RESULTS FROM THE MEASUREMENTS OF ELECTROWEAK PROCESSES AT LEP1

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Abstract

The measurements of electroweak processes performed at LEP by the experiments ALEPH, DELPHI, L3 and OPAL in the energy range of the Z resonance are summarized. The data which include recent preliminary results from LEP1 and measurements of the W-mass from LEP2, are combined to make a precise determination of the fundamental parameters of the electroweak interaction:

$$m_{\mathrm{Z}} = 91.1863 \pm 0.0019 \text{ GeV}$$
$$m_{\mathrm{W}} = 80.285 \pm 0.045 \text{ GeV}$$
$$m_{\mathrm{top}} = 155^{+15}_{-11} \text{ GeV}$$

The LEP measurements provide stringent tests of the Standard Model at the quantum level and the data confirm the predictions. The W mass and the top quark mass determined at LEP by means of the precise measurements of electroweak radiative corrections are in excellent agreement with the direct measurements by CDF and DØ. Combining all electroweak data it is possible to restrict the Higgs mass to the range from 70 to 465 GeV with 95% confidence.

1. Introduction

From the autumn 1989 to October 1995 the LEP e^+e^- storage ring was operated at centre-of-mass energies close to the Z resonance. This program is usually called LEP1. An integrated luminosity of 110 pb^{-1} per experiment has been collected at the Z peak and about 40 pb^{-1} per experiment at the wings of the Z resonance, mostly at the points $m_Z \pm 1.8$ GeV. The measurements of electroweak parameters are mainly done by the following reactions,

$$e^+e^- \rightarrow \text{hadrons}(\gamma), \quad e^+e^- \rightarrow \mu^+\mu^-(\gamma), \quad e^+e^- \rightarrow \tau^+\tau^-(\gamma), \quad e^+e^- \rightarrow e^+e^-(\gamma), \tag{1}$$

where the notation (γ) indicates the possible presence of additional photons due to initial and/or final state radiation.

About 4 million Z decays have been collected by each of the four LEP experiments ALEPH [1], DELPHI [2], L3 [3] and OPAL [4]. Most of the data are preliminary and not yet published. Combined fits to the LEP data have been done by the LEP electroweak working group. For details on the input data and the averaging procedure the reader is referred to the reports of this working group [5], [6]. The large data sample allows a precise determination of the Z boson properties, *i.e.* the Z mass, the total and partial width and its couplings to leptons and quarks.

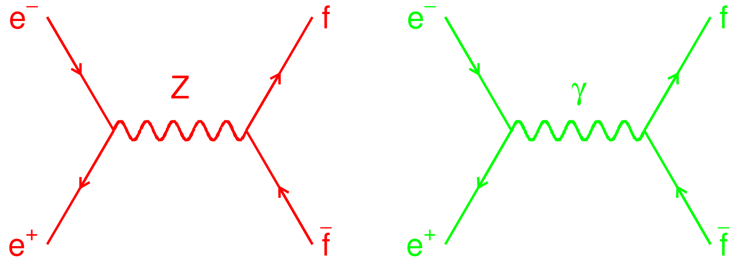

Figure 1: Lowest order graphs contributing to the reaction $e^+e^- \rightarrow f\bar{f}$

To lowest order the process $e^+e^- \rightarrow f\bar{f}$ is mediated by Z and photon exchange, as shown in Figure 1. Therefore, the lowest order cross-section consists of three parts, the Z exchange, the photon exchange and their interference.

$$\sigma \;=\; \sigma_Z \;+\; \sigma_\gamma \;+\; \sigma_{int} \tag{2}$$

The cross-section due to the Z exchange can be expressed in a model-independent way by the Z mass, m_Z, the total Z width, Γ_Z, and the corresponding partial width, Γ_f, of $Z \rightarrow f\bar{f}$.

$$\sigma_Z = \sigma_f^0 \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + (s\Gamma_Z/m_Z)^2} \qquad \text{with} \qquad \sigma_f^0 = \frac{12\pi\Gamma_e\Gamma_f}{m_Z^2\Gamma_Z^2} \tag{3}$$

For the photon contribution the validity of QED is assumed and the number of colours, N_f^C, is taken as predicted by QCD.

$$\sigma_\gamma = \frac{4\pi\alpha^2}{3s} {Q_e}^2 {Q_f}^2 N_f^C \tag{4}$$

The interference term contains combinations of electroweak parameters and lepton and quark charges, which cannot be expressed in terms of the parameters given in equation (3) and (4). They are comprised within the parameter J_f.

$$\sigma_{\mathrm{int}} = \frac{4\pi\alpha^2}{3}\,\mathrm{J_f}\,\frac{\mathrm{s}-\mathrm{m_Z^2}}{(\mathrm{s}-\mathrm{m_Z^2})^2+\mathrm{s^2\Gamma_Z^2/m_Z^2}} \tag{5}$$

Since the interference term is expected to be small, it is usually set to the Standard Model value. A truly model-independent extraction of electroweak parameters can be achieved by using a S-Matrix ansatz and fitting the the data including the 130 to 172 GeV measurements.

