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M. Pepe Altarelli:

TESTS OF THE ELECTROWEAK THEORY AT LEP

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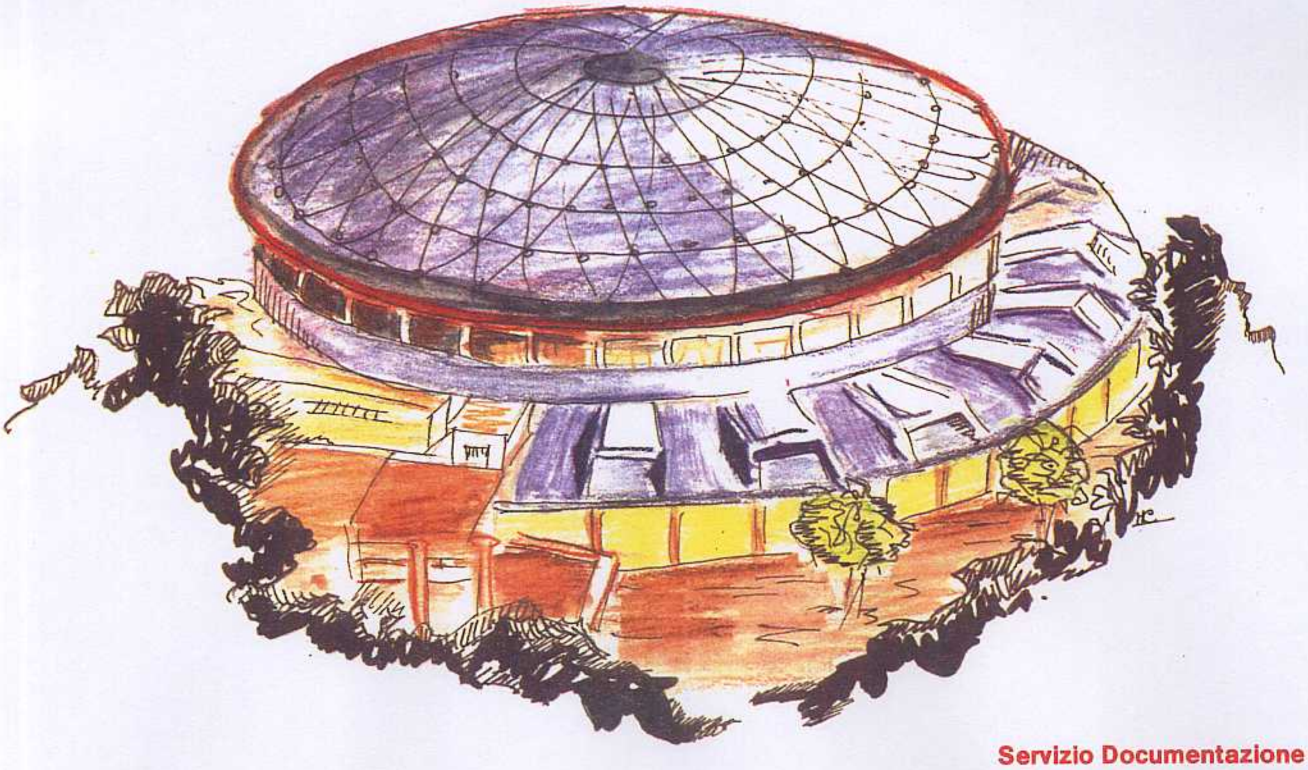

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TESTS OF THE ELECTROWEAK THEORY AT LEP

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Abstract

Recent data on precision tests of the Standard Model at LEP are presented and compared to the theoretical expectations. The results include those obtained by a preliminary analysis of the data collected in the 1992 run. The data show excellent agreement with the Standard Model.

1 Introduction

Each LEP experiment has collected a statistics of $\sim$ 1.3 million Z^0 decays, corresponding to a total integrated luminosity of $\sim 43\text{pb}^{-1}$ during the years 1990-1992. The analysis of the '91 data is by now completed [1, 2, 3, 4] and the results are presented here. In addition the preliminary analysis of the data collected during the '92 run is reported.

2 Z lineshape and lepton forward-backward asymmetries

$\mathrm{M_Z}$ and Γ_Z are extracted by a scan of the Z resonance [5], i.e. by measuring the cross-sections $e^+e^- \rightarrow f\bar{f}$ for hadronic ($q\bar{q}$) and leptonic ($\ell^+\ell^-$) final states as a function of $\sqrt{s} \sim \mathrm{M_Z}$. In 1992 no scan was performed, so that the results on $\mathrm{M_Z}$ and Γ_Z are essentially the same as in Dallas [6]. The number of selected events and the systematic errors on the event selections are shown in table 1. The uncertainty of 0.3% in the theoretical cross-section of Bhabha scattering used for the luminosity measurement is common to all experiments and represents the theoretical accuracy of the Monte Carlo generators BHLUMI[7] and BABAMC

Table 1. Number of selected events and systematic errors of the event selections. The data sample corresponds to an integrated luminosity of $\sim 43\text{pb}^{-1}$ collected between 1990 and 1992 by each experiment.

