THE VALUES OF $m_t$ AND $\bar{\alpha}_s$ DERIVED FROM THE NON-OBSERVATION OF ELECTROWEAK RADIATIVE CORRECTIONS AT LEP: GLOBAL FIT

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Abstract

A set of equations representing the $W/Z$ mass ratio and various observables of $Z$ decays in terms of $\bar{\alpha} \equiv \alpha(m_Z)$, $G_\mu$, $m_Z$, $m_t$, $m_H$, $\bar{\alpha}_s \equiv \alpha_s(m_Z)$, $m_b$ and $m_\tau$ (all other fermion masses being neglected) are compared with the latest data of the four LEP detectors, which at the level of one standard deviation coincide with their Born values. Our global fit gives: $m_t = 161^{+15+16}_{-16-22}$, $\bar{\alpha}_s = 0.119 \pm 0.006 \pm 0.002$, where the central values correspond to $m_H = 300$ GeV, the first errors are statistical and the second ones represent shifts of the central values corresponding to $m_H = 1000$ GeV(+) and 60 GeV(−). The predicted mass of the top is smaller than in the recent fits by 4 GeV. The predicted values of $m_W/m_Z$ and the LEP observables, based on the fitted values of $m_t$ and $\bar{\alpha}_s$, show a weak dependence on $m_H$ and differ by several predicted standard deviations from the corresponding Born values. The uncertainties of the predicted values and their deviations from the corresponding Born values determine the experimental accuracy required to observe electroweak radiative corrections.

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Precision measurements of 5 million events of $Z$ decays observed at LEP has allowed a test of the Standard Model of unprecedented accuracy. It turned out [1] that all these data, for each observable separately, can be described within 1\(\sigma\) by a simple Born approximation, using as a basis the value of the running electromagnetic $\alpha$ at $q^2 = m_Z^2$:

\[
\bar{\alpha} \equiv \alpha(m_Z^2) = 1/128.87(10) ,
\]

the Fermi coupling constant:

\[
G_\mu = 1.16639(2) \times 10^{-5} \text{GeV}^{-2} ,
\]

and the mass of the $Z$ boson:

\[
m_Z = 91.187(7) \text{ GeV} .
\]

The non-observation of genuinely electroweak radiative corrections by the high precision LEP experiments allows us within the framework of the Standard Model, to obtain rather accurate predictions of the mass of the top quark and of the gluon coupling constant at $q^2 = m_Z^2$, $\bar{\alpha}_s = \bar{\alpha}_s(m_Z^2)$. In this paper we present the results of a global fit of all LEP data and $m_W/m_Z$ ratio within the Standard Model one-loop approximation based on three most accurately measured observables: $G_\mu$, $m_Z$ and $\bar{\alpha}$. Our results for $m_t$ and $\bar{\alpha}_s$ are close to but slightly different from those obtained by other authors, who based their global fits on other parametrizations in which the running of $\alpha$ was not separated from genuinely electroweak corrections. In particular, our central value of $m_t$ is 2–4 GeV lower than in the previous fits.

The predicted theoretical values of $m_W/m_Z$ and of various LEP observables (including their uncertainties) calculated with the fitted values of $m_t \pm \delta m_t$ and $\bar{\alpha}_s \pm \delta \bar{\alpha}_s$ are compiled in Table 1. It can be seen that the predicted values differ by several standard deviations from their $\bar{\alpha}$ Born values. Table 1 shows what accuracy should be reached by experiments in order to observe the electroweak radiative corrections and to test in this way the Standard Model.

