

# Z LINESHAPE AND FORWARD-BACKWARD ASYMMETRIES

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Preliminary but close to final results on the Z Lineshape and Forward-Backward asymmetries from the four LEP experiments are presented. Combined values extracted from ALEPH, DELPHI, L3 and OPAL data recorded at energies around the Z pole are discussed.

## 1 Introduction

Preliminary results of the four LEP experiments<sup>1</sup>, including the whole data set recorded around the Z pole from 1990 to 1995, are presented here. Emphasis will be given to changes since the last report presented at Winter Conferences and experimental systematic errors evaluation. The discussion of the results as a test of the Standard Model can be found in another talk of this session<sup>2</sup>.

## 2 Lineshape parameters

The parametrisation of the dominant contribution to the cross section at energies around the Z resonance is based on a Breit-Wigner shape with an s-dependent width. After deconvolution of pure QED corrections, this is given in the “improved Born approximation” by

$$\sigma_{\text{ff}}(s) = \sigma_{\text{ff}}^0 \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2}, \quad (1)$$

where the parameters are the Z mass,  $M_Z$ , the width,  $\Gamma_Z$ , and the pole cross section,  $\sigma_{\text{ff}}^0$ . The contributions from  $\gamma$  exchange and from  $\gamma$ -Z interference are small at energies  $\sqrt{s} = M_Z$  and are set to their Standard Model values.

The pole cross section can be written in terms of partial decay widths of the initial and final states,  $\Gamma_{ee}$  and  $\Gamma_{\text{ff}}$ ,

$$\sigma_{\text{ff}}^0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_{ee}\Gamma_{\text{ff}}}{\Gamma_Z^2}. \quad (2)$$

The definition of the widths explicitly includes QED and QCD corrections,

$$\Gamma_{\text{ff}} = \frac{G_F M_Z^3}{6\pi\sqrt{2}} N_c^f (g_{V_f}^2 + g_{A_f}^2) (1 + \delta_{QED} + \delta_{QCD}); \quad (3)$$

$g_{V_f}$  and  $g_{A_f}$  are effective vector and axial vector couplings of the Z to fermion species f, and  $N_c^f$ , the QCD colour factor, is one for leptonic final states and three for hadrons. Due to the effect of radiative corrections, these effective couplings are complex numbers. As the pole cross sections,  $\sigma_{\text{ff}}^0$ , have in common the statistical and systematic error from the luminosity determination,

it is more practical to use the ratios of pole cross sections in the parametrisation of the leptonic channels,

$$R_f = \frac{\sigma_{\text{had}}^0}{\sigma_{\text{ff}}^0} \equiv \frac{\Gamma_{\text{had}}}{\Gamma_{\text{ff}}} \quad \text{for } \text{ff} = e^+e^-, \mu^+\mu^-, \tau^+\tau^-. \quad (4)$$

The energy dependence of the leptonic Forward-Backward asymmetry depends on the axial coupling which is mainly determined by the leptonic width. Therefore, the measurements of the leptonic Forward-Backward asymmetries can be condensed into one single parameter per lepton species in the final state, the pole asymmetry  $A_{\text{FB}}^{0,f}$ . This is given by the following combinations of effective couplings

$$A_{\text{FB}}^{0,f} \equiv \frac{3}{4} \mathcal{A}_e \mathcal{A}_f \quad (5)$$

with:

$$\mathcal{A}_f \equiv \frac{2g_{V_f}g_{A_f}}{g_{V_f}^2 + g_{A_f}^2}. \quad (6)$$

The contributions from  $\gamma$ -Z interference, imaginary parts of the photon vacuum polarisation, and the imaginary parts of the effective couplings are set to their Standard Model expectations and not included in the definition of  $A_{\text{FB}}^{0,f}$ .

## 3 The fit procedure

Each experiment provides a set of nine parameters ( $M_Z$ ,  $\Gamma_Z$ ,  $\sigma_{\text{had}}^0$ ,  $R_e$ ,  $R_\mu$ ,  $R_\tau$ ,  $A_{\text{FB}}^{0,e}$ ,  $A_{\text{FB}}^{0,\mu}$ ,  $A_{\text{FB}}^{0,\tau}$ ) fitted to the whole set of cross sections and Forward-Backward lepton asymmetries accumulated by the four LEP experiments during the LEP 1 period. This is done with the latest versions of the computer codes MIZA<sup>3</sup> and ZFITTER<sup>4,5</sup>. These codes provide parametrisations of the fermion pair production cross sections and Forward-Backward asymmetries at energies around the Z resonance in terms of effective couplings and also calculate pure QED corrections to full  $\mathcal{O}(\alpha^2)$  with exponentiation of the soft part or with leading  $\mathcal{O}(\alpha^3)$ .

