Z^0 LINESHAPE RESULTS FROM LEP-1993

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Abstract

In 1993 LEP performed a scan at three energy points around the Z^0 mass, with the primary aim of substantially improving the errors on M_Z and Γ_z. The results of the preliminary lineshape analyses of the 4 LEP experiments are presented here, together with the combined LEP averages. The Z^0 mass and width are determined as $M_Z = 91.1899 \pm 0.0017_{exp} \pm 0.004_{lep}$ Gev and $\Gamma_z = 2.4971 \pm 0.0027_{exp} \pm 0.0027_{lep}$ Gev. Improvements in R_{had} and σ^{had}_{pole}, and a Standard Model fit for m_t are also presented. Finally the data are analysed in terms of R_{inv} and ϵ_3 which do not depend strongly on m_t and m_H. These show no evidence for any significant deviations.

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	OPAL	ALEPH	L3	DELPHI
Acceptance +efficiency	99.5%	99.1%	99.2%	94.7%
Systematic error '92	0.2%	0.14%	0.15%	0.13%
Systematic error '93 prelim	0.24%	0.1%	0.25%	0.13%
Non-Res Background	$10 \pm 6pb^{-1}$	$71 \pm 12pb^{-1}$	$35 \pm 15pb^{-1}$	$14 \pm 4pb^{-1}$

Table 1: For the hadronic data selection of each of the LEP experiments: (i) the overall acceptance+efficiency (ii) the total systematic error and (iii) the non resonant background contribution

1 Introduction

The primary aim of the 1993 LEP running was to substantially improve the errors on the determination of the fundamental Z^0 parameters, M_Z and Γ_z. In order to do this LEP ran at 3 energy points, and at each of these the beam energy was accurately measured using the technique of resonant spin depolarisation. The total integrated luminosity delivered to the 4 LEP experiments was approximately $36pb^{-1}$, $66pb^{-1}$, and $37pb^{-1}$ at 81.5, 91.2 and 93.0 Gev respectively. These data represent a 4 fold increase in the "off peak" data over that recorded in previous years. The 4 LEP experiments (ALEPH,DELPHI,L3,OPAL) were over 90% efficient at collecting this data, leading to approximately 2.6×10^6 multi-hadronic events and 2.3×10^5 leptonic events from the 1993 run alone. Adding these to previous data results in 7.1×10^6 multi-hadronic and 7.2×10^5 leptonic events. The results from the 4 LEP experiments of the preliminary analyses of the cumulative data up to 1993 are presented here. This article concentrates on the improvements to M_Z and Γ_z, and also updates the results for other quantities. The results of a standard model fit for m_t and α_s are then presented, and finally the data is analysed in terms of variables which are relatively insensitive to the top and Higgs masses (R_{inv} and ϵ_3).

2 LEP Energy Measurement

One of the major improvements for the 1993 run, was the systematic calibration of the LEP beam energy using resonant spin depolarisation. The details of this procedure are described elsewhere in these proceedings [1]. The resulting contribution to the errors on M_Z and Γ_z from the 1993 scan alone are 4 Mev and 3 Mev respectively. This is a substantial improvement over previous years.

3 Hadronic Data Selection

M_Z and Γ_z are determined mainly from the multi-hadronic cross sections. Event selections make use of tracking information and calorimeter deposits. Typical 'average' criteria are: (i) number of charged tracks/neutral clusters > 4, (ii) visible energy $> 0.1\times$ centre of mass energy, and (iii) energy imbalance along beam pipe $< 0.35 \times E_{cm}$. The high degree of hermiticity of each of the experiments allows them to achieve very inclusive selections, these are shown in table 1.

Full details of the respective 1992 analyses are given in references [5, 6, 8, 7]. The preliminary analysis of the 1993 data is very similar. It can be appreciated that the statistical error per experiment is now less than 1 per mille, and this sets the target scale for the understanding of systematic errors.