Four relations describing four “gluon-free” observables $m_W/m_Z$, $g_\nu$, $g_A$ and $g_\nu/g_A$ in terms of $\bar{\alpha} \equiv \alpha(m_Z^2)$, $G_\mu$ and $m_Z$, and of the masses of the top quark $m_t$ and Higgs boson $m_H$ have been derived in ref. [2] in electroweak one-loop approximation:

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

\[
g_\nu = \frac{1}{2} + \bar{\alpha} \frac{3}{64\pi s^2 c^2} V_\nu(t, h) ,
\]
\[ g_A = -\frac{1}{2} - \frac{3}{64\pi s^2c^2} V_A(t, h) \],
\[ g_V/g_A = 1 - 4s^2 + \frac{3}{4\pi(c^2 - s^2)} V_R(t, h) \],

where \( t = (m_t/m_Z)^2 \), \( h = (m_H/m_Z)^2 \), while \( c \equiv \cos \theta \) and \( s \equiv \sin \theta \) were defined by
\[ c^2 s^2 = \frac{\pi \bar{\alpha}}{\sqrt{2G_\mu m_Z^2}}. \]

From Eqs. (1), (2), (3), (8) it follows that
\[ s^2 = 0.23118(33). \]

Explicit expressions of \( V_m, V_\nu, V_A, V_R \) in terms of \( t \) and \( h \) and parameters \( s \) and \( c \) are given by eqs. (40), (68), (78) and (103) of ref. [2].

Each function \( V_i \) is a sum of four terms:
\[ V_i(t, h) = t + T_i(t) + H_i(h) + C_i. \]

Explicit expressions for \( T_i(t) \) in terms of \( t, c, s \) are given in ref. [2]: eq.(42) for \( T_m \); eq. (84) for \( T_A \); eq. (104) for \( T_R \).

As for the \( H_i(h) \) they have been presented in [2] by explicit functions of \( h, c, s \) plus certain, rather cumbersome, combinations of \( c \) and \( s \) that were not written out but were evaluated in [2] numerically for \( s^2 = 0.2315(3) \) and \( m_Z = 91.175 \) GeV. For the updated values of the above combinations and constants \( C_i \) in eq. (10), see Appendix B of ref. [3].

In ref. [4] the contribution of virtual gluons in the quark loops have been taken into account; for the sum of light and heavy quark loops up to terms \( O(\frac{1}{t^3}) \) [misprints of the preprint [4] has been corrected in the text to be published in Yadernaya Fizika [4]]:
\[ \delta V_m(t) = \frac{\bar{\alpha}_s}{\pi} \left( -2.86t + 0.46 \ln t - 1.92 - \frac{0.68}{t} - \frac{0.21}{t^2} \right), \]
\[ \delta V_A(t) = \frac{\bar{\alpha}_s}{\pi} \left( -2.86t + 2.24 - \frac{0.19}{t} - \frac{0.05}{t^2} \right), \]
\[ \delta V_R(t) = \frac{\bar{\alpha}_s}{\pi} \left( -2.86t + 0.22 \ln t - 1.51 - \frac{0.42}{t} - \frac{0.08}{t^2} \right). \]

The expressions (11)-(13) are valid for \( t \geq 1 \). For \( m_t < m_Z \) we either put \( \delta V_m = 0 \), \( \delta V_A = 0 \), \( \delta V_R = 0 \), or used interpolation to the massless limit in which
\[ \delta V_m = \frac{\bar{\alpha}_s}{\pi} 4(c^2 - s^2) \ln c^2 = -\frac{\bar{\alpha}_s}{\pi} \cdot 0.57 \]
As the corrections are anyway small at $t < 1$ they practically do not change the fitted values of $m_t$ and $\bar{\alpha}_s$. In the global fit condition, we also used $t \geq 1$, which is definitely valid in view of the recent results [5] of CDF and D0 ($m_t > 108$ GeV at 95% CL). This latter procedure does not change the fitted values of $m_t$ and $\bar{\alpha}_s$.