The measured cross sections and Forward-Backward asymmetries are treated in a  $\chi^2$  minimisation procedure

Table 1: Typical correlation matrix for a five parameter fit.

	$M_Z$	$\Gamma_Z$	$\sigma_{\text{had}}^o$	$R_\ell$	$A_{\text{FB}}^{0,\ell}$
$M_Z$	1.	0.05	-0.01	-0.02	0.06
$\Gamma_Z$		1.	-0.16	0.00	0.00
$\sigma_{\text{had}}^o$			1.	0.14	0.00
$R_\ell$				1.	0.01
$A_{\text{FB}}^{0,\ell}$					1.

to extract the nine parameters and their errors and correlations. The full error matrix of the input measurement is constructed. The covariance matrix includes the statistical and systematic errors as well as their correlations.

Under the assumption of lepton universality, the nine parameters set reduces to a five parameters one ( $M_Z$ ,  $\Gamma_Z$ ,  $\sigma_{\text{had}}^o$ ,  $R_\ell$ ,  $A_{\text{FB}}^{0,\ell}$ ). The chosen parameters are almost uncorrelated and thus well adapted to fitting and averaging procedures. Table 1 gives a typical correlation matrix.

The only relevant correlations are between ( $\Gamma_Z$  and  $\sigma_{\text{had}}^o$ ) and ( $R_\ell$  and  $\sigma_{\text{had}}^o$ ). They contain the sensitivity to the Standard Model parameters  $M_H$  and  $\alpha_s$ .

#### 4 Statistics analysed

Analyses have been performed on data sets recorded from 1990 to 1995. Several energy scans were archived, first in 1990 and 1991 within  $\pm 3\text{GeV}$  of  $\sqrt{s} = M_Z$  value, then again in 1993 and 1995 (within  $\pm 2\text{GeV}$ ), while 1992 and 1994 were devoted to peak energy only. In total the four LEP experiments accumulated 4 times 4 Millions of Z decays, corresponding to an integrated Luminosity of  $120\text{ pb}^{-1}$  at the peak energy and  $40\text{ pb}^{-1}$  off peak. The statistical error on  $\sigma_{\text{had}}^o$  is therefore about 0.05% per experiment and about 0.15% per experiment for leptonic cross-sections. As no more running at the Z peak energy is foreseen before the end of LEP era, the results presented here contain the final word on statistical errors. The details of the improvements achieved in the experimental systematic errors will be discussed in the next sections.

#### 5 Experimental errors

Each experiment provides a set of nine (five) parameters values and the corresponding covariance matrix where common systematic error sources are clearly identified. Their origine is of two types: first, uncertainties in the theoretical calculations, dominated by the uncertainty on the small angle Bhabha cross section and the  $t$ -channel contribution to the wide angle Bhabhas, second, a common experimental error from the LEP beam energy uncertainties. All will be discussed below in the appropriate

Table 2:  $M_Z$  value per experiment and combined result in MeV.

ALEPH	$91188.4 \pm 3.1$
DELPHI	$91186.6 \pm 2.9$
L3	$91188.3 \pm 2.9$
OPAL	$91184.8 \pm 3.0$
LEP	$91186.7 \pm 2.1$

sections.

Most of the correlations are specified via detailed correlation matrices constructed from the specific interdependencies of the various error contributions. Particular care is given to the evaluation of the correlated and uncorrelated contribution of each source between data sets of different years as well as data sets of the same year recorded at different center of mass energies.

#### 6 $M_Z$

The very precise relative error obtained for  $M_Z$  (about  $2.10^{-5}$ ) has been achieved after the impressive work of the LEP Energy Calibration group<sup>6</sup>. Starting with a 45 MeV error from a simple on-line Field Display in 1989, the breakthrough was obtained in 1991 with the use of the depolarization resonance method to calibrate the beam energy. Later this technique was applied at several energy points and other internal (Radio Frequency corrections) and external sources causing geometrical deformations of the LEP ring (terrestrial tides) were corrected for in 1992, leading to a 7 MeV uncertainty. Today the ultimate precision on the beam energy achieved is 1.5 MeV. A correlation matrix has been carefully built describing the contributions of the different terms between years and energy points of the same year. The mass measurement is directly affected by the uncertainty of the absolute energy scale, i.e., uncertainties correlated between energy points. The combined result from the LEP experiments is given in Table 2.