Table 1 also shows the total systematic errors quoted by the experiments. The background comes mainly from $\tau^+\tau^-$ and non-resonant events. The taus are of little significance to the M_Z and Γ_z measurement, since they are resonant. The non-resonant background deserves special mention as it adds a constant number of events at each energy point, which can significantly alter the fit value of Γ_z.

	OPAL	ALEPH	L3	DELPHI
$\mu^+\mu^-$	0.19%	0.5%	0.5%	0.37%
e^+e^-	0.22%	0.4%	0.3%	0.59%
$\tau^+\tau^-$	0.44%	0.3%	0.7%	0.63%

Table 2: Systematic errors associated with lepton selection for each experiment. These are the 1992 errors, those from 1993 are in some cases slightly larger at present, but will reduce for the final numbers.

Studies show that an error of $10pb^{-1}$ on the estimation of this background leads to an error of about 1Mev on Γ_z. Various techniques are used to estimate this. ALEPH and OPAL use a method whereby the data is split into two parts, one containing relatively little, and the other a larger fraction, of non-resonant background (this is achieved with a separation on, say, visible energy). The ratio of the numbers of events in these two samples would be constant as a function of cms energy if there were no background, hence by plotting one against the other, the background fraction is extracted from the intercept. DELPHI and L3 employ methods whereby the background outside the data selection cuts is used, with the aid of monte-carlo, to extrapolate into the signal region. The resultant errors shown in the table lead to errors on Γ_z which are well below the level of statistics.

4 Leptonic Data Selection

The leptons (e,μ,τ) contribute to M_Z and Γ_z, and in conjunction with the hadrons determine R_{had} for each species.

$\mu^+\mu^-$ pairs are selected on criteria of (i) low multiplicity, (ii) muon identification (penetration, minimum ionising deposit in calorimeters), (iii) high visible momentum, and (iv) time of flight cuts to remove cosmic rays. Geometrical acceptances vary between 70 - 90% across the experiments, Selection efficiencies within this range average over 95%, and residual backgrounds are typically 1 or 2%.

e^+e^- pairs are selected on (i) high visible energy, particularly in the electromagnetic calorimeters (ii) low multiplicity and (iii) small acollinearity. The geometrical acceptance for electrons is normally chosen to be lower than for muons (typically $|\cos\theta| < 0.7$) in order to reduce the contribution from Bhabha events (t channel photon exchange) to around 10 - 15 %. Within this range the selection efficiencies are again high, with backgrounds in the region of 1%

$\tau^+\tau^-$ pairs are identified by searching for 2 narrow back to back jets with low multiplicity. In addition they are separated from muons and electrons by a requirement of low visible energy. The combined geometrical acceptance and efficiency tends to be a little lower, ranging from 50 to 78%. The background is slightly higher, typically 2-3%. The overall systematic errors associated with all of these selections are shown for each experiment in table 2.

5 Luminosity Measurement

Luminosity measurement has become a precision art at LEP in the last few years. The absolute luminosity measurement determines the precision of any cross section based quantities, such as the hadronic pole cross section, σ^{had}_{pole}, and the partial widths. The relative accuracy between energy points contributes directly to the error on M_Z and Γ_z.

Luminosity is measured by counting the rate of the well known t-channel QED Bhabha process, whereby the incoming e^+e^- are scattered into low angle luminosity monitors. The Bhabha cross section rises steeply as the scattering angle approaches zero, and hence to achieve high accuracy requires the

detectors to be (i) very close to the beampipe (statistics) and (ii) that the fiducial acceptance is very well known and surveyed (an error of $\approx 250\mu$m at the inner edge leads to a 1% error in the luminosity). In addition, the current accuracy is limited by the theoretical error in the programs used to calculate the acceptance.

