $1\sigma$ uncertainties (see Fig. 2). The crossing point of central-value isolines determines in principle the values of $m_t$ and $m_H$. Unfortunately the $\delta V_i$’s are so large that reliable limits may be obtained only for $m_t$.

As for $m_H$, the minimum $\chi^2$ lies at $m_H = 10$ GeV, which is much below the lower experimental LEP bound (62 GeV). This false minimum corresponds to the crossing point of central-value isolines in Fig. 2. It is evident that this contradiction is statistically not significant: by shifting the $V_A$ isolines to the right by slightly more than $1\sigma$ one can readily get the crossing point at an $m_H$ of several hundred GeV.

A similar analysis may be performed for the hadronic decays of $Z$-bosons. As basic observables one can choose $\Gamma_Z$, $R_l = \Gamma_h/\Gamma_l$ and $\sigma_H$, which depend on $\bar{\alpha}_s$, and also $R_b$, whose dependence is less pronounced. From these observables, stringent limits can be obtained not only on $m_t$, but also on $\bar{\alpha}_s$ [8]. Our results for $m_t$ and $\bar{\alpha}_s$ are in qualitative agreement with the results of $\chi^2$ fits published by other authors (see, for instance: [1], [4], [16], [32], [33]).

In the last three columns of the Table, we give the values of MSM radiative corrections, which illustrate the sensitivity of various observables to the values of $\bar{\alpha}, \bar{\alpha}_s$ and $m_t$. (These corrections also include the effects of virtual gluons in electroweak quark loops [34]).

When the data from LEP and the SLC have a better accuracy, and when the top quark is discovered and its mass is measured, the MSM corrections may become non-adequate. This would signal the existence of New Physics. A convenient parametrization of it has already been worked out [35].

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| Observable   | Exp. value | “Born”    | MSM corrections | ∆mt shifts |
|-------------|------------|-----------|----------------|------------|
| mW/mZ       | 0.8798(29) | 0.8768(2) | 33             | 7          |
| gA          | -0.4999(9) | -0.5000   | -8             | -2         |
| gV/gA       | 0.0728(28) | 0.0753(12)| -31            | -12        |
| Γℓ (MeV)    | 83.51(28)  | 83.57(2)  | 27             | 9          |
| Γh (MeV)    | 1740(6)    | 1742(5)   | -1             | 1.5        |
| ΓZ (MeV)    | 2487(7)    | 2490(5)   | 3.6            | 2.1        |
| σh (nb)     | 41.45(17)  | 41.44(5)  | -0.4           | 0.7        |
| Rℓ ≡ Γh/Γℓ  | 20.83(6)   | 20.84(6)  | -6             | 0.3        |
| Rb ≡ Γh/Γh  | 0.2201(32) | 0.2197(1) | -31            | 3          |

Table - Comparison of experimental values of various LEP observables with the electroweak “Born” approximation (column 3). The quotation marks indicate that for the hadronic decays the virtual gluons are taken into account by the universal factor $G$ [see Eq. (33) and the discussion following Eq. (35)].

The next three columns (4,5,6) give the values of the MSM one-loop electroweak corrections to the “Born” approximation (and also of specific gluonic corrections depending on $m_b$ and $m_t$) for $m_t = 150$ GeV and for three values of $m_H$: 100, 300 and 1000 GeV, respectively. The last two columns, 7 and 8, show the increments of the MSM corrections for $\Delta m_t = \pm 10$ GeV and $\pm 20$ GeV, respectively. As not all terms of the order $\bar{\alpha}\bar{\alpha}_s$ have been taken into account, the numbers in columns 4-8 should not be taken too literally.

The 1σ uncertainties in columns 2 and 3 are quoted in brackets, with the customary convention regarding digits. The figures in columns 4-8 are again given in the corresponding units.

The Born uncertainties for $mW/mZ$ and $gV/gA$ derive mainly from $\Delta\bar{\alpha}/\bar{\alpha} = \pm 9.3 \times 10^{-4}$. The uncertainty of $gA$ is “hidden” in $\Gamma_0$ [Eq. (22)]. The uncertainties of hadronic observables in column 3 correspond to $\Delta\bar{\alpha}_s = \pm 0.01$. A figure for uncertainty or shift is underlined when the coefficient in front of $\Delta\bar{\alpha}_s$ or $\Delta m_t$ is negative.
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Fig. 1 $V_R$ the one-loop radiative correction to the ratio $R = g_V/g_A$ defined by Eqs. (20) and (40). The curves 1, 2, 3 correspond to $m_H = 50, 300$ and $1000$ GeV, respectively. The solid horizontal line corresponds to the central experimental value $\bar{V}_R$ and the dashed lines to $\pm \delta V_R$ as given by Eq. (45). The dotted parabola describes the $m_t^2$ dependence, which dominates at large values of $m_t$. These curves are taken from Ref. [4], which contains similar graphs for $V_m$ and $V_A$; the experimental value of $V_R$ is a new one.

Fig. 2 Isolines corresponding to the central values $\bar{V}_A, \bar{V}_m$ and $\bar{V}_R$ (solid lines) and to $V_A + \delta V_A, \bar{V}_m - \delta V_m, \bar{V}_R - \delta V_R$ (dashed lines). The horizontal dashed line at $m_H = 700$ GeV shows the theoretical upper limit for the mass of an elementary Higgs. The horizontal dashed line at $m_H = 62$ GeV shows the lower experimental bound for $m_H$ from direct searches at LEP. The figure is taken from Ref. [36].