		ALEPH	DELPHI	L3	OPAL
Number of events	$q\bar{q}$	1140K	1047K	1103K	1168K
	$\ell^+\ell^-$	138K	101K	102K	147K
systematic error	$q\bar{q}$	0.2%	0.3%	0.2%	0.2%
	e^+e^-	0.4%	0.5%	0.5%	0.3%
	$\mu^+\mu^-$	0.5%	0.5%	0.5%	0.3%
	$\tau^+\tau^-$	0.6%	0.7%	0.7%	0.5%
experimental systematic error on luminosity		0.45%	0.5%	0.6%	0.5%
common theoretical error		0.3%			

[8]. The LEP energy uncertainty has an important impact on the determination of M_Z and Γ_Z: the error on the mass is in fact entirely dominated by the calibration error, while the error on the width due to calibration uncertainties is almost as large as the statistical one [9]. In 1991 a precise calibration of the LEP energy scale has been achieved by resonant spin depolarization of the vertically polarized beam [10] and by a better understanding of the properties of the LEP magnets and RF systems. As a consequence, the common systematic error of the four experiments due to the LEP energy uncertainty is now 6.3 MeV on M_Z (while it was 20 MeV in 1990) and 4.5 MeV on Γ_Z (5 MeV in 1990).

The observed cross-sections $\sigma^{Meas.}$ can be written in the form of a convolution [5]:

$$\sigma_{f\bar{f}}^{Meas.}(s) = \int H(s,s')\sigma_{f\bar{f}}(s')ds' \tag{1}$$

where H is the radiator function describing the effect of the initial state radiation and σ is the bare cross-section which, at the peak, takes the form:

$$\sigma_{f\bar{f}}^0 = \frac{12\pi\Gamma_e\Gamma_f}{M_z^2\Gamma_z^2} \, .$$

The leptonic forward-backward asymmetries $A_{FB}^M(s)$ are obtained by a fit of the angular distribution of the cross-section measured at each center of mass energy [5]:

$$\frac{d\sigma(s)}{d\cos\theta} \propto 1+\cos^2\theta + \frac{8}{3}A_{FB}^M(s)\cos\theta \tag{2}$$

where θ is the angle between the e^- beam and the outgoing fermion. By deconvoluting the initial state radiation and correcting for some small additional QED contributions, one can extract the bare asymmetry A_{FB}^0 (see. e.g. ref.[6]). One may express this asymmetry directly in terms of the ratio of the vector (g_v) and axial vector (g_a) coupling constants of the neutral current to the fermion f:

$$(A_{FB}^0)_f = \frac{3}{4}A_e^0 A_f^0$$

$$A_f^0 = \frac{2g_v^f g_a^f}{(g_v^f)^2+(g_a^f)^2} \, . \tag{3}$$

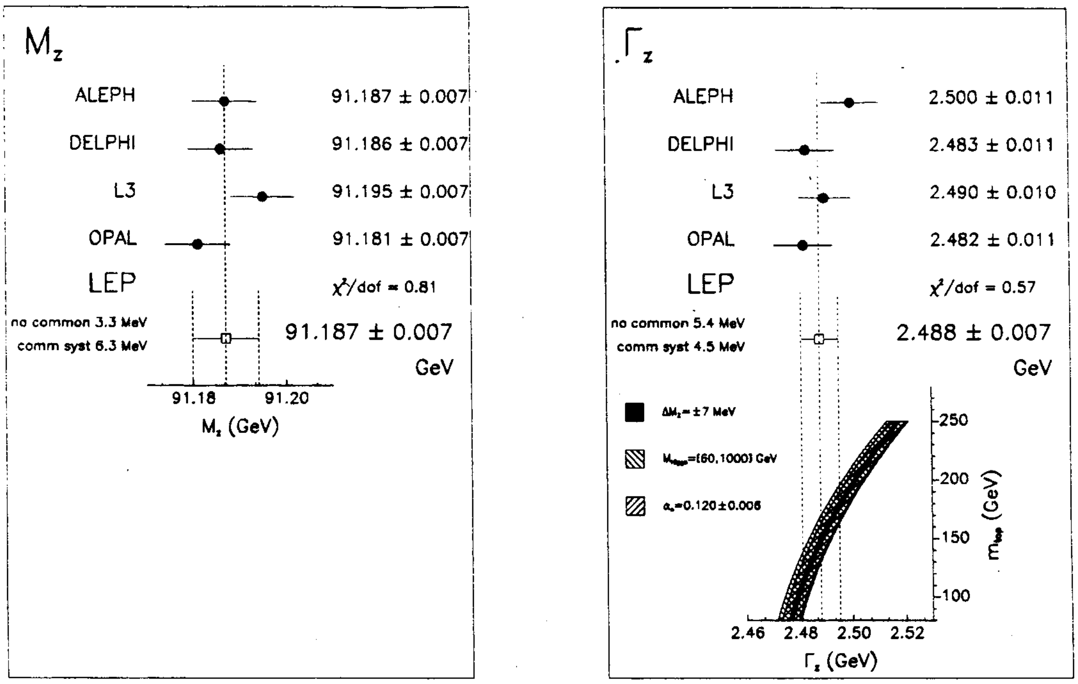

Figure 1. Fit results for $\mathrm{M_Z}$ and Γ_Z. The theoretical prediction in the Standard Model for Γ_Z is also shown as a function of $\mathrm{m_{top}}$ for the indicated ranges of $\mathrm{m_H}$ and α_s.

The cross-sections and the lepton forward-backward asymmetries were simultaneously fitted using the programs MIZA [11] and ZFITTER [12] which agree to a level well below the experimental accuracy.

Each LEP experiment provides a set of parameters and a covariance matrix for these parameters [13]. In addition, when combining the data of the four collaborations, one has to properly take into account the common uncertainties arising from the absolute LEP energy scale, from the relative energies of the different scan points and from the theoretical uncertainty in the luminosity determination.