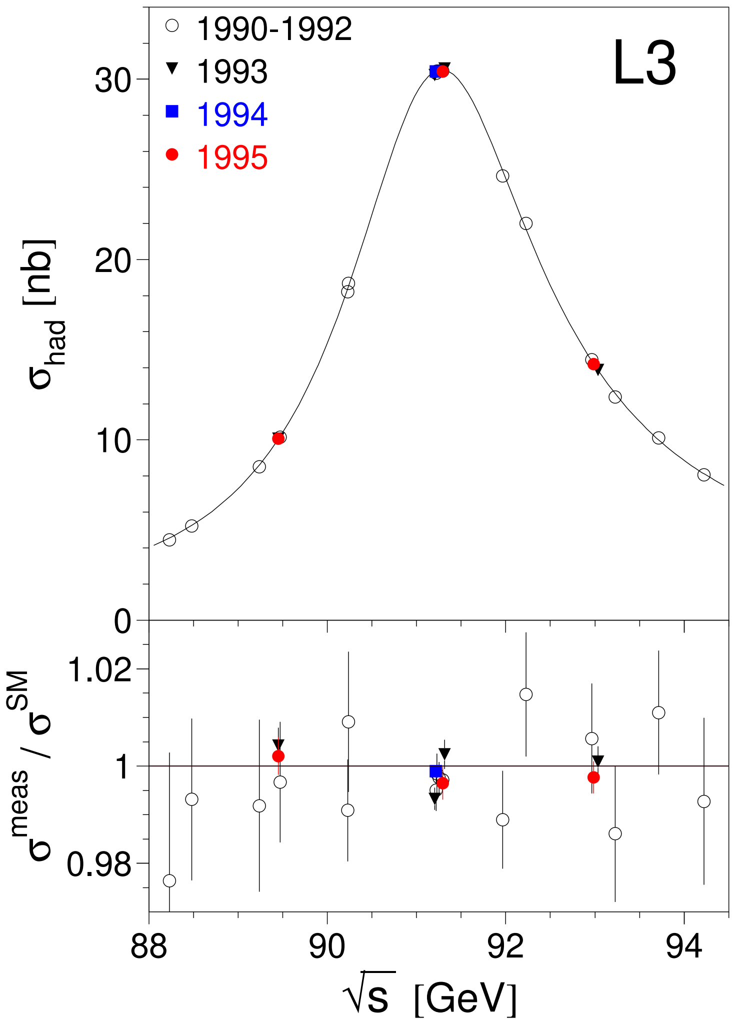

Figure 2: Measurements of the cross-section $e^+e^- \rightarrow$ hadrons(γ) performed by the L3 experiment in the years 1990 to 1995. The continues curve is the Standard Model fit to the data. The ratio of data to theoretical prediction is shown in the lower part of the figure for better displaying the high precision achieved in the years 1993 to 1995.

A brief remark should be made on the way how radiative corrections are applied to the data. The so-called "model-independent" parameters are defined by Born term level equations as (3) and (4). Determining these parameters only the QED radiative corrections are taken into account in the fits. However, for the parameters of the Standard Model the full electroweak radiative corrections are included using the program ZFITTER [7]. For details on the calculations of the radiative corrections see [8].

2. Cross Section Measurements

It is impossible to describe here in detail how the cross-sections of the reactions (1) are measured by the LEP experiments and how the systematic errors are determined. The reader should consult the individual publications of the LEP experiments [1], [2], [3], [4].

In general one proceeds in the following way: The different reactions are selected from the total data sample by appropriate cuts. The data are then corrected for acceptance and detector efficiencies and the cross-sections are determined from a simultaneous measurement of the luminosity which is typically measured with an systematic accuracy of less than one per mille.

For illustrating the high precision of the measurements Figure 2 shows the hadronic cross-section measured by the L3 experiment. The points of highest precision have been measured in the years 1993 to 1995. Instead of comparing the data with the Standard Model, as done in Figure 2, we discuss in this chapter the results of the "model-independent" fit where the Breit-Wigner form of equation (3) including QED radiative corrections is fitted to the data.

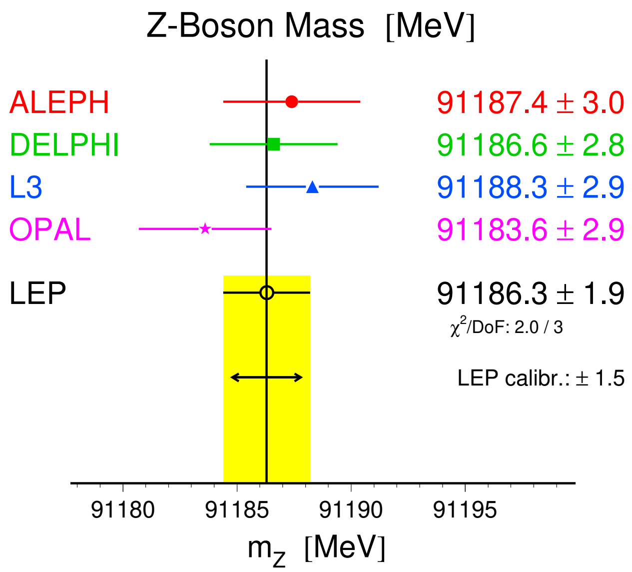

Figure 3: Measurements of the Z mass from ALEPH, DELPHI, L3 and OPAL and the combined LEP value. The errors include statistical and systematic errors and a contribution of ± 1.5 MeV from the uncertainty of the LEP energy scale.