In ref. [6] the same approach based on the $\bar{\alpha}$, $G_\mu$, $m_Z$ parametrization and on the functions $V_i$ was used to calculate the hadronic ($q\bar{q}$) decays of $Z$. In the gluonless approximation the differences of $V$’s for quarks and leptons are given by eqs. (7)–(10) of ref. [6]. In this approximation the largest two-loop terms should be considered, which are proportional to $m_t^4$: one of them is in the $t\bar{t}$ contribution to the $Z$ boson self energy, the second – in the $t\bar{t}$ contribution to $Z \to b\bar{b}$ vertex. These terms have been calculated in ref. [6]. They become noticeable for large values of $m_H/m_t$. To take into account the first of them one has to multiply the term $t$ in eq. (10) of the present paper by factors in brackets derived from equations (16a) and (17a) of ref. [6]. To take into account the second term one has to multiply the term $t$ in the eq. (18) of ref. [6] by factors in brackets from equation (16b) and (17b) of ref. [6]. Note that Eqs. (16) refer to $m_H = 60$ GeV, while Eqs. (17) – to $m_H = 300$ and 1000 GeV.

In order to take into account the virtual gluons in the $Z \to b\bar{b}$ vertex one has also to multiply the term $t$ in eq. (18) of ref. [6] by a factor $(1-2.29\alpha_s/\pi)$ calculated in refs. [5], [6]. All other gluonic corrections, up to $(\alpha_s/\pi)3$, known in the literature, are included in the eqs. of ref. [6]. In particular the running mass of the $b$-quark was also included in ref. [6]. We present the results of our fit for $m_b(m_Z) = 3.1$ GeV according to refs. [14], [15]. If we change $m_b(m_Z)$ from 2.4 to 3.4 GeV, the predicted value of $R_b$ at $m_H = 300$ GeV in Table 1 decreases from 0.2164 to 0.2158, the fitted central value of $m_t$ decreases by 0.5 GeV, while that of $\bar{\alpha}_s$ increases by 0.002. The latter will change the Born values of $\Gamma_b$, $\Gamma_Z$, $\sigma_b$, $R_t$. All masses of fermions lighter than $b$ give very small contributions. Thus inclusion of $m_\tau$ decreases $\Gamma_\tau$ by 0.19 MeV. As for the running mass of the charmed quark $(m_c(m_Z) < 1$ GeV), we neglect it.

It should be emphasized that not all two-loop corrections of the order of $\alpha\alpha_s$ have been calculated in the literature. In particular the vertex triangle electroweak diagrams with a gluon connecting a quark line in the triangle with an external quark line are unknown. Such two-loop corrections may substantially change the values of $m_t$ given in Fig. 3, but its overall fitted value is expected to be changed by approximately 1 GeV. This can be seen by using two different expressions for $\Gamma_b$: one in which the specific corrections due to the $ttW$ triangle and those due to external gluons are treated
separately for the vector and axial channels (ref. 6, eq. (27)), the other in which they enter as a single correction (ref. 6, eq. (17)).

The equations of refs. 1-4, 6 – 11 described above and the latest experimental LEP data 12, 13 (see Fig. 3 and Table 1) are used in this paper to fit the values of \( m_t \) and \( \bar{\alpha}_s \). Assuming \( m_H = 60, 300 \) and 1000 GeV, the results of the fit are:

\[
m_t = 162^{+16+17}_{-17-23} \quad (17)
\]
\[
\bar{\alpha}_s = 0.119 \pm 0.006 \pm 0.002 \quad , \quad (18)
\]
\[
\chi^2/\text{d.o.f.} = 3.5/8 \quad , \quad (19)
\]

where the central values correspond to \( m_H = 300 \) GeV, the first error is experimental, the second one corresponds to the variation of \( m_H \): sign + corresponds to \( m_H = 1000 \) GeV, sign – to \( m_H = 60 \) GeV. (Note that according to ref. 14, for \( m_H = 60 \) GeV and \( m_t \) from 110 to 190 GeV the vacuum is unstable but with a lifetime > \( 10^{10} \) yr.; for \( m_t > 190 \) GeV the vacuum is dangerously unstable. For \( m_H > 300 \) GeV vacuum is stable for any reasonable value of \( m_t \).)