There are nine independent parameters to be fitted: $\mathrm{M_Z}$, Γ_Z, σ^0_{had}, R_e, R_μ, R_τ, $(A^0_{FB})_e$, $(A^0_{FB})_\mu$, $(A^0_{FB})_\tau$, where R gives, for each lepton species, the ratio of the hadronic and the leptonic partial widths. These parameters are chosen because they are most directly related to the experimental quantities and are weakly correlated. The number of fitted quantities is reduced to five when lepton universality is assumed. Starting from these primary measurements one can derive important additional quantities as, for example, Γ_{inv}, Γ_{had} and Γ_{lept}. The results of the five

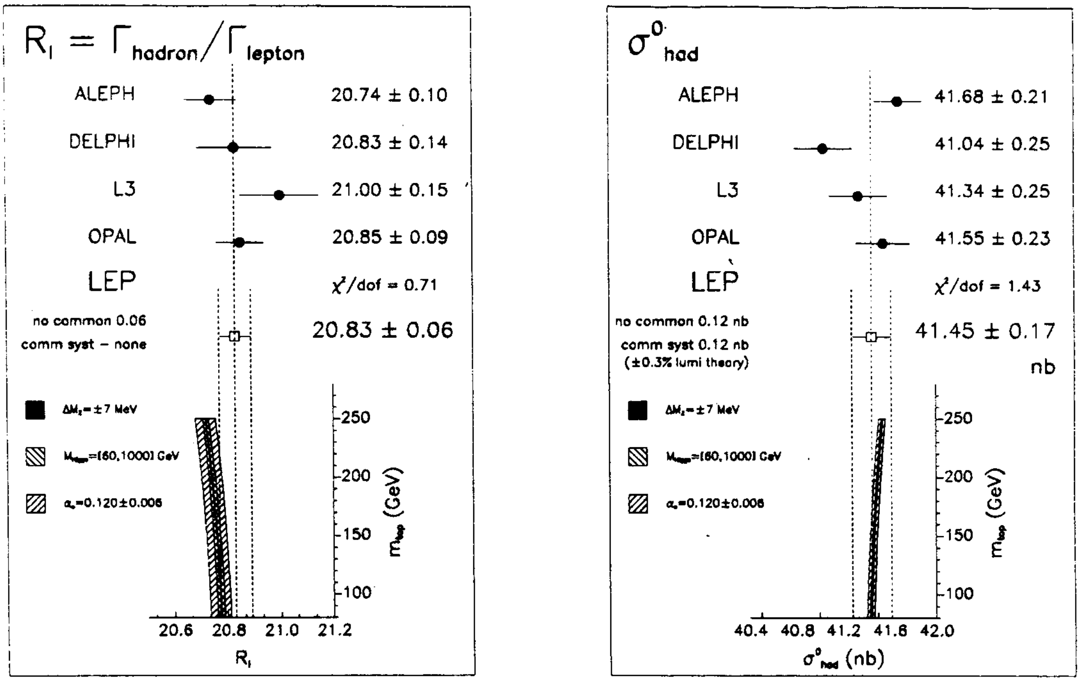

Figure 2. Fit results for the ratio between the hadronic and the leptonic partial widths (R_l) and for the hadronic peak cross-section.

parameter fit are summarised in the plots of fig.1 to 3. The resulting values of the charged lepton widths and of N_ν, the number of light neutrino species, are shown in fig.4.

All the numbers represent preliminary results based on the full data sample (i.e. including the 1992 data as well) except for L3, which only presents the final 1991 results.

It should be noted that, in these figures, the effect of the common systematics is first subtracted from the errors quoted by the individual experiments and then added again in the weighted average.

From the ratio R_l of the hadronic and the leptonic partial widths one can extract a measurement of α_s by using the equation [14]:

$$R_l = R^0(1 + 1.05\frac{\alpha_s}{\pi} + (0.9 \pm 0.1)(\frac{\alpha_s}{\pi})^2 - 13(\frac{\alpha_s}{\pi})^3) \qquad (4)$$

where $R^0 = 19.95 \pm 0.03$ [15]. One obtains $\alpha_s = 0.131 \pm 0.010$.

In september '92 ALEPH installed a new luminosity calorimeter (SICAL) characterized by a very small experimental systematic uncertainty ($\frac{\delta L}{L} \sim 0.1\%$)[16].

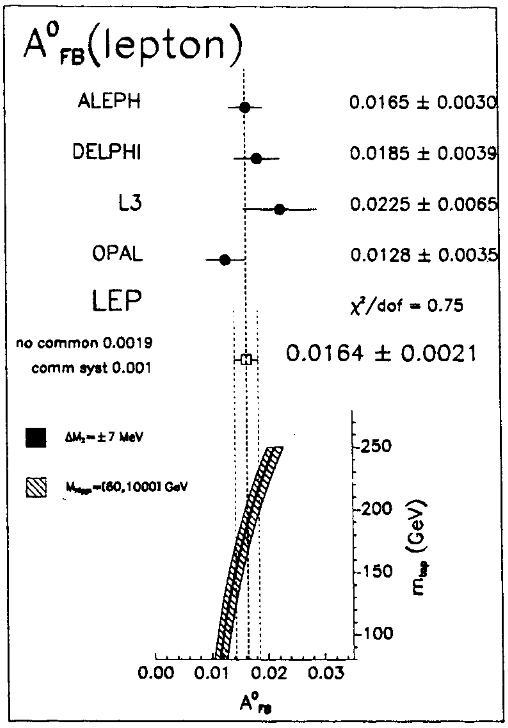

Figure 3. Fit results for the lepton forward-backward asymmetry.