In late 1992 ALEPH installed a silicon-tungsten calorimeter which measures from 30 to 50 mrad. This results in an acceptance of about 84 nb, which is three times the hadronic cross section. It contains 12 alternating Si/W layers. Each silicon layer comprises 16 radial rows of 5 mm pads, leading to a position accuracy of approximately 14 μm. Applied to the 1993 data ALEPH quote an error on absolute luminosity of 0.09% from the detector alone. OPAL have also installed a silicon-tungsten calorimeter comprising 19 layers. Each silicon layer contains 32 rows of 2.5 mm wide silicon pads. The relative point-to-point error obtained is 0.028%, which is negligible compared to the statistical precision. The absolute measurement analysis is however still in progress. For this reason OPAL do not quote a luminosity measurement for 1993 data. As a result all cross section measurements become normalised to the 1992 published data [6], with an error of 0.41%. Similarly, L3 have recently installed silicon strips in front of their BGO calorimeter. The luminosity measurement from this has just been released, and is reported elsewhere in these proceedings [3]. However this number had at the time of this conference not been fed into their cross section analysis, thus L3 also use their 1992 result of 0.5% [7]. DELPHI have continued to improve the understanding of their "Small Angle Tagger (SAT)" and have reduced the error from this to 0.28%.

There is in addition a common theory error which must be added. This arises mainly form missing LL and NLL terms, and is currently quoted as 0.25%. Theoretical work in this area is already underway, and improvements are expected. Most of the error is cms energy independent, however some part is due to the calculation of the Z terms which vary with energy. A recent review of this [4] concluded that for the acceptances of the LEP luminosity monitors, the resultant error on M_Z and Γ_z is small compared to other factors.

6 Combined Fit Results

The procedure for producing the combined LEP results is the following

- Each of the experiments fits its own cross-sections and asymmetries to obtain the best values for the standard parameter set: M_Z, Γ_z, σ^{had}_{pole}, R_{had} and A^{pole}_{FB}. Each experiment also provides the information to construct the part of the error correlation matrix which is specific to each detector. The fits are performed using ZFITTER [9], MIZA [10], and ALIBABA [11] for the electron t-channel. Details of these fitting procedures can be found in [5, 8, 7, 6].

- The individual parameter sets are combined by the LEP Electroweak Working Group [12]. In this process the full correlation matrix is constructed, taking into account the common correlated errors due to energy and luminosity. Details can be found in [12].

- For the purposes of Γ_z, the 1993 data is considered to be uncorrelated with previous data, and hence all data up to 1993 is used. However for M_Z only the 1993 data is used at present. This is because the M_Z correlations with previous years are still under study.

Figure 1 shows the DELPHI hadronic cross section points along with their lineshape fit. Note the size of the errors from 1993 data compared to previous years. Figure 2 shows the OPAL leptonic cross-sections against their lineshape fit.