Independent constraints on \( m_t \) are given by the measurements of the \( m_W/m_Z \) mass ratio on \( pp \) colliders by UA2 15 and CDF 16 experiments. The Particle Data Group fit of the \( m_W/m_Z \) ratio from these experiments 17 is:

\[
m_W/m_Z = 0.8798 \pm 0.0028. \quad (20)
\]

The combined fit of LEP and \( pp \) collider data gives:

\[
m_t = 161^{+15+16}_{-16-22} \quad , \quad (21)
\]
\[
\bar{\alpha}_s = 0.119 \pm 0.006 \pm 0.002 \quad , \quad (22)
\]
\[
\chi^2/\text{d.o.f.} = 3.5/9 \quad . \quad (23)
\]

The allowed region of \( m_t \) and \( \bar{\alpha}_s \) is shown in Fig. 1. The value of the Higgs mass is fixed here to \( m_H = 300 \) GeV. The lines represent the \( s \)-standard deviation ellipsoids (\( s=1, 2, 3, 4, 5 \)), corresponding to constant values of \( \chi^2 \) (\( \chi^2 = \chi^2_{\text{min}} + s^2 \)). So in the case of validity of Gaussian errors the projections of the ellipsoids on the \( m_t \) and \( \bar{\alpha}_s \) axis define \( s \)-standard deviation confidence intervals of the corresponding parameters.

The existing data do not put real limits on the mass of the Higgs. The corresponding contour plots are shown in Fig. 2, where \( \bar{\alpha}_s \) was fixed to \( \bar{\alpha}_s = 0.119 \). The minimum of \( \chi^2 \) is at a very low value of \( m_H \), but even the two-standard deviation contour is not contained in the 1000 GeV range of Higgs mass. Similar results were obtained by many authors 12, 13, 18-21 by

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1 Note a misprint in the sign of the third term in the third line of eq. (27) in ref. 3.
using various computer codes [22]-[29]. Our fit favours slightly smaller ($\approx 4$ GeV) values of $m_t$.

The individual values of $m_t$ for each of the LEP observables for $m_H = 300$ GeV and $\bar{\alpha}_s = 0.119$, are shown in Fig. 3. The data on $A_e^\tau$, $R_l$ and $\alpha_{\text{had}}$ are insensitive to the top mass. The data on $R_b$ and $R_l$ are compatible with low values of the $m_t$, excluded by the direct search on the Tevatron.

According to ref. [30], there should exist substantial non-perturbative parts of gluonic corrections, which appear at the $t\bar{t}$ threshold and enter the $Z$-boson propagator through dispersion relations. These non-perturbative corrections, according to ref. [30], may reach 25–50% of the perturbative ones. The authors of ref. [31] insist that these corrections are fully non-controllable and eventually would prevent extraction of any information about the Higgs from LEP precision measurements. We consider these results as artifacts of dispersion calculation of Feynman integrals. When real parts of the same integrals are calculated directly (without referring to their imaginary parts), it is obvious that the non-perturbative effects are absolutely negligible, because of the asymptotic freedom of QCD and large virtuality of $t\bar{t}$ loop for external momenta not larger than $m_Z : 2m_t - m_Z \geq 200$ GeV $\gg \Lambda_{\text{QCD}}$. (See for instance ref. [32], where these arguments were applied to charmonium.) Thus we neglect $t\bar{t}$ threshold effects in our fit.

However we should note that another source of uncertainty in $O(\alpha\alpha_s)$ corrections really exists – the virtuality of quarks in the vector boson self energy loops varies with varying internal and external momenta, which influence the value of $\alpha_s$ [4].