For completeness, I give here the corresponding improved preliminary ALEPH results on the hadronic peak cross-section and on the number of neutrinos, even if these numbers were not included in the global fits: $\sigma^0_{had} = 41.60 \pm 0.19$ nb and $N_\nu = 2.97 \pm 0.04$. The main contributions to the error on the hadronic peak cross-section arise from the theoretical uncertainty on the luminosity and from the hadron statistics.

The average correlation coefficients in the case of the five parameter fit are given in table 2.

3 τ polarization

The τ polarization is determined by measuring the longitudinal polarization of τ pairs produced in Z decays. It is defined as [5]

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \tag{5}$$

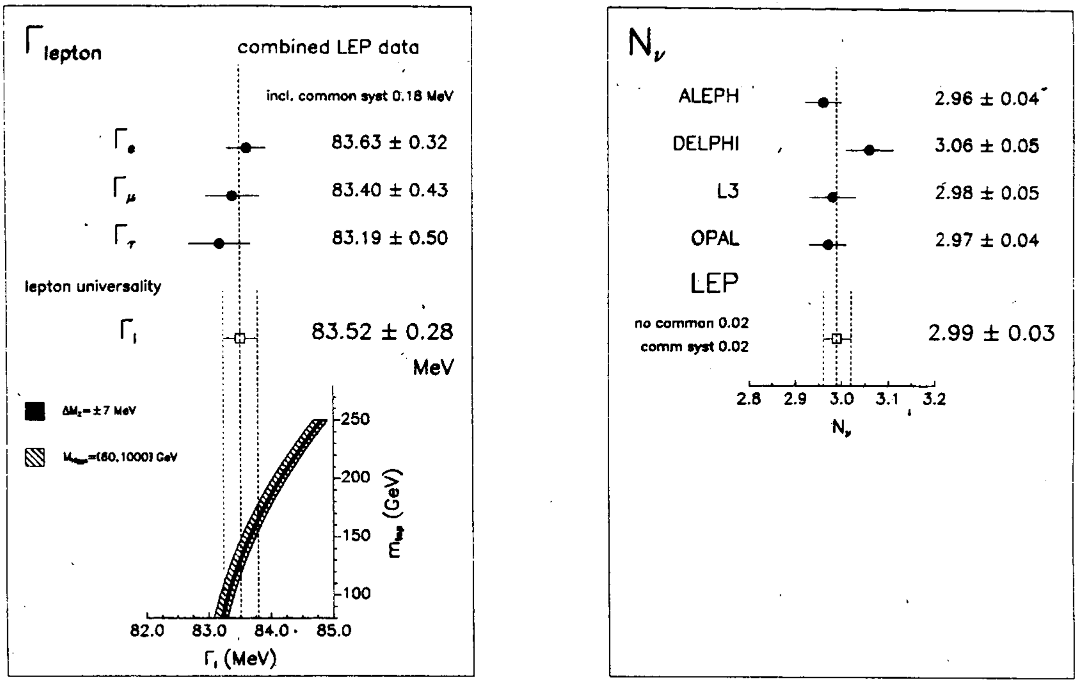

Figure 4. Fit results for the leptonic partial widths and the number of neutrino species.

where σ_R and σ_L are the cross-sections for production of a right-handed and left-handed τ, respectively.

The angular dependence of P_τ as a function of the angle θ between the e^- and the τ^- is given by:

$$P_\tau(\cos\theta) = -\frac{A_\tau + A_e \frac{2\cos\theta}{1+\cos^2\theta}}{1 + A_\tau A_e \frac{2\cos\theta}{1+\cos^2\theta}} \, . \tag{6}$$

When averaged on all production angles P_τ is a measurement of A_τ, while as a function of *cosθ*, P_τ provides nearly independent determinations of A_τ and A_e,

Table 2. Average correlation coefficients for the five parameter fit.

	M_Z	Γ_Z	σ^0_{had}	R_l	$(A^0_{FB})_l$
M_Z	1.00	-0.15	0.02	0.01	0.07
Γ_Z	-0.15	1.00	-0.14	0.01	0.01
σ^0_{had}	0.02	-0.14	1.00	0.13	0.00
R_l	0.01	0.01	0.13	1.00	0.01
$(A^0_{FB})_l$	0.07	0.01	0.00	0.01	1.00