From the fit we determine the Z mass, the total and the different partial widths of the Z. The data with the largest number of events have been collected in the years 1993 to 1995. Since these measurements were done only at three points, *i.e.* at the Z peak and at $m_Z \pm 1.8$ GeV, three independent parameters can be determined from the measurements of the one of the reactions (1), but with no additional constraints. In case of the reaction $e^+e^- \to$ hadrons(γ) we choose the Z mass, m_Z, the total Z width, Γ_Z, and hadronic pole cross-section σ_f^0, which is related to the product of the partial hadronic width, Γ_{had}, and the partial width, Γ_e, of the Z$\to e^+e^-$ as given in equation (3). From measurements of leptonic reactions $e^+e^- \to e^+e^-(\gamma)$, $e^+e^- \to \mu^+\mu^-(\gamma)$ and $e^+e^- \to \tau^+\tau^-(\gamma)$ we extract the partial of the width of the Z into electrons, muons or taus or the leptonic width asuming lepton universality.

The measurements of the Z mass by the ALEPH, DELPHI, L3 and OPAL are displayed in Figure 3. Combining the four measurements one obtains a Z mass of

$$m_Z \ = \ 91.1863 \ \pm \ 0.0019 \text{ GeV}, \tag{6}$$

where the error includes the systematic error, which is dominated by the uncertainty on the LEP energy. A large effort has been made for precisely calibrating the LEP energy scale [9]. The observation of the electron polarisation and especially its resonant depolarisation at the three energy points, the Z pole and at $m_Z \pm 1.8$ GeV, have made it possible to reduce the LEP energy error to ± 1.5 MeV. The Z boson mass is now determined with the same relative accuracy as the Fermi coupling constant, G_F , because

$$\frac{\Delta m_Z}{m_Z} \ \leq \ 2 \cdot 10^{-5}. \tag{7}$$

We have now two high precision input parameters at our hands to test the predictions of the Standard Model and the relations between its parameters.

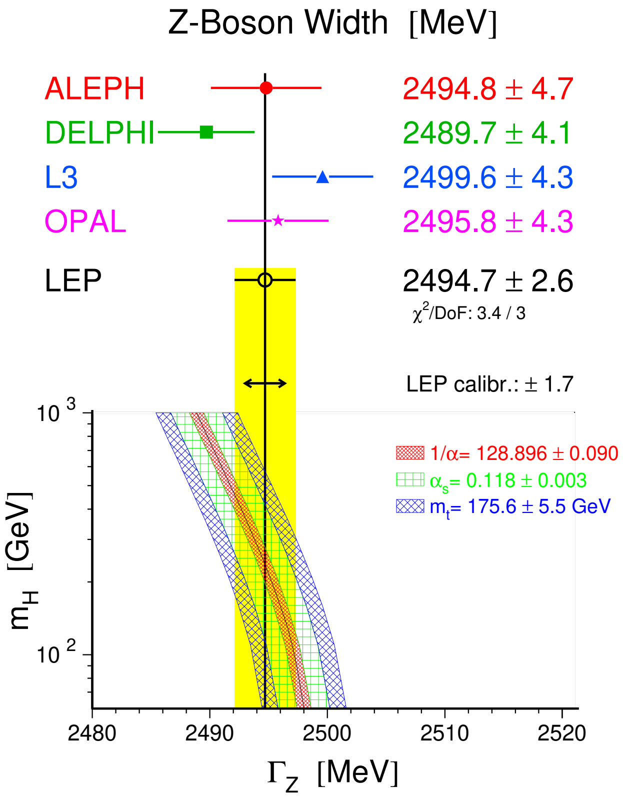

Figure 4: Measurements of the total Z width from ALEPH, DELPHI, L3 and OPAL and the combined LEP value. The errors include statistical and systematic errors. The contribution of the LEP energy calibration error amounts to ± 1.7 MeV and is included in the errors.

The total width of the Z boson is measured with leptonic and hadronic reactions, but the main accuracy comes from the measurement of the hadronic cross-section due to the large number of events. Figure 4 compares the values of the total width of the Z determined by the four LEP experiments and gives the combined LEP average. For the measurement of the total width it is important to know precisely the energy difference between the two points at the wings of the Z resonance curve. The experimental error quoted in Figure 4 contains the contribution of ± 1.7 MeV due to the point-to-point uncertainties on the LEP energy scale. The combined LEP value of the total Z width is

$$\Gamma_Z \;=\; 2494.7 \;\pm\; 2.6 \text{ MeV}, \tag{8}$$

where the error includes statistical and systematic errors. Its is remarkable that the relative precision of the combined LEP value of Γ_Z is about one per mille. The predictions of the Standard Model for the Z width are shown in the lower part of Figure 4. We have chosen to display the dependence of the Standard Model prediction on the Higgs mass since other parameters, such as the mass of the top quark are now quite accurately measured. The combined value of CDF and DØ is $m_{\text{top}} = 175.6 \pm 5.5$ GeV [10]. The Standard Model prediction of the total Z width depends also on the fine structure constant α and on the strong coupling constant α_s, both taken at $q^2 = m_Z$. We show the band of $\alpha(m_Z)^{-1} = 128.896 \pm 0.090$ [11] and $\alpha_s(m_Z) = 0.118 \pm 0.003$ [12].

The combined LEP value of the total Z width agrees very well with the predictions of the Standard Model for the above listed parameters. However, the mass of the Higgs boson cannot be restricted to less than 1000 GeV by this measurement alone since Γ_Z depends on α_s and m_{top} and their error increase the uncertainty on the Standard Model prediction.