It is instructive to use the fitted value of $m_t$ in order to predict the theoretical values of every LEP observable for three values of $m_H = 60$, 300 and 1000 GeV. The corresponding central values of $m_t$ are, according to Eq. (17), $m_t = 139$, 162 and 178 GeV, respectively. The results of this procedure are presented in Table 1. One can easily see that the central predicted values of observables depend on $m_H$ rather weakly. One can also see that the uncertainties of the predicted values of observables are much smaller than their present experimental uncertainties; also, the predicted theoretical central values differ from the corresponding Born values by several standard deviations, calculated from the fitted errors of $m_t$ and $\bar{\alpha}_s$. For instance, in the case of $R_b$ it is $4.5\sigma-6.5\sigma$ while in the case of $m_W/m_Z$ it is $3\sigma$. The latter fact was used recently by Sirlin [33] to argue that in the case of $m_W/m_Z$ the existence of radiative corrections has been proved at the $3\sigma$ level. It is obvious, however, that the high accuracy of the predicted theoretical value of any of the observables in Table 1 cannot serve as evidence for the observation of electroweak radiative corrections. Only direct high-precision measurements could provide such evidence. At present the experimental uncertainties accommodate comfortably both the $\bar{\alpha}$ Born values and the central one-loop-corrected values.
The quality of the description of the data is not very different at the
tree level and at the one-loop level and weakly depends on $m_H$. Of course
we do not think that the $\bar{\alpha}$ Born approximation would provide a universal
description of all LEP data when their accuracy would be much better than
now. However at present it seems to be sufficient.

As for the weak dependence on $m_H$, one has to bear in mind that it partly
follows from the correlation between $m_H$ and $m_t$ in the fit: the heavier is the
Higgs the heavier is the top. Therefore when the top is discovered and its
mass is known the limits on the Higgs mass will be more stringent (see
columns 4–7 of the table in ref. [1]).

Inspection of Table 1 reveals that before the top is discovered the natu-
ral experimental strategy is to reduce the experimental uncertainties of the
observables to the level of the predicted ones (by a factor of 4 for $R_b$ and
$\sigma_h$, by a factor of 2.5 for $m_W/m_Z$). After the mass of the top is measured
with accuracy $\pm 5$ GeV the reduction of uncertainties for $g_V/g_A$ by a factor
of 4 will be especially promising. Such a program requires not only increas-
ing the LEP statistics by a factor of 20 ($10^8 Z$ bosons), but – what may be
much more difficult – reaching a qualitatively new level of sophistication in
controlling systematics. If this can be done, LEP1 will test the electroweak
corrections of the Standard Model and may possibly reveal new physics.

We do not discuss in this paper other possible manifestations of elec-
troweak loops, such as in $\nu e$ scattering, deep inelastic $\nu N$ interaction, parity
violation in atoms, $K^0 \leftrightarrow \bar{K}^0$, $B^0 \leftrightarrow \bar{B}^0$, $B_s^0 \leftrightarrow \bar{B}_s^0$ transitions, radiative
corrections to superallowed $\beta$ decays, such as $^{14}O$. In some of these experi-
ments the accuracy is much worse than in $Z^0$ decays, in others - the results
of calculations heavily depend on nonperturbative QCD effects which can be
estimated only roughly. As for $^{14}O$ the virtual $W$ boson serves here only to
cut off the logarithmically divergent large electromagnetic correction. The
genuine electroweak corrections must be isolated from the trivial elec-
magnetonic ones in order to see whether the former can be quantitatively compared
with available experimental data on $^{14}O$.

Finally, we would like to present in Table 2 our fit in the traditional
form used by the LEP collaborations in spite of its obvious shortcomings as
compared with Table 1: it contains only two of six independent observables
($s^2_W \equiv \sin^2 \theta_W \equiv 1 - m_W^2/m_Z^2$ and $s^2_{eff} \equiv \sin^2 \theta_{eff}^{\text{lep}} = \frac{1}{2}(1 - g_V/g_A)$) and
the way it averages the predicted and measured values of $s^2_W$ is potentially
misleading.

The second and the fourth columns of Table 2 are taken from ref. [13], the
third and the fifth present similar results of our fit taken from our Table 1.
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References

[1] V.A. Novikov, L.B. Okun and M.I. Vysotsky, Mod. Phys. Lett. A, Reviews, 8 (1993) 2529, Errata 8 (1993) 3301; CERN preprint TH.6943/93 (1993).

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

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

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

[5] A. Barbaro-Galtieri, Rapporteur talk “Top Physics at the Tevatron”, EPS-HEP Conference, Marseille (1993).