#### 7 $\Gamma_Z$

The Z width uncertainty is affected only by the error on the difference in energy between energy points (1.3 MeV), and not by the error on the absolute energy scale. An additional 0.2 MeV comes from the energy spread around the mean value. The combined result from the LEP experiments is given here and is shown in Figure 1, the overall relative precision achieved is 0.1%

$$\Gamma_Z = (2.4939 \pm 0.0019 \pm 0.015 (LEP))\text{GeV}/c^2. \quad (7)$$

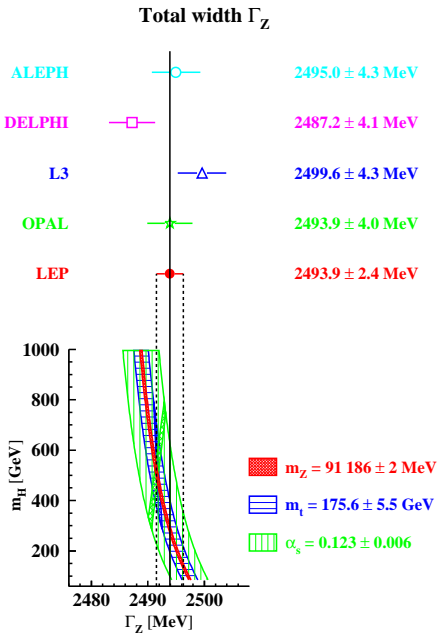


Figure 1:  $\Gamma_Z$  value for each LEP experiment and combined result.

## 8 $\sigma_{\text{had}}^o$

The main source of uncertainty comes here from the Luminosity error. All four experiments have decreased their experimental error at the 0.1% level. The common theoretical error amounts to 0.11%. There are some hints of a further decrease in its evaluation<sup>7</sup>. One should note that an increased (with respect to reports at Winter Conferences) overall systematic error is quoted due to the theoretical uncertainty (0.021 nb) on the third order terms introduced in the lineshape description. The combined result from the LEP experiments is shown in Figure 2.

## 9 $R_\ell$

The errors on  $R_e$ ,  $R_\mu$  and  $R_\tau$  do not depend on luminosity but on the knowledge of relative acceptance and selection efficiencies. They are entirely dominated by the total error on the lepton cross sections, with very small correlations of about 5% from the common normalisation to the number of hadrons. Substantial improvements have been achieved by ALEPH and OPAL who decreased the systematics uncertainty on  $R_\ell$  by almost a factor 2. Aleph has developed a new global lepton analysis which reduces the uncertainty on the flavour separation and is in very good agreement with the classical exclusive analysis. Therefore both analyses have been combined. Particular care has been given to the  $t$ -channel subtraction, using the prescription from the authors of ALIBABA<sup>8</sup>. The

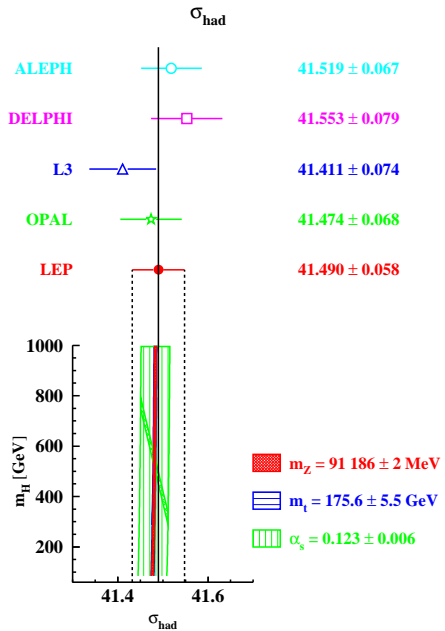


Figure 2: Pole hadronic cross-section value for each LEP experiment and combined result.

Table 3:  $R_\ell$  ratio value for each experiment and each lepton specie.

	$R_e$	$R_\mu$	$R_\tau$
ALEPH	$20.69 \pm 0.07$	$20.81 \pm 0.06$	$20.72 \pm 0.06$
DELPHI	$20.87 \pm 0.12$	$20.67 \pm 0.08$	$20.78 \pm 0.12$
L3	$20.78 \pm 0.11$	$20.84 \pm 0.10$	$20.75 \pm 0.14$
OPAL	$20.92 \pm 0.09$	$20.82 \pm 0.06$	$20.85 \pm 0.09$
LEP	$20.78 \pm 0.05$	$20.79 \pm 0.03$	$20.76 \pm 0.05$

combined result from the LEP experiments assuming lepton universality is shown in Figure 3. The splitting into individual lepton species is given in Table 3