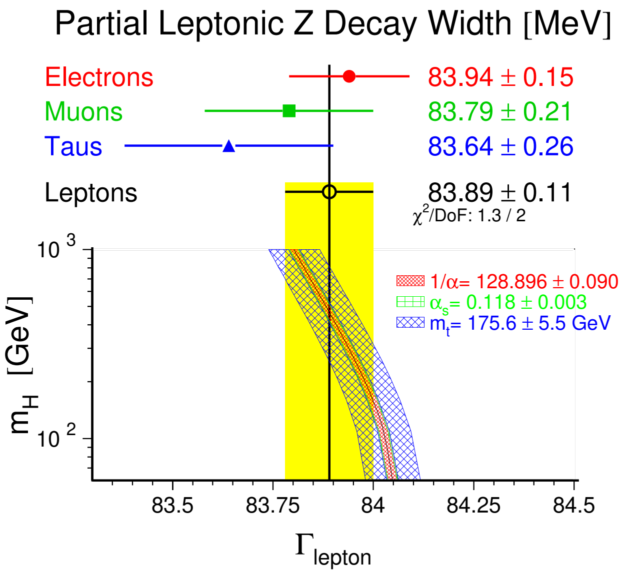

Figure 5: Comparison of the partial Z width into electrons, muons and taus as obtained from a combination of the measurements of ALEPH, DELPHI, L3 and OPAL. The leptonic width of the Z is calculated with the asumption of lepton universality. The errors include statistical and systematic errors.

A parameter which does not depend on α_s is the partial leptonic width. Figure 5 shows the combined LEP values for the partial width into electrons, muons and taus. The measurements agree with lepton universality and can therefore be combined. We correct for mass effects such that the leptonic width, Γ_ℓ, and especially Γ_τ correspond to the decay into massless charged leptons:

$$\Gamma_\ell \;=\; 83.89 \;\pm\; 0.11 \text{ MeV}. \tag{9}$$

This value has a remarkable precision of 1.3 per mille. Note, that the leptonic width restricts the Higgs mass somewhat stronger than Γ_Z since the Standard Model prediction is independent of α_s.

On the other hand, the ratio of the hadronic width to the leptonic width, R_ℓ, shown in Figure 6 depends strongly on α_s, but is independent of the mass of the top quark. R_ℓ and Γ_Z are the main quantities which determine α_s. We will give the result later in the chapter 6 where we discuss the Standard Model fits.

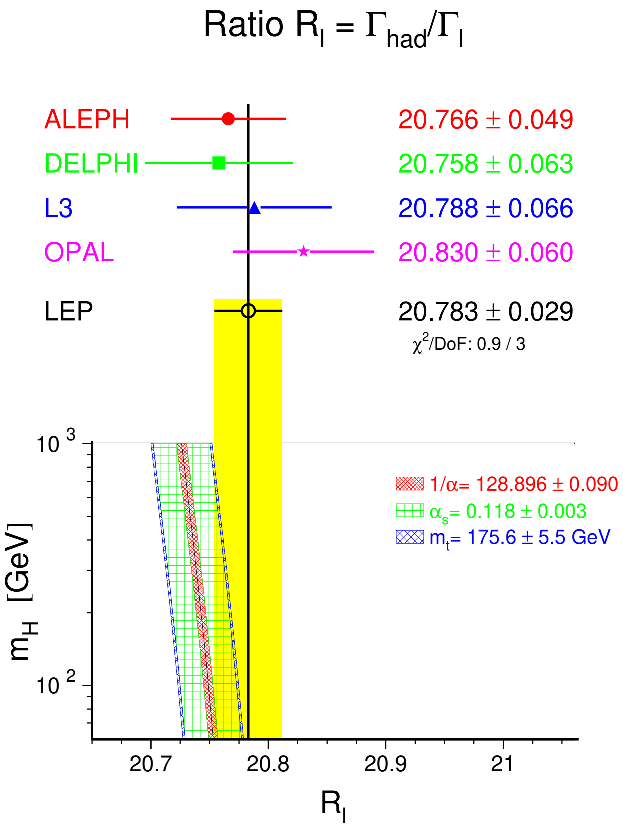

Figure 6: Comparison of the ratio, R_ℓ , of the hadronic width to the leptonic width measured by ALEPH, DELPHI, L3 and OPAL and the combined LEP value. The errors include statistical and systematic errors.

3. Asymmetry Measurements

Additional information on the weak couplings of fermions can be obtained from the measurement of the angular distributions of reactions (1). The angular distribution shows a forward-backward charge asymmetry from which the leptonic pole asymmetry, $A_{fb}^{0,\ell}$ can be determined. For including the measurements of the asymmetry we express cross-sections and asymmetries in terms of the vector and axial-vector couplings. Since we need the relations later also for quarks we write them down for the process $e^+e^- \to f\bar{f}$:

$$A_{fb}^{0,f} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f \qquad \text{with} \qquad \mathcal{A}_f \equiv \frac{2g_{vf}g_{af}}{g_{vf}^2 + g_{af}^2} \tag{10}$$

$$\Gamma_{\mathrm{f}} \sim (g_{v\mathrm{f}}^2 + g_{a\mathrm{f}}^2)\,. \tag{11}$$

Furthermore, the tau polarisation which can be inferred from the energy spectra of its decay products, measures

$$\mathcal{P}_\tau \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -\mathcal{A}_\tau, \tag{12}$$

where σ_R and σ_L are the τ-pair cross sections for the production of a right-handed and left-handed τ^-, respectively. The angular dependence of $\mathcal{P}_\tau$ as a function of the angle θ between the e^- and the τ^-, for $\sqrt{s} = m_{\mathrm{Z}}$, measures $\mathcal{A}_{\mathrm{e}}$ and $\mathcal{A}_\tau$:

$$\mathcal{P}_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_{\mathrm{e}}\cos\theta}{1+\cos^2\theta + 2\mathcal{A}_\tau\mathcal{A}_{\mathrm{e}}\cos\theta}. \tag{13}$$