[6] V.A. Novikov, L.B. Okun and M.I. Vysotsky, CERN preprint TH.6855/93 (1993), to be published in Phys. Lett. B.

[7] R.Barbieri, M.Beccaria, P.Ciafaloni, G.Curci, and A.Vicere, Phys. Lett. B288 (1992) 95.

[8] J.Fleisher, O.Tarasov, F.Jegerlehner, and P.Raczka, Phys. Lett. B293 (1992) 437.

[9] K.Chetyrkin, A.Kwiatkowski, and M.Steihauser, Preprint Karlsruhe University TTP 93-12. Submitted to Z. Phys. C.

[10] A.L. Kataev, Phys. Lett. B287 (1992) 209.

[11] K.G. Chetyrkin, J.H. Kühn and A. Kwiatkowski, Phys. Lett. B282 (1992) 221.

[12] J. Lefrançois, Rapporteur talk “Precision tests of the Standard Model”, EPS-HEP Conference, Marseille (1993).

[13] The LEP Collaborations ALEPH, DELPHI, L3, OPAL and the LEP Electroweak Working Group, preprint CERN-PPE/93-157.

[14] M.Duncan, R.Philippe, and M.Sher, Phys. Lett. B153 (1985) 165.

[15] J. Alitti et al., Phys. Lett. B276 (1992) 354.

[16] F. Abe et al., Phys. Rev. D44 (1991) 29.
[17] Particle Data Group, Review of Particle Properties, Phys. Rev. D45 (1992).

[18] G. Quast, talk “Z-couplings”, EPS-HEP Conference, Marseille (1993).

[19] M. Pepe-Altarelli, talk at LaThuile-93 Conference (1993), preprint LNF-93/019(F).

[20] G. Passarino, Phys. Lett. B313 (1993) 213-220.

[21] P. Langacker, Preprint UPR–0555 T (1993).

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

[23] F.A. Berends, G.J.H. Burgers, and W.L. Van Neerven, Nucl. Phys. B297 (1988) 429; E: Nucl. Phys. B304 (1988) 921 (ZSHAPE).

[24] S. Jadach, B. Ward and Z. Was, Comput. Phys. Commun. 66 (1991) 276.

[25] S. Riemann, Zeuthen preprint PHE 91-04 (1991).

[26] A. Borrelli, L. Maiani, M. Consoli, and R. Listo, Nucl. Phys. B333 (1990) 357 (ITAL.I).

[27] B.A. Kniehl and R.G. Stuart, CERN-TH.6439/92 (ZOPOLE).

[28] M. Martinez, L. Garido, R. Miquel, G.L. Harton, and R. Tanaka Z. Phys. C49 (1991) 645 (MIZA).

[29] G. Montagna et al., Comput. Phys. Commun. 76 (1993) 328.

[30] B. Kniehl, A. Sirlin, Phys.Rev. D47, (1993) 883.

[31] M.C. Gonzalez-Garcia, F. Halzen and R.A. Vazquez, University of Wisconsin preprint. December 16 (1993).

[32] V.A. Novikov, L.B. Okun, M.A. Shifman, A.I. Vainshtein, M.B. Voloshin and V.I. Zakharov, Phys. Rep. 41C, (1978) 1.

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

[34] CDHS Collaboration, A. Blondel et al., Z. Phys. C45 (1990) 361.

[35] CHARM Collaboration, J.V. Allaby et al., Z. Phys. C36 (1987) 611.