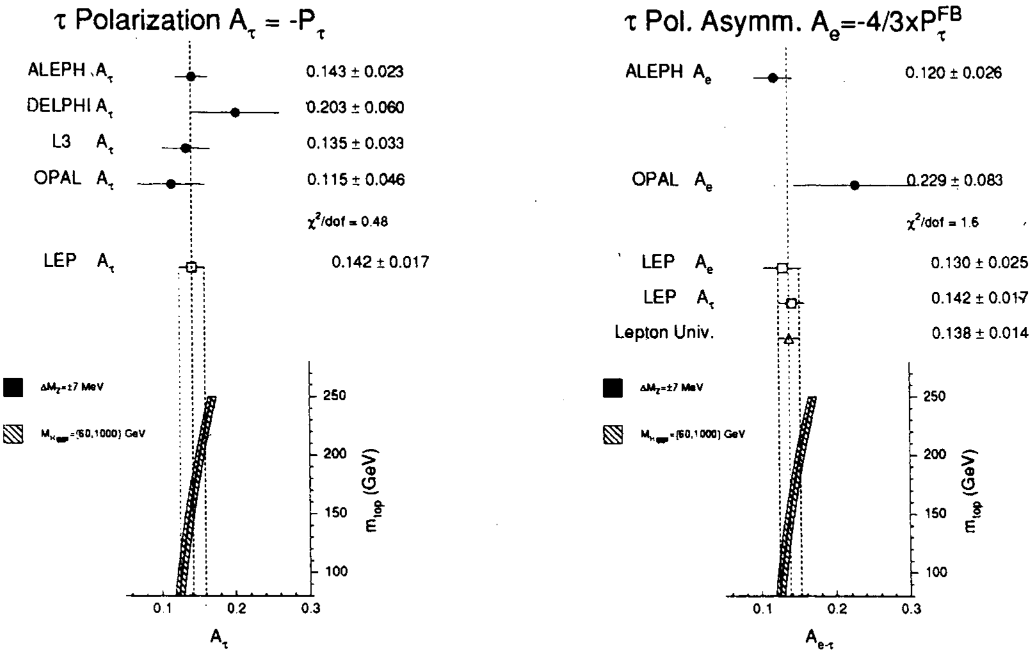

Figure 5. τ polarization and τ polarization asymmetry.

allowing thus to test universality of the couplings of the Z to e and τ. Taking small QED corrections into account, as done for the lepton forward-backward asymmetry, one can extract the bare quantities A_τ^0 and A_e^0 [6], which are directly related to the ratio of the vector and axial vector couplings for τ and e (eq.3). Figure 5 shows the results for A_τ^0 and A_e^0 obtained by the four experiments and their combination. Some of the above results have already been published in ref.[17, 18, 3, 19]. Only OPAL and ALEPH have so far provided a measurement of A_e^0.

4 Leptonic vector and axial vector couplings and lepton universality

Assuming lepton universality, the widths of the Z into leptons, the lepton forward-backward asymmetries, the τ polarization and τ polarization asymmetry can all be combined to determine the leptonic vector and axial vector couplings. The asymmetries determine the ratio g_v/g_a (eq.3), while the axial vector coupling squared is derived from the leptonic partial width :

$$\Gamma_\ell = \frac{G_F M_z^3}{6\sqrt{2}\pi} \left((g_a^\ell)^2 + (g_v^\ell)^2\right) (1 + \frac{3}{4}\frac{\alpha}{\pi}) .$$

The combined results are :

$$g_v^l = -0.0372 \pm 0.0024 \text{ and } g_a^l = -0.4999 \pm 0.0009 \ .$$

In addition, the measured ratios of the e, μ and τ couplings provide a test of universality:

$$g_a^\mu / g_a^e = 0.999 \pm 0.003 \ , \ g_a^\tau / g_a^e = 0.997 \pm 0.003 \ ,$$

$$g_v^\mu / g_v^e = 0.85^{+0.27}_{-0.22} \ , \ g_v^\tau / g_v^e = 1.04^{+0.17}_{-0.14} \ .$$

5 Quark asymmetries

The selection of Z decays into $b\bar{b}$ is based on the identification of electrons or muons with large p and p_T with respect to the parent jet direction. The b direction is defined by the thrust axis, while its charge is inferred from the lepton charge. The observed asymmetry $A_{FB}^{obs}(b\bar{b})$ is determined by fitting the angular distribution of the thrust axis weighted by the lepton charge. Due to the effect of $B^0 - \bar{B}^0$ mixing, the true asymmetry is diluted with respect to the measured one [5]:

$$A_{FB}(b\bar{b}) = A_{FB}^{obs}(b\bar{b})/(1 - 2\chi) \qquad (7)$$

where χ represents the b mixing parameter. The results on $A_{FB}(b\bar{b})$ [20, 21, 3, 22] reported by the LEP collaborations (each corrected by its own mixing) are given in figure 6. The uncertainties caused by common systematics in the measurements from the four experiments are taken into account when the results are combined [23].

In the same figure, the results obtained on the $c\bar{c}$ asymmetry [20, 3, 23] are also shown. For this last measurement, two different tagging techniques are used: one based on the semileptonic decays of charm and the other on $D^{*\pm}$ identification.