The measurements cannot be discussed in detail in this article. We refer the reader to references [5], [6] and the publications of the individual experiments listed therein. We will compare all results in chapter 5 in terms of the effective weak mixing angle which can, for example, be derived from the vector and axial-vector coupling of leptons, $g_{v\ell}$ and $g_{a\ell}$, by the relation

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} \equiv \frac{1}{4}(1 - g_{v\ell}/g_{a\ell})\,. \tag{14}$$

4. Heavy quarks

Studies of the electroweak and strong interactions of single quark flavour is very interesting for testing the doublett structure predicted by the Standard Model. The measurement of the $\mathrm{b\bar{b}}$ production is especially important because of its direct coupling to the top quark which leads to additional corrections of the partial $\mathrm{b\bar{b}}$ width, $\Gamma_{\mathrm{b\bar{b}}}$ as illustrated in Figure 7.

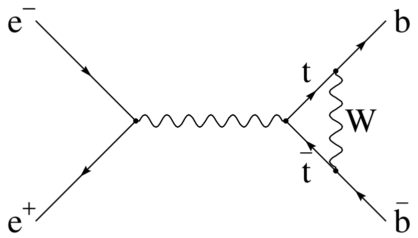

Figure 7: Vertex corrections to the partial width of Z $\to\mathrm{b\bar{b}}$ due to the Wtb coupling.

The Wtb vertex corrections cancel practically the increase of $\Gamma_{\mathrm{b\bar{b}}}$ due to the top-bottom loop in the W self energy which affects the total and all partial Z widths. This makes $\Gamma_{\mathrm{b\bar{b}}}$ insensitive to the mass of the top quark and thus sensitive to new physics. On the other hand the ratio [1] of the b and c quark partial widths of the Z to its total hadronic partial width, $R_{\mathrm{b}}^0 \equiv \Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}}$, is only sensitive to the top quark mass via the Wtb vertex correction. The widely discussed deviations of R_{b} and R_{c} from the Standard Model have diminished in summer 1996 due to the new results of ALEPH [13], DELPHI [14], L3 [15] and OPAL [16] using a variety of b-tagging methods. Figure 8 summarizes the measurements of $\Gamma_{\mathrm{b\bar{b}}}/\Gamma_{\mathrm{had}}$ using different sets of b-tagging

[1] The symbols R_{b}^0, R_{c}^0 denote the ratio of partial widths whereas R_{b}, R_{c} usually denote the experimentally measured ratios of cross sections ($R_{\mathrm{b}}^0 = R_{\mathrm{b}} + 0.0003$, $R_{\mathrm{c}}^0 = R_{\mathrm{c}} - 0.0003$).