[36] CCFR Collaboration, C.J. Arroyo et al., preprint NEVIS R 1498, (1993).
Table 1

| Observable | Exp. value | Predicted values for observables, $\bar{\alpha}$ Born values and radiative corrections. |
|------------|------------|-----------------------------------------------------------------------------------|
| $m_W/m_Z$  | 0.8798(28) | $\begin{array}{llll}m_H = 60$ GeV & $m_H = 300$ GeV & $m_H = 1000$ GeV \\
m_t = 139(17) & m_t = 161(16) & m_t = 178(14) \\ GeV & GeV & GeV \\
$\bar{\alpha}_s = 0.116(6) & \bar{\alpha}_s = 0.119(6) & \bar{\alpha}_s = 0.121(6) \end{array}$ |
| $g_A$      | -0.50093(82) | $\begin{array}{llll}-0.50067(37) & -0.50092(33) & -0.50096(30) \\
-0.50000(0) & -0.50000(0) & -0.50000(0) \\
-0.00067(32) & -0.00092(33) & -0.00096(32) \end{array}$ |
| $g_V/g_A$  | 0.0716(28) | $\begin{array}{llll}0.0711(21) & 0.0704(19) & 0.0697(17) \\
0.0753(12) & 0.0753(12) & 0.0753(12) \\
-0.0042(19) & -0.0049(19) & -0.0056(18) \end{array}$ |
| $\Gamma_l$ (GeV) | 0.08382(27) | $\begin{array}{llll}0.08373(15) & 0.08381(13) & 0.08382(12) \\
0.08357(2) & 0.08357(2) & 0.08357(2) \\
0.00017(13) & 0.00024(13) & 0.00025(13) \end{array}$ |
| $\Gamma_h$ (GeV) | 1.7403(59) | $\begin{array}{llll}1.7374(40) & 1.7384(39) & 1.7382(38) \\
1.7394(36) & 1.7407(36) & 1.7420(36) \\
-0.0020(23) & -0.0023(24) & -0.0038(22) \end{array}$ |
| $\Gamma_Z$ (GeV) | 2.4890(70) | $\begin{array}{llll}2.4888(48) & 2.4905(45) & 2.4904(43) \\
2.4877(36) & 2.4890(36) & 2.4903(36) \\
0.0011(33) & 0.0015(34) & 0.0001(33) \end{array}$ |
| $\sigma_h$ (nb) | 41.560(140) | $\begin{array}{llll}41.463(34) & 41.466(34) & 41.468(34) \\
41.462(34) & 41.450(34) & 41.438(34) \\
0.000(9) & +0.016(9) & +0.027(9) \end{array}$ |
| $R_l$      | 20.763(49) | $\begin{array}{llll}20.749(41) & 20.742(41) & 20.738(42) \\
20.815(41) & 20.830(43) & 20.845(43) \\
-0.066(5) & -0.088(5) & -0.107(5) \end{array}$ |
| $R_b$      | 0.2200(27) | $\begin{array}{llll}0.2168(6) & 0.2160(5) & 0.2154(5) \\
0.2197(0) & 0.2197(0) & 0.2197(0) \\
-0.0029(5) & -0.0036(5) & -0.0042(5) \end{array}$ |
Table 2

| Parameter          | LEP ADLO [13] | Our fit | LEP + collider and $\nu N$ data | Ref. [13] | Our fit |
|--------------------|---------------|---------|---------------------------------|-----------|---------|
| $m_t$ (GeV)        | $166^{+17+19}_{-19-22}$ | $162^{+16+17}_{-17-23}$ | $164^{+16+18}_{-17-21}$ | $162^{+14+16}_{-15-22}$ |
| $\bar{\alpha}_s$  | $0.120(6)^{+2}_{-2}$     | $0.119(6)^{+2}_{-2}$     | $0.120(6)^{+2}_{-2}$     | $0.119(6)^{+2}_{-2}$     |
| $\chi^2$/d.o.f.   | 3.5/8          | 3.5/8   | 4.4/11                          | 3.5/10    |
| $\sin^2 \theta_{\text{lept}}^e$ | $0.2324(5)^{+1}_{-2}$ | $0.2324(6)^{+1}_{-2}$ | $0.2325(5)^{+1}_{-2}$ | $0.2324(5)^{+1}_{-2}$ |
| $\sin^2 \theta_W$ | $0.2255(19)^{+3}_{-5}$ | $0.2258(19)^{+3}_{-5}$ | $0.2257(17)^{+3}_{-4}$ | $0.2258(16)^{+2}_{-5}$ |
| $m_W$ (GeV)        | $80.25(10)^{+2}_{-3}$ | $80.23(10)^{+2}_{-3}$ | $80.24(9)^{+1}_{-2}$ | $80.23(8)^{+1}_{-2}$ |
Figure and Table Captions