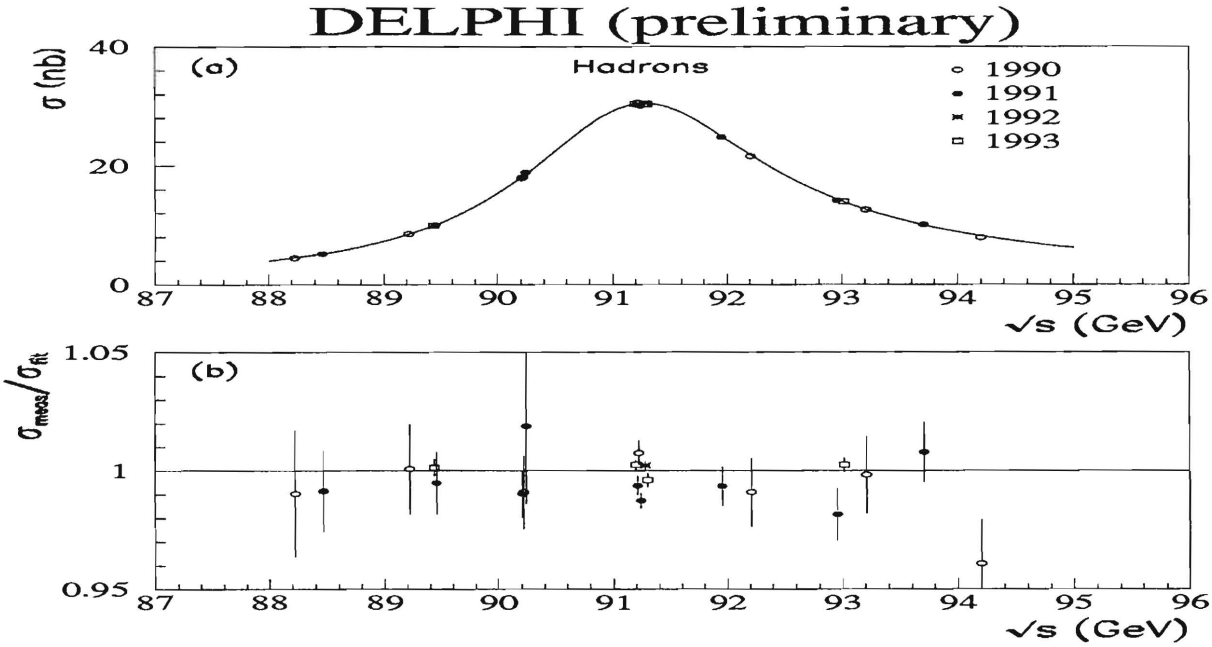

Figure 1: Hadronic cross sections from DELPHI as a function or cms energy, corrected for acceptance. The solid line shows the result of the lineshape fit to all DELPHI hadron and lepton data. The lower plot shows the deviation of data points from this fit.

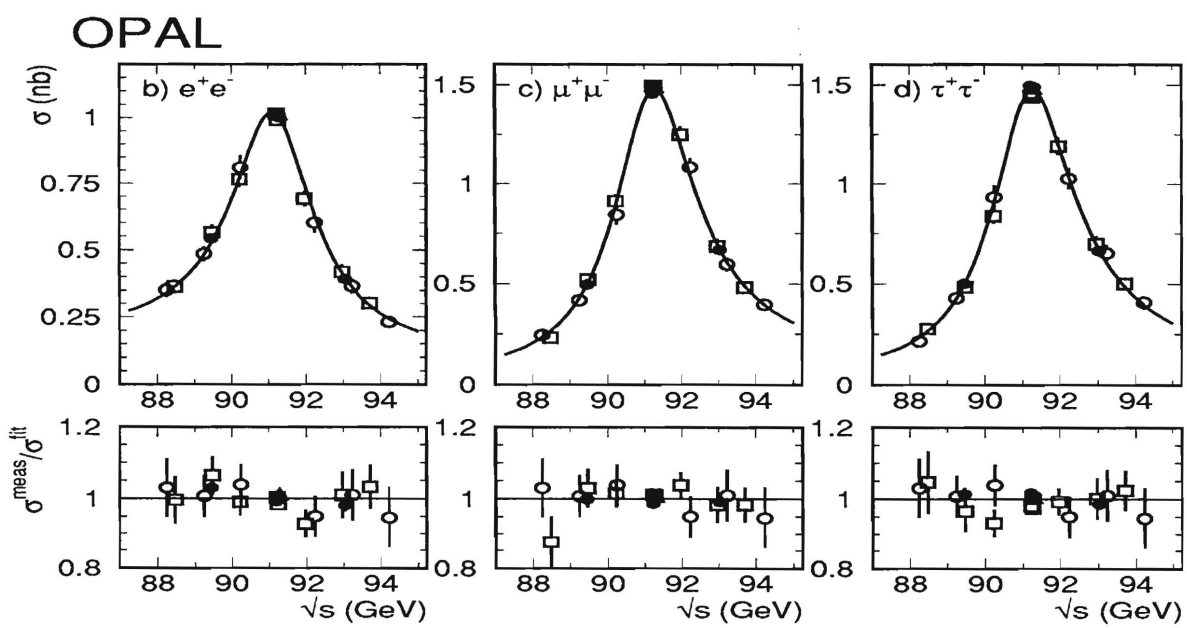

Figure 2: Lepton cross-sections from OPAL as a function of cms energy. b) electrons in the range $|\cos\theta < 0.7|$, c) muons corrected for acceptance, and d) taus corrected for acceptance. The solid lines are the results of the lineshape fit to all the OPAL hadron and lepton data. The lower plot shows the deviation of data points from this fit. The solid circles are the 1993 data, open triangles 1992, open squares 1991, and open circles 1990.