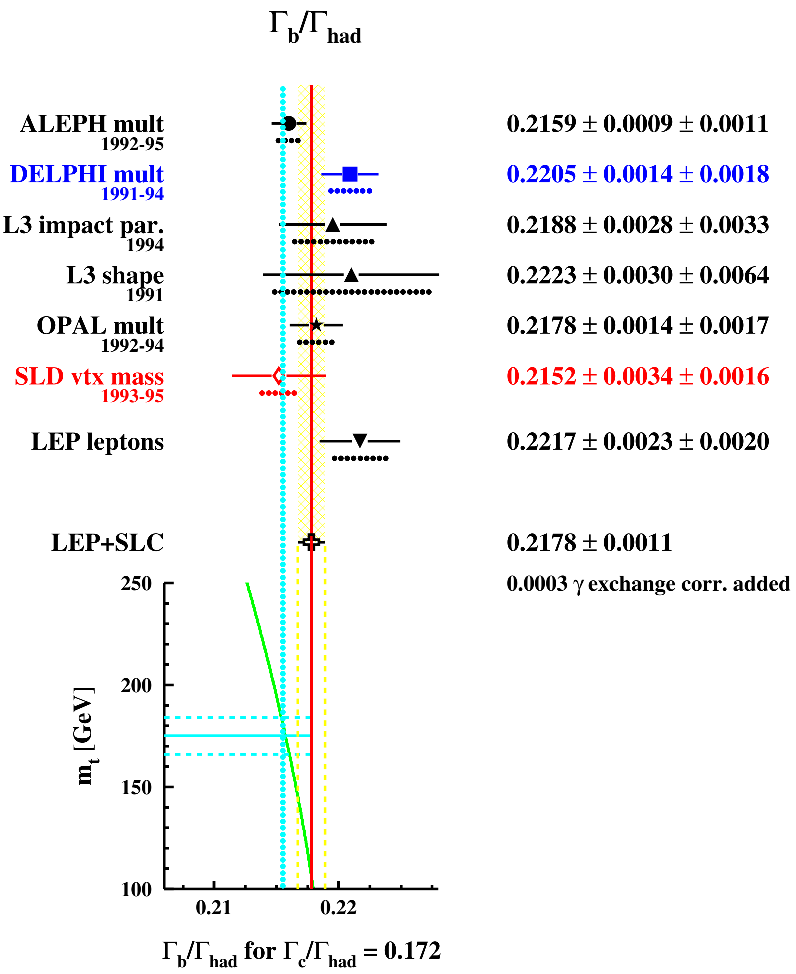

Figure 8: Measurements of partial width of Z $\rightarrow b\bar{b}$ by ALEPH [13], DELPHI [14], L3 [15], OPAL [16] and SLD [17] using different sets of b-tagging methods. The errors (horizontal solid lines) include statistical and systematic errors (horizontal dotted lines). The Standard Model prediction is indicated by a vertical dotted line.

methods. The actual status of the measurements has not much changed since last year and there is still a 1.8 σ deviation of $R_{\rm b}$ from the Standard Model prediction if one takes all data into account. There is, however, good agreement with the Standard Model prediction, if one averages only the most recent measurements with the improved b-tagging as pointed out by Jack Steinberger [18].

5. Effective Weak Mixing Angle

The measurements of the lepton, the b and c quark asymmetries and the hadronic charge asymmetry $< {\rm Q_{fb}} >$ can best be compared by extracting the effective weak mixing angle. We have chosen to present the results in Figure 9 in terms of the effective weak mixing angle of **leptons**, $\sin^2\theta_{\rm eff}^{\rm lept}$. This may look insuitable since we include also hadronic asymmetries such as $A_{\rm fb}^{0,\rm b}$, $A_{\rm fb}^{0,\rm c}$ and $< {\rm Q_{fb}} >$. However, all asymmetries contain the Z$\rightarrow$ e$^+$e$^-$ coupling and since we want to present the results in terms of a single variable we choose the effective weak mixing angle of leptons. All effective weak mixing angles are then corrected to correspond to the one for massless leptons.

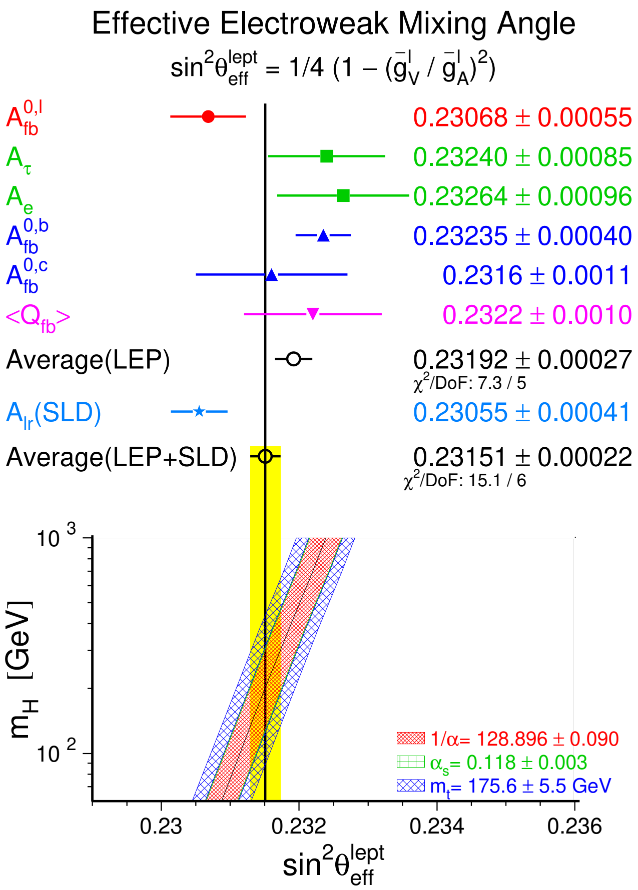

Figure 9: Measurements of $\sin^2\theta_{\rm eff}^{\rm lept}$ from the different asymmetry measurements at LEP [6] and SLD [17] and the combined LEP and SLD value. The errors include statistical and systematic errors.

The results of $\sin^2\theta_{\rm eff}^{\rm lept}$ from the different asymmetry measurements at LEP [6] and SLD [17] are compared in Figure 9. Two values of $\sin^2\theta_{\rm eff}^{\rm lept}$ lie below the LEP and SLD average, the one from the forward-backward asymmetry of leptons and from the left-right asymmetry measured by SLD. The latter deviates about 2.5 σ from the average. One could make the hypothesis that the leptons deviate from the quarks, but the LEP values of $\mathcal{A}_{\rm e}$ and $\mathcal{A}_\tau$, being above the average, stem from the measurements of the tau polarisation and therefore again from a leptonic channel. Furthermore, the low values of $A_{\rm fb}^{0,\ell}$ come mainly from $A_{\rm fb}^{0,\tau}$ and thus the origin of this deviation cannot be attributed to effects of the electron and muon couplings alone. In short, the large spread of the measurements in Figure 9 is probably of statistical origin, but one should follow this up in future. Since most of the LEP data are already analysed, at least in a preliminary fashion, new measurements can only come from SLC.