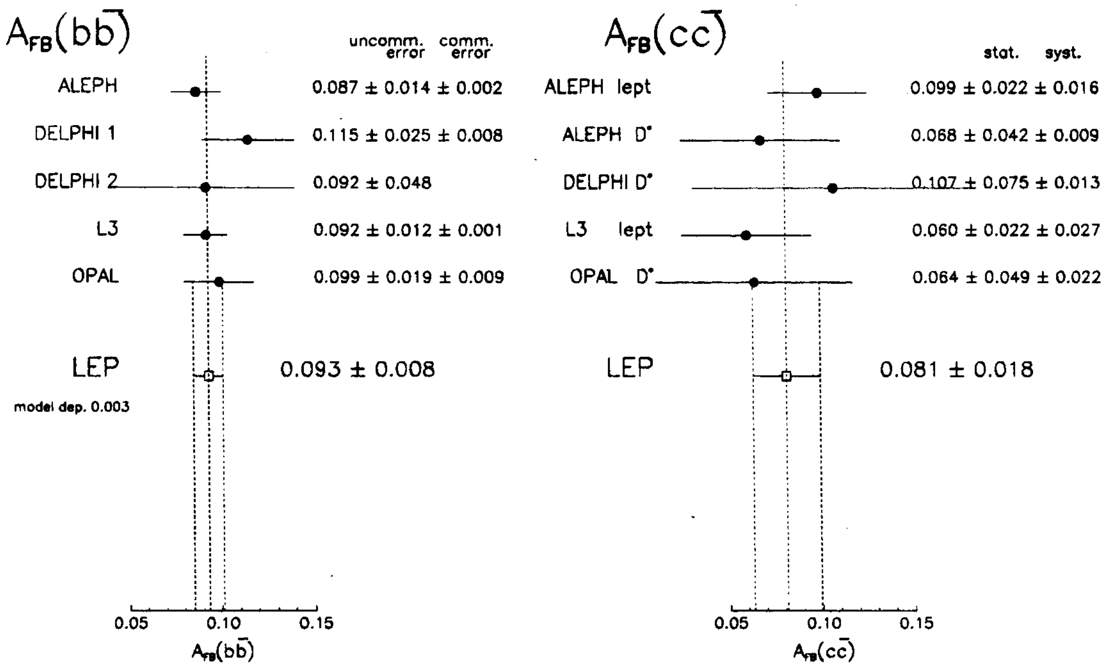

Figure 6. $A_{FB}(b\bar{b})$ and $A_{FB}(c\bar{c})$. The results named DELPHI1 and DELPHI2 refer to two measurements based on the lepton tag and on the jet charge, respectively. The first error associated to the individual measurements of $A_{FB}(b\bar{b})$ contains the statistical effects and the uncorrelated systematics while the second error represents the uncertainty which is common between at least two experiments [23].

All the results are based on the 1991 data sample alone, except for L3, that has also included the 1992 data for this analysis.

Some important QED and QCD corrections are necessary to convert the measured asymmetries shown in fig.6 to the bare ones A^0_{FB} (again see , e.g., ref.[6]). One obtains :

$$\begin{aligned} A^0_{FB}(b\bar{b}) &= 0.098 \pm 0.009 \\ A^0_{FB}(c\bar{c}) &= 0.090 \pm 0.019 \end{aligned}$$

In addition, one can take advantage of the large hadron statistics in order to measure the average quark charge asymmetry for all hadronic events. To infer the original quark charge, one relies on the fact that the leading particles in a jet carry information on its primary charge. The interpretation necessary in order to go from

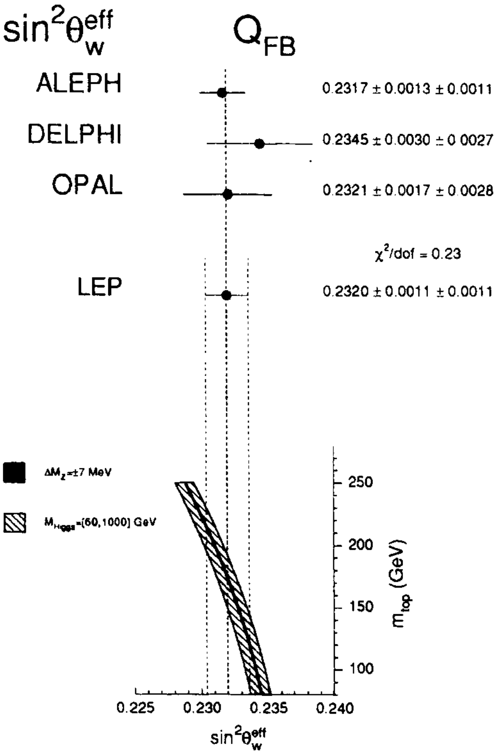

Figure 7. Measurement of $\sin^2\theta_W^{eff}$ based on quark charge asymmetry.

the experimental observation to the underlying charge asymmetry heavily relies on Monte Carlo simulation. The measurement of the quark asymmetry directly translates in a value for $\sin^2\theta_W^{eff}$. The corresponding results are shown in figure 7 [24, 25, 26]. Only ALEPH has reported a preliminary measurement which also includes the 1992 data.

6 The effective electroweak mixing parameter $\sin^2\theta_W^{eff}$

The effective electroweak mixing parameter $\sin^2\theta_W^{eff}$ is defined from the expression [5]:

$$\frac{g_v^\ell}{g_a^\ell} = 1 - 4\sin^2\theta_W^{eff} \tag{8}$$

and, in the Standard Model, can be extracted from the combined LEP measurements for the various asymmetries. The results of the determinations of $\sin^2\theta_W^{eff}$ are shown in figure 8.

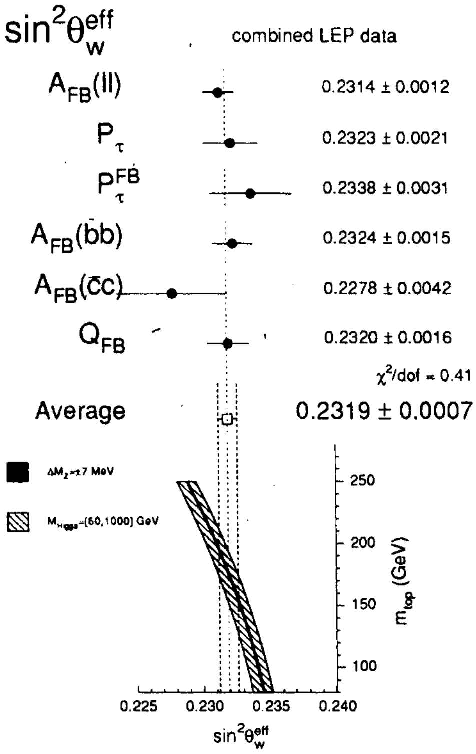

Figure 8. Comparison among different determinations of $\sin^2\theta_W^{eff}$.

7 The b partial width

In the final Standard Model fit I will also include the results on the ratio R_{bh} of the b and the hadronic partial widths [27, 23]. The measurement of the b partial width is particularly important due to the additional quadratic m_{top} dependence present in the $Z \to b\bar{b}$ vertex [5]. The results are shown in figure 9. The ALEPH result includes a preliminary measurement at the 2% level based on the 1992 data, which makes use of a lifetime tagging technique.