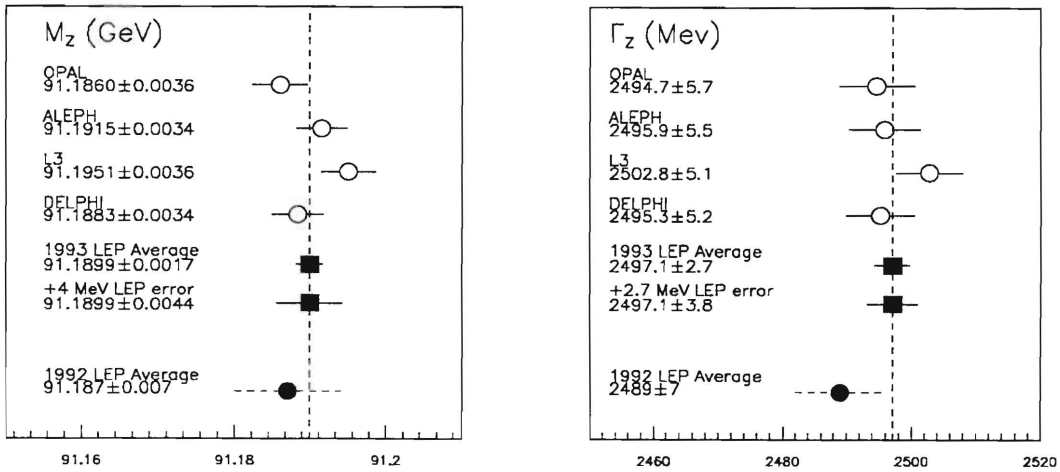

Figure 3: The 1993 preliminary LEP results for a) M_Z and b) Γ_z. The plots show the individual experiment results and the combined result allowing for correlations. The common LEP error is then added to give the final result. For comparison the 1992 values are shown (note: The Γ_z result is inclusive of 1992 result, whereas the M_Z value does not include 1992 result as the correlations are still under study).

6.1 M_Z and Γ_z

The M_Z value obtained from each experiment, along with the combined result, are shown in figure 3a. The results are in good agreement within the errors. The 4 Mev common systematic error arising from the LEP energy calibration is added in quadrature to give the final result of

$$M_Z = 91.1899 \pm 0.0017_{exp} \pm 0.004_{lep} \text{ Gev} \tag{1}$$

A substantial reduction in the error has been achieved. The accuracy of this result can be compared to the other inputs to the Standard Model . The electromagnetic coupling constant, α, is measured to 5 parts in 10^8, and the fermi constant G_μ to 2 parts in 10^5. To this we can now add M_Z measured to 5 parts in 10^5, making it truly a precision quantity.

Figure 3b shows the results for Γ_z. The LEP average result is

$$\Gamma_z = 2.4971 \pm 0.0027_{exp} \pm 0.0027_{lep} \text{ Gev} \tag{2}$$

The first error is due to the combined experimental statistics and systematics, including about 1Mev from the non-resonant background. The second is due to the LEP error (7Mev from 1992 and 3Mev from 1993),

6.2 σ_{pole}^{had} and R_{had}

σ_{pole}^{had} is determined by the absolute hadronic cross-section. It is equivalent to:

Stat	Syst	Lumi-exp	Lumi-theory	Total
0.03	0.05	0.04	0.1	0.12

Table 3: Contributions to the total absolute error on σ_{pole}^{had} for a single experiment. The luminosity error is broken down into an experimental and theoretical component (assumes a 0.1% detector error).

$$\sigma_{pole}^{had} = \frac{12\pi}{M_Z^2}\frac{\Gamma_e \Gamma_{had}}{\Gamma_z^2} \tag{3}$$

The unknown top and Higgs masses affect each of the partial widths in a "similar" way, and hence cancel to some extent in the ratio. The same is true regarding α_s whereby there is some cancellation of its appearance in Γ_{had} and Γ_z. As a result σ_{pole}^{had} is a quantity which has a relatively small variation within the Standard Model , and is one of the places where unambiguous evidence of new physics could show. Figure 4a shows the results, which are completely consistent with the Standard Model The LEP average is 41.51 ± 0.12. The errors are currently dominated by luminosity measurement errors, and hence the LEP average is currently dominated by the ALEPH result. To emphasis this, table 3 shows the approximate contribution to the total error from different sources for a single experiment assuming a 0.1% luminosity error.