6. Standard Model Results

It is most important to compare the measurements to the predictions of the Standard Model and determine the electroweak parameters of this theory. We use as input parameters

$$
\begin{aligned}
m_{\rm Z} &= 91.1863 \pm 0.0019 \text{ GeV from equ.(6)},\\
\alpha(m_{\rm Z})^{-1} &= 128.896 \pm 0.090 \text{ from Ref. [11] and}\\
{\rm G_F} &= (1,16639 \pm 0.00002)\cdot 10^{-5}\ \text{GeV}^{-2} \text{ from the } \mu\text{-decay}
\end{aligned}
$$

and determine $m_{\rm top}$ from a fit to the LEP1 data including W mass measurements of LEP2 [19]. The result is

$$m_{\rm top} = 155\ ^{+15}_{-11}\ \mathrm{GeV}$$

The main contribution to the error comes from the uncertainty on the Higgs mass, since it is varied simultaneously in the fit with no external constraint. The LEP result on $m_{\rm top}$ can be compared to the direct measurement of the mass of the top quark from CDF and DØ [10]:

$$m_{\rm top} = 175.6 \pm 5.5\ \mathrm{GeV}.$$

The agreement is impressive and shows the validity of the Standard Model asumptions in calculating the electroweak radiative corrections, at the quantum level. It leaves very little room for additional effects of new physics.

For testing the Standard Model relations and determining the parameters $m_{\rm top}$,$m_{\rm H}$ and $\alpha_{\rm s}$ we proceed by including step by step more electroweak measurements. In Table 1 we list the results of fitting three data sets:

a. LEP1 data and the $m_{\rm W}$ measurements from LEP2.
b. LEP1 data including SLD [17] and νN [20] data, but not $m_{\rm top}$ and $m_{\rm W}$ measurements.
c. All electroweak data including the $m_{\rm top}$ and $m_{\rm W}$ measurements.

	LEP (including LEP-II $m_{\rm W}$)	all data except $m_{\rm top}$ and $m_{\rm W}$	all data
$m_{\rm top}$ [GeV]	155^{+15}_{-11}	155^{+10}_{-9}	172.7 ± 5.4
$m_{\rm H}$ [GeV]	70^{+147}_{-40}	36^{+52}_{-18}	127^{+127}_{-72}
$\alpha_s(m_{\rm Z}^2)$	0.122 ± 0.003	0.121 ± 0.003	0.120 ± 0.003
χ^2/d.o.f.	10/9	18/12	21/15
$\sin^2\theta_{\rm eff}^{\rm lept}$	0.23190 ± 0.00026	0.23152 ± 0.00022	0.23157 ± 0.00022
$1 - m_{\rm W}^2/m_{\rm Z}^2$	0.2248 ± 0.0009	0.2241 ± 0.0008	0.2232 ± 0.0006
$m_{\rm W}$ [GeV]	80.285 ± 0.045	80.323 ± 0.042	80.366 ± 0.031

Table 1: Results of the fits to LEP data alone, to all data except the direct determinations of $m_{\rm top}$ and $m_{\rm W}$ (TEVATRON and LEP2) and to all electroweak data including the top quark mass determination at Fermilab. The bottom part of the table lists the results for $\sin^2\theta_{\rm eff}^{\rm lept}$, $1 - m_{\rm W}^2/m_{\rm Z}^2$ and $m_{\rm W}$ which can be derived from the $m_{\rm top}$, $m_{\rm W}$ and $\alpha_s(m_{\rm Z}^2)$. All errors include statistical and systematic errors. Theoretical errors due to small differences in the calculation of electroweak radiative corrections are not included.

The LEP data alone or the fit including the SLD measurements prefer a somewhat lower mass of the top quark than the TEVATRON. The Higgs mass can only be determined with a large error due to the logarithmic Higgs mass dependence of the radiative corrections. A low Higgs mass is prefered as can be seen from Table 1. It is very interesting that $\alpha_{\rm s}(m_{\rm Z})$ from LEP given in Table 1 agrees very well with the world average $\alpha_{\rm s}(m_{\rm Z}) = 0.118 \pm 0.003$ [12] and