Fig. 1: Allowed region of $m_t$ and $\bar{\alpha}_s$ with $m_H = 300$ GeV. The lines represent the $s$-standard deviation ellipsoids ($s=1, 2, 3, 4, 5$), corresponding to the constant values of $\chi^2$ ($\chi^2 = \chi^2_{\text{min}} + s^2$).

Fig. 2: Allowed region of $m_t$ and $m_H$ with $\bar{\alpha}_s = 0.119$. The lines represent the $s$-standard deviation ellipsoids ($s=1, 2, 3, 4, 5$), corresponding to the constant values of $\chi^2$ ($\chi^2 = \chi^2_{\text{min}} + s^2$).

Fig. 3: The fitted values of $m_t$ from the individual observables measured at LEP and $p\bar{p}$ colliders, assuming $m_H = 300$ GeV and $\bar{\alpha}_s = 0.118$. The hatched region corresponds to $m_t < m_Z$, which is definitely excluded by the direct search for the top quark. The central values of $R_b$ and $R_l$ are in the excluded region.

Table 1: Observables: their experimental and predicted values. The first column contains observables (four of them -- $g_A$, $g_V/g_A$, $\Gamma_l$, $\Gamma_h$ -- are secondary ones connected by well-known phenomenological relations with the observables of Fig. 3). The second column contains the experimental value of the observables. Columns 3, 4, 5 have three lines for each observable: the first line contains the predicted values which are the sum of the $\bar{\alpha}$ Born and one-loop contributions for $m_H = 60$, 300, and 1000 GeV. The second line contains the $\bar{\alpha}$ Born values, while the third gives one-loop contributions. The values in columns 3, 4, 5 are calculated for the fitted values of $m_t \pm \delta m_t$ and $\bar{\alpha}_s \pm \delta \bar{\alpha}_s$, for each value of $m_H$ respectively. Figures for uncertainties are underlined when the coefficient in front of $\delta \bar{\alpha}_s$ or $\delta m_t$ is negative.

Table 2: Comparison of our fit with that of the LEP Collaborations and the LEP Electroweak Working Group (see Table 24 of ref. [13]); $\sin^2 \theta_{\text{eff}}^{\text{lept}} \equiv \frac{1}{4} (1 - g_V/g_A)$, $s_W^2 \equiv \sin^2 \theta_W \equiv 1 - m_W^2/m_Z^2$. The collider and $\nu N$ data referred to in columns 4 and 5 were obtained in the collider experiments UA2 [15] and CDF [16] (see Eq. (20)) and the $\nu N$ experiments CDHS [34], CHARM [35] and CCFR [36]. The latter been fitted (see ref. [33]) by $s_W^2 = 0.2256(47)$ ($m_W/m_Z = 0.8800(27)$; $m_W = 80.24(25)$ GeV). The central values in the table correspond to $m_H = 300$ GeV, the upper and lower shifts to $m_H = 1000$ GeV and 60 GeV respectively.
Figure 1: Allowed region of $m_t$ and $\bar{\alpha}_s$ with $m_H = 300$ GeV. The lines represent the $s$-standard deviation ellipsoids ($s=1, 2, 3, 4, 5$), corresponding to the constant values of $\chi^2 (\chi^2 = \chi^2_{min} + s^2)$. 
Figure 2: Allowed region of $m_t$ and $m_H$ with $\bar{\alpha}_s = 0.119$. The lines represent the s-standard deviation "ellipsoids" ($s=1, 2, 3, 4, 5$), corresponding to the constant values of $\chi^2$ ($\chi^2 = \chi^2_{\text{min}} + s^2$).
Figure 3: Value for $m_t$ from different experimental measurements. $\alpha_s$ was fixed to 0.119.