## 10 $A_{\text{FB}}^{0,\ell}$

The differential cross section for the reaction  $e^+e^- \rightarrow \ell^+\ell^-$  is expected to have an approximate quadratic dependence on the cosine of the polar angle:

$$\frac{d\sigma}{d\cos\theta} \propto \left( 1 + \cos^2\theta^* + \frac{8}{3}A_{\text{FB}}\cos\theta \right), \quad (8)$$

where  $\theta$  is the angle between the incoming electron and the outgoing negative lepton. The LEP experiments have finalized the lepton asymmetry analyses including periods in 1993,1994 and 1995 where precise LEP energy calibration was not available but data could be used however for asymmetry measurements. In the case of muons and taus, the selection has been designed to minimize any

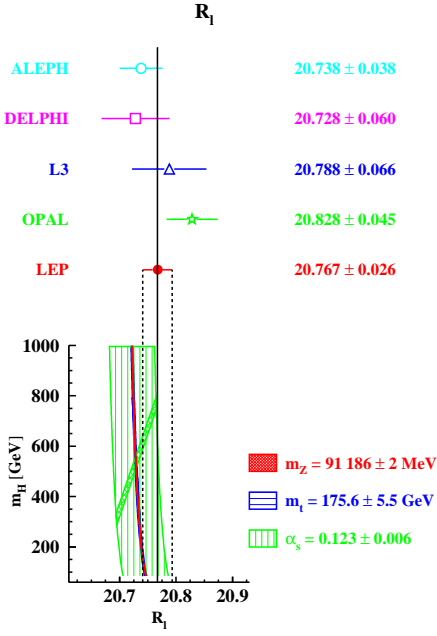


Figure 3:  $R_\ell$  ratio value for each LEP experiment and combined result, assuming lepton universality.

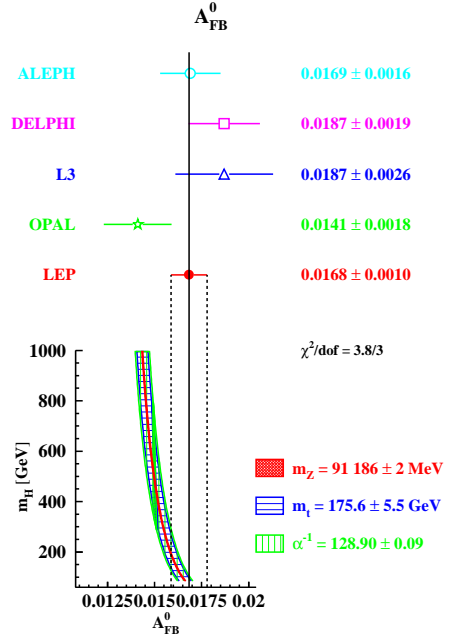


Figure 4:  $A_{\text{FB}}^{0, \ell}$  value assuming lepton universality, for each LEP experiment and combined result.

Table 4:  $A_{\text{FB}}^{0, \ell}$  value for each experiment and each lepton specie.

Unit is $10^{-4}$	$A_{\text{FB}}^{0, e}$	$A_{\text{FB}}^{0, \mu}$	$A_{\text{FB}}^{0, \tau}$
ALEPH	$181. \pm 33.$	$170. \pm 25.$	$166. \pm 28.$
DELPHI	$189. \pm 48.$	$160. \pm 25.$	$244. \pm 37.$
L3	$148. \pm 63.$	$176. \pm 35.$	$233. \pm 49.$
OPAL	$70. \pm 51.$	$156. \pm 25.$	$143. \pm 30.$
LEP	$153. \pm 25.$	$164. \pm 13.$	$183. \pm 17.$

final state invariant mass dependence as an acolinearity cut between the two final leptons is equivalent to an invariant mass dependent cut. For the electron final state, the final error is dominated by the uncertainty on the  $t$ -channel subtraction. The error correlation between the  $R_\ell$  and the  $A_{\text{FB}}^{0, \ell}$  parameters is also taken into account. The combined result from the LEP experiments is shown in Figure 4, assuming lepton universality. The splitting into individual lepton species is given in Table 4.

Figure 5 shows for each lepton species and for the combination assuming lepton universality, the resulting 68% probability contours in the  $(R_\ell, A_{\text{FB}}^{0, \ell})$  plane.