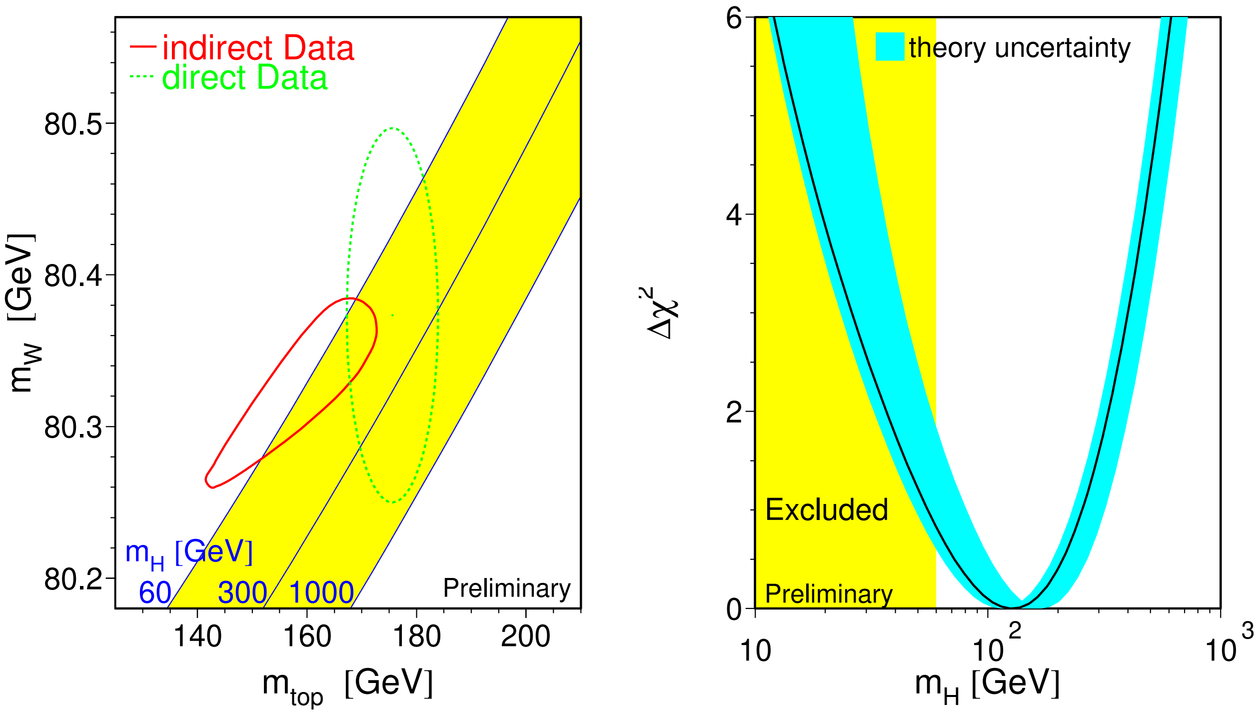

Figure 10: Left: 68% confidence contours of m_{W} and m_{top} from the indirect measurements (solid contour) at LEP, SLD and by νN data compared the one from direct measurements (dotted contour) at TEVATRON and LEP2. Right: $\Delta\chi^2$ versus the Higgs boson mass obtained from a fit to all electroweak data. The light dark band marks the Higgs mass limit from the direct search at LEP and the dark shaded band at the $\Delta\chi^2$ line indicates the theoretical uncertainties.

has the same error[2]. Since it is determined by the measurement of R_ℓ and Γ_{Z} it is independent of the α_{s} values obtained from event shape or jet rate studies.

The quantities $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$, $(1 - m_{\mathrm{W}}^2/m_{\mathrm{Z}}^2)$ and m_{W} derived from the m_{top} , m_{H} and α_{s} fits are listed in the lower part of Table 1. It is most remarkable that all these quantities have now very small errors. The W mass from LEP which is mainly determined by the LEP1 measurements has an error of $\pm$45 MeV. It will take a very large effort to achieve this error with the direct mass measurements at the TEVATRON and LEP2, where the combined average W mass is now $m_{\mathrm{W}} = 80.37 \pm 0.08$ GeV [19]. Figure 10 compares the m_{W}-m_{top} contour of direct measurements from TEVATRON and LEP2 with the one of the indirect measurements of from LEP, SLD and νN data . Both contours are calculated for 95% confidence. Also show is the band of the Standard Model predictions using the measurement of $\mathrm{G_F}$ and varying the Higgs mass between 60 and 1000 GeV. One sees that the top mass is better measured by the direct measurements, while the indirect data (mainly LEP and SLD) make a stronger constraint to the W mass and the Higgs mass.

The right part of Figure 10 shows the increase of the χ^2 from its minimum fitting all electroweak data and varying the Higgs mass. Low Higgs masses are excluded by the direct search. While a lower limit of 60 GeV is indicated in Figure 10, it is now increased to about 70 GeV due to the recent preliminary results from the LEP 172 GeV run [22]. No combined limit has yet been done for the lower Higgs mass limit. In summary all electroweak data constrain the mass of the Higgs boson between 70 GeV and 465 GeV with 95% confidence.

[2]There are different opinions on the error of $\alpha_{\mathrm{s}}(m_{\mathrm{Z}})$. Compare Ref. [12] with Ref. [21].

7. Conclusions

LEP1 is a great success! Many fundamental parameters of electroweak and strong interactions are now precisely determined in the framework of the Standard Model.

$$\begin{aligned} m_{\mathrm{Z}} &= 91.1863 \pm 0.0019 \text{ GeV} \quad \text{LEP1} \\ m_{\mathrm{W}} &= 80.285 \pm 0.045 \text{ GeV} \quad \text{LEP1+(LEP2)} \\ m_{\mathrm{top}} &= 155^{+15}_{-11} \text{ GeV} \quad \text{LEP1+(LEP2)} \end{aligned}$$

The W mass and the top quark mass determined at LEP mainly through the measurements of electroweak radiative corrections are in excellent agreement with the direct measurements at Fermilab by CDF and DØ.

$$\begin{aligned} m_{\mathrm{W}} &= 80.37 \pm 0.08 \text{ GeV} \quad \text{CDF, DØ and LEP2} \\ m_{\mathrm{top}} &= 175.6 \pm 5.5 \text{ GeV} \quad \text{CDF and DØ} \end{aligned}$$

Furthermore, the LEP measurements provide stringent tests of the Standard Model at the quantum level and the results show very good agreement. Combining all electroweak data it is possible to restrict the Higgs mass to the range from 70 to 465 GeV with 95% confidence.

We now look forward for the LEP2 measurements with energies up to nearly 200 GeV and high luminosity. Let's hope that we find the Higgs or the SUSY particles or other new physics!

Acknowledgements

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