The ratio of the hadronic to leptonic partial widths, R_{had}, is a quantity which is experimentally very clean, being independent of luminosity errors, and subject only to statistics and selection systematics. It is determined by the ratio of the number of hadronic to leptonic events. The LEP results are shown in figure 4b, the average being $R_{had} = 20.789 \pm 0.040$. This quantity has only improved slightly since the statistics have only increased by a factor of about 1.5.

The measurements of $(R_{had})_l$ for $l = e, \mu, \tau$ provide a test of lepton universality. Apart from a small correction due to the tau mass, the values should be equal. The LEP averages for each are shown in figure 5, where there is good agreement within the statistics.

The standard parameter set can be transformed to derive the leptonic partial widths, these are:

$$\begin{aligned} \Gamma_e &= 83.96 \pm 0.22 \text{ Mev} \\ \Gamma_\mu &= 83.90 \pm 0.31 \text{ Mev} \\ \Gamma_\tau &= 84.07 \pm 0.36 \text{ Mev} \\ \Gamma_l &= 83.98 \pm 0.18 \text{ Mev} \end{aligned} \tag{4}$$

7 m_t and α_s within the Standard Model

M_Z, G_f and α define the Standard Model , whence other quantities are then predicted up to α_s and the unknown m_t,m_H. Γ_z depends upon m_t, m_H and α_s, whereas R_{had} depends mainly upon α_s alone. Thus in a full standard model fit m_t and α_s are unambiguously determined for a fixed m_H. The results of such a fit to the lineshape data alone (ie: excluding any asymmetries) are:

$$m_t = 172^{+17}_{-18} \pm 19 \text{ Gev} \tag{5}$$

$$\alpha_s = 0.127 \pm 0.006 \tag{6}$$

where the first error is experimental, and the second m_t error is for m_H in the range 100 to 1000 Gev.

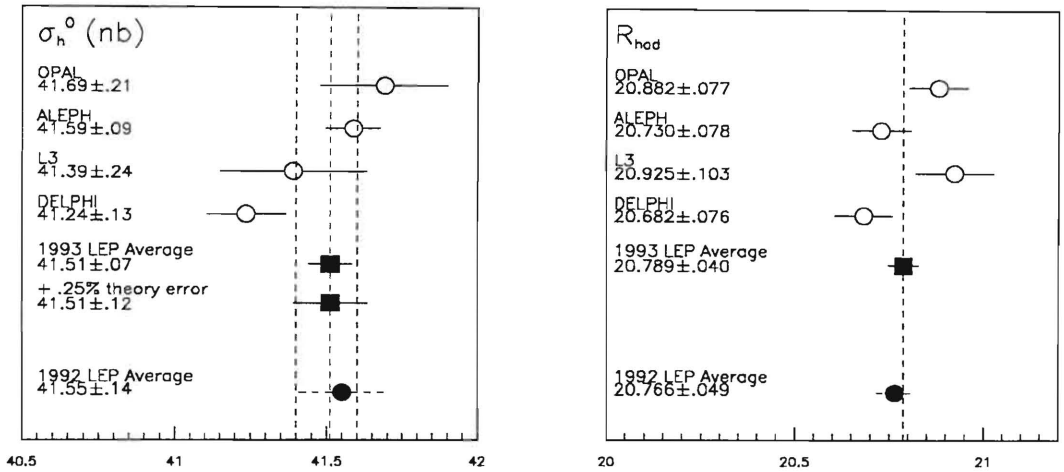

Figure 4: The 1993 preliminary LEP results for a) σ_{pole}^{had} and b) R_{had}. The plots show the individual experiment results and the combined result allowing for correlations. The common LEP error is then added to give the final result. The plot of σ_{pole}^{had} also shows the Standard Model range for m_t in the range 100-300 Gev and m_H in the range 100-1000 Gev (outer dotted lines). For comparison the 1992 values are also shown.