## 11 Derived quantities

The partial decay widths into hadrons and leptons can be obtained by parameter transformation from the original nine and five parameters. Since the total Z width is

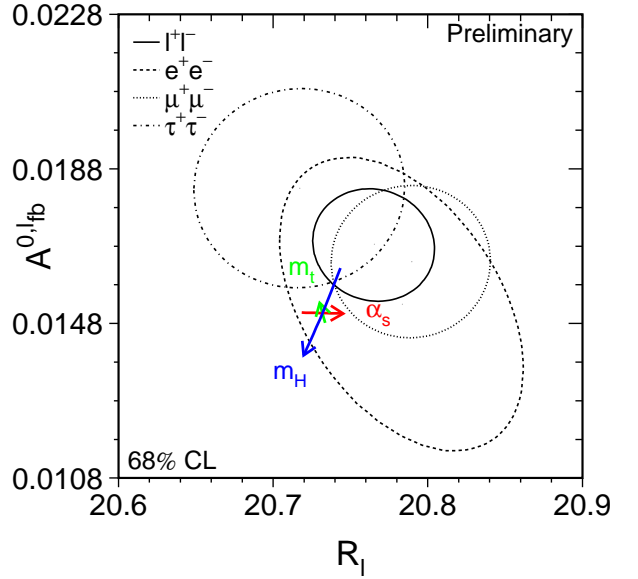


Figure 5: 68% probability contours in the  $(R_\ell, A_{\text{FB}}^{0, \ell})$  plane with and without the assumption of lepton universality. The SM prediction shown by the arrows was computed for  $M_t = 173.8 \pm 5.0 \text{ GeV}$ ,  $90 \text{ GeV} < M_H < 1000 \text{ GeV}$  and  $\alpha_s(M_Z^2) = 0.119 \pm 0.002$ .

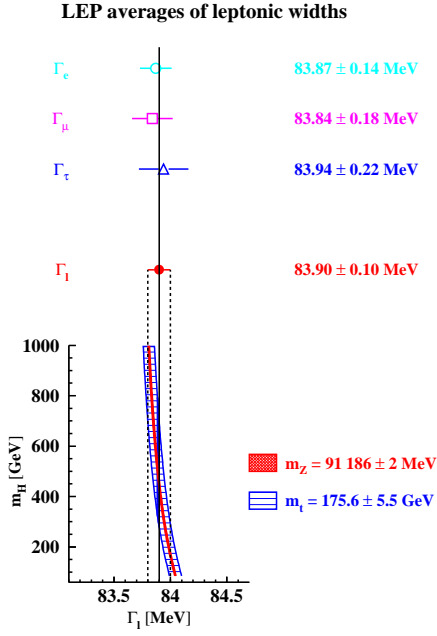


Figure 6: Partial leptonic width values from combined LEP experiments.

the sum of all partial widths, the decay width into invisible particles,  $\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - \Gamma_{\ell\ell} (3 + \delta_m)$ , can also be determined; here,  $\delta_m = -0.0023$  is a small correction which accounts for the  $\tau$  mass effect. The results are summarised in Figure 6. The comparison of the partial decay widths of the Z into  $e$ ,  $\mu$  and  $\tau$  shows good consistency with lepton universality. To check whether the invisible width is completely explained by decays into the three neutrino species, the “number of neutrinos”,  $N_\nu$  can be calculated according to

$$\frac{\Gamma_{\text{inv}}}{\Gamma_{\ell\ell}} = N_\nu \left( \frac{\Gamma_\nu}{\Gamma_{\ell\ell}} \right)_{SM}. \quad (9)$$

The Standard Model value for the ratio of the partial widths to neutrinos and to charged leptons is  $1.991 \pm 0.001$ , where the uncertainty arises from variations of the top quark mass within  $M_t = 174 \pm 5 \text{ GeV}$  and of the Higgs mass within  $70 \text{ GeV} < M_H < 1000 \text{ GeV}$ . The number of neutrinos from all experiments are shown in Table 5.

## 12 Conclusion

The four LEP experiments have provided very precise measurements of the lineshape parameters and Forward-Backward asymmetries. Many results are still preliminary but will become final soon. They will provide, together with results from SLD and NUTEV experiments

Table 5: Number of light neutrino species determined by each experiment and combined result.

ALEPH	$2.993 \pm 0.015$
DELPHI	$2.988 \pm 0.018$
L3	$3.005 \pm 0.018$
OPAL	$2.988 \pm 0.015$
LEP	$2.994 \pm 0.011$

further constraints on the Standard Model.

## Acknowledgements

The averaging of the results was done inside the four-LEP experiments electroweak group. The impressive achievement of the LEP energy calibration group is also to be acknowledged. Therefore it is a pleasure to thank all my colleagues from the two groups who helped me in preparing this talk.

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