The average preliminary LEP value $\Gamma_{b\bar{b}}/\Gamma_{had} = 0.220 \pm 0.003$ is slightly higher than the Standard Model prediction ($\sim 1\sigma$ above the Standard Model for $m_{top} >$ 120 GeV), as shown in fig.9. Note that the theoretical prediction is practically independent on m_H and nearly insensitive to α_s ($R_{bh} = R_0(1 + 0.15\alpha_s/\pi)$ [14].

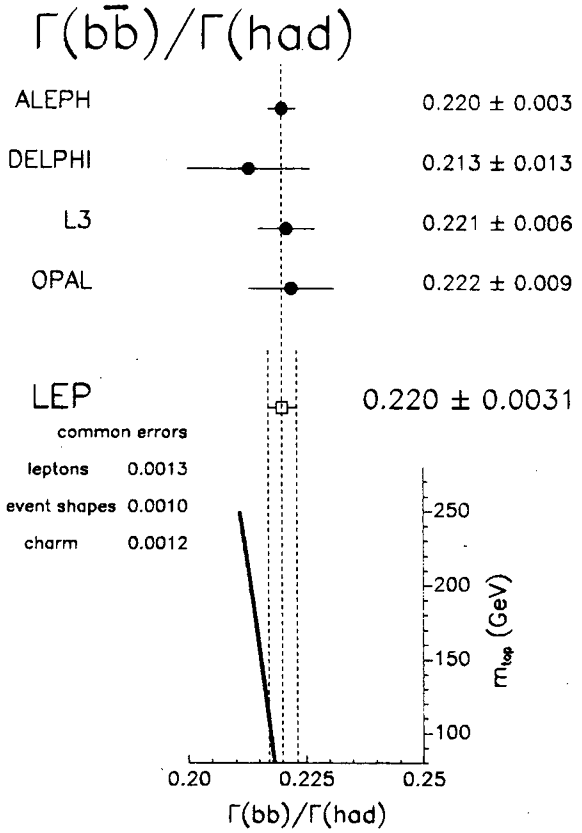

Figure 9. Ratio of b and hadronic partial widths. The theoretical prediction in the Standard Model is also shown.

8 Standard Model fits

All the results described in the previous sections (listed in table 3) can be compared with the Standard Model predictions. For this purpose we use the electroweak fitting routines of ref.[15].

Once the consistency of the data with the Standard Model has been demonstrated, the main goal is to extract information on the unknown parameters of the theory, in particular on m_{top}.

We first consider fits with $\alpha_s(\mathrm{M_Z^2})$ fixed at the value measured at LEP from hadronic event shape, jet production and energy correlation observables using resummed $O(\alpha_s^2)$ QCD calculations i.e. $\alpha_s(\mathrm{M_Z^2}) = 0.123 \pm 0.006$ [28]. Since the sensitivity to the Higgs mass is rather limited, we fit m_{top} at fixed values of m_H chosen as $m_H = 60, 300, 1000$ GeV.

We first take only the LEP data into account, i.e. we fit Γ_Z, σ^0_{had}, R_l, $(A^0_{FB})_l$,

Table 3. Electroweak results for the 1993 winter conferences.
The entry denoted by Q_{FB} is actually the corresponding value of $\sin^2\theta_W^{eff}$.
The resulting combined values of $\sin^2\theta_W^{eff}$, g_v^l and g_a^l are also indicated.

	S.M. fit results
M_Z (GeV)	91.187 ± 0.007
Γ_Z (GeV)	2.488 ± 0.007
σ^0_{had} nb	41.45 ± 0.17
R_l	20.83 ± 0.06
$\Gamma_{b\bar{b}}/\Gamma_{had}$	0.220 ± 0.003
N_ν	2.99 ± 0.03
Γ_l (MeV)	83.52 ± 0.28
Γ_{had} (MeV)	1739.9 ± 6.3
$(A^0_{FB})_l$	0.0164 ± 0.0021
A^0_τ	0.142 ± 0.017
A^0_e	0.130 ± 0.025
$A^0_{FB}(b\bar{b})$	0.098 ± 0.009
$A^0_{FB}(c\bar{c})$	0.090 ± 0.019
Q_{FB}	0.2320 ± 0.0016
$\sin^2\theta_W^{eff}$	0.2319 ± 0.0007
g_v^l	-0.0372 ± 0.0024
g_a^l	-0.4999 ± 0.0009

A^0_τ, A^0_e, $A^0_{FB}(b\bar{b})$, $A^0_{FB}(c\bar{c})$, $\Gamma_{b\bar{b}}/\Gamma_{had}$ with the correlation matrix given in table 2, we obtain the following results (assuming $\alpha_s(M_Z^2) = 0.123 \pm 0.006$):

$$\begin{array}{lll} m_{top} = 143^{+20}_{-23}\,\text{GeV} & m_H = 60\,\text{GeV} & \chi^2/d.o.f. = 3.4/8 \\ m_{top} = 164^{+19}_{-21}\,\text{GeV} & m_H = 300\,\text{GeV} & \chi^2/d.o.f. = 4.8/8 \\ m_{top} = 182^{+18}_{-19}\,\text{GeV} & m_H = 1000\,\text{GeV} & \chi^2/d.o.f. = 5.9/8\,. \end{array}$$

We also derive an indirect determination of the W mass:

$$M_W = 80.23 \pm 0.12 \pm 0.02\text{GeV}.$$

If instead we perform a fit with $\alpha_s(M_Z^2)$ unconstrained, again for $m_H = 60, 300, 1000$ GeV respectively, we obtain:

$$
\begin{array}{lll}
m_{top} = 143^{+20}_{-23}\,\mathrm{GeV} & \alpha_s(M_Z^2) = 0.125 \pm 0.007 & \chi^2/d.o.f. = 3.4/7 \\
m_{top} = 163^{+19}_{-21}\,\mathrm{GeV} & \alpha_s(M_Z^2) = 0.127 \pm 0.007 & \chi^2/d.o.f. = 4.6/7 \\
m_{top} = 181^{+18}_{-20}\,\mathrm{GeV} & \alpha_s(M_Z^2) = 0.129 \pm 0.007 & \chi^2/d.o.f. = 5.5/7\,.
\end{array}
$$

We note the following salient features:

- The central value of m_{top} increases with m_H
- The χ^2 favours smaller values of m_H but not in a way that allows us to put a significant bound on the Higgs mass in the interesting region below 1 TeV
- The central values of m_{top} in the fit with unconstrained α_s are practically identical to the ones obtained in the α_s constrained fit. Also the values of α_s from the two types of fit are entirely compatible within errors.
- It is also interesting to note that the central value of α_s obtained from the whole set of LEP data is slightly smaller than the one derived from R_l alone using equation 4.

We can also repeat the same procedure by adding precision electroweak data obtained outside LEP. In the following fits we thus introduce the input data listed below:

- the mass ratio M_W/M_Z directly measured by UA2 [29] $M_W/M_Z = 0.8813 \pm 0.0041$
- the W mass measured at CDF [30] $M_W = 79.91 \pm 0.39$ GeV
- the value of $\sin^2\theta_W \equiv 1 - {M_W}^2/{M_Z}^2 = 0.2256 \pm 0.0047$ extracted, assuming the S.M., from $\nu - nucleus$ [31] deep inelastic scattering
- the values of g_a^e and g_v^e obtained from $\nu - e$ [32] scattering $g_a^e = -0.503 \pm 0.018$ and $g_v^e = -0.025 \pm 0.019$

- the effective weak coupling Q_w obtained from atomic parity violation experiments in Cesium [33] $Q_w = -71.04 \pm 1.81$
- A_{LR} measured with a polarized beam by SLD al SLAC, $A_{LR} = 0.100 \pm 0.044 \pm 0.004$ which translates into $\sin^2\theta_W = 0.2378 \pm 0.0056 \pm 0.0005$ [34].

Also in this case we first perform a fit fixing $\alpha_s(\mathrm{M_Z^2})$ to the event shapes value (for $m_H = 60, 300, 1000$ GeV, respectively) obtaining:

$$\begin{array}{ll} m_{top} = 141^{+17}_{-19}\ \mathrm{GeV} & \chi^2/d.o.f. = 7.3/15 \\ m_{top} = 160^{+16}_{-17}\ \mathrm{GeV} & \chi^2/d.o.f. = 8.7/15 \\ m_{top} = 178^{+15}_{-16}\ \mathrm{GeV} & \chi^2/d.o.f. = 9.9/15\ . \end{array}$$

with $M_W = 80.21 \pm 0.10 \pm 0.01$ GeV.

If we finally fit $\alpha_s(\mathrm{M_Z^2})$ as well we get:

$$\begin{array}{lll} m_{top} = 140^{+17}_{-19}\ \mathrm{GeV} & \alpha_s(\mathrm{M_Z^2}) = 0.125 \pm 0.007 & \chi^2/d.o.f. = 7.2/14\quad . \\ m_{top} = 160^{+16}_{-18}\ \mathrm{GeV} & \alpha_s(\mathrm{M_Z^2}) = 0.127 \pm 0.007 & \chi^2/d.o.f. = 8.5/14 \\ m_{top} = 177^{+16}_{-17}\ \mathrm{GeV} & \alpha_s(\mathrm{M_Z^2}) = 0.129 \pm 0.007 & \chi^2/d.o.f. = 9.4/14 \end{array}$$

As one can see, the LEP data by now dominate the determination of m_{top}.

Table 4. Results of the S.M. fit to top mass and α_s for $m_H = 300$ GeV. The first error is statistical, the second is due to the variation of m_H between 60 and 1000 GeV.

Data Set	m_{top}(GeV)	α_s	$\chi^2/d.o.f.$
LEP	164^{+19+18}_{-21-20}	constrained	4.8/8
ALL	160^{+16+18}_{-17-20}	constrained	8.7/15
LEP	163^{+19+18}_{-21-20}	$0.127 \pm 0.007 \pm 0.002$	4.6/7
ALL	160^{+16+18}_{-18-19}	$0.127 \pm 0.007 \pm 0.002$	8.5/14

All the Standard Model fit results are shown in a compact way in table 4 where the central value corresponds to $m_H = 300$ GeV and the variation between $m_H = 60$ and $m_H = 1000$ GeV is displayed as the second error.

9 Conclusions

At present, with the LEP1 phase being about half way in terms of number of collected Z^0 decays, the data continue to support the Standard Model in a remarkable way. An increasingly precise set of different measurements indicate consistent ranges of m_{top}. To summarize the results for m_{top} we can quote the value $m_{top} = 160^{+16+18}_{-18-19}$ GeV, taken from the last row of table 4. The upper limit on m_{top} which occurs for $m_H = 1000$ GeV is $m_{top} < 203$ GeV at 95% C.L.. The data also yield a lower limit on m_{top} , i.e. $m_{top} > 109$ GeV at 95% C.L. for $m_H = 60$ GeV. No significant constraint on m_H can be given until m_{top} is known independently.

10 Acknowledgements

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