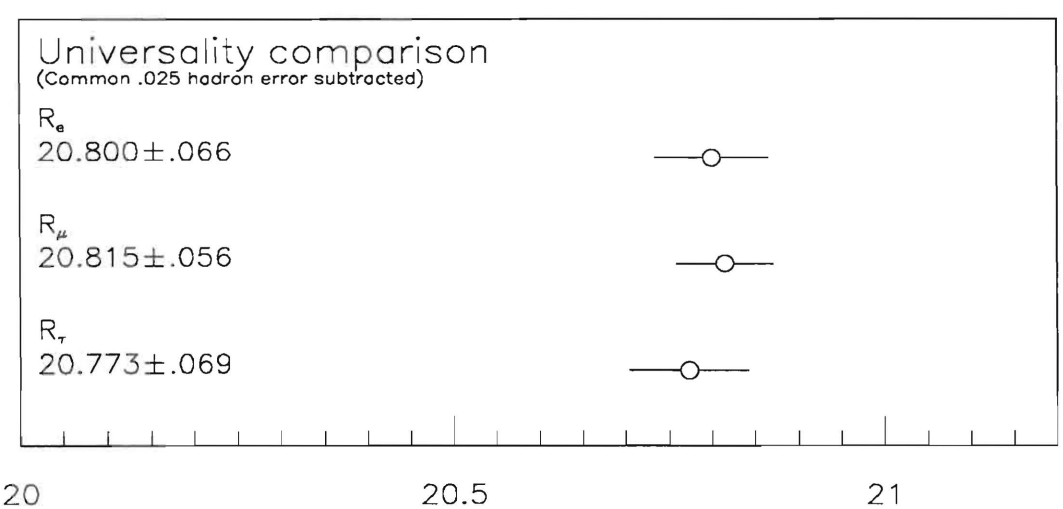

Figure 5: LEP average R_{had} shown for the individual lepton species.

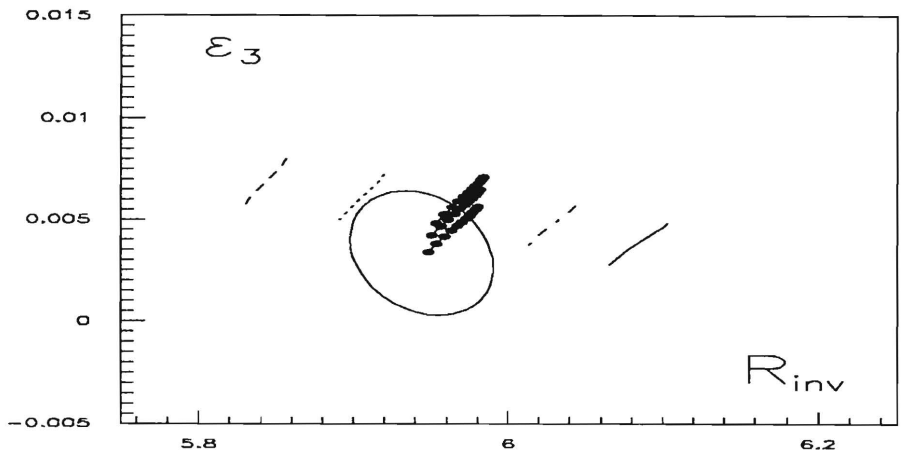

Figure 6: The one sigma contour plot of R_{inv} against ϵ_3. The Standard Model allowed range are the solid circles in the centre, and cover a range of m_t from 100-250 Gev, and m_H from 100-1000 Gev. The extra dotted, dashed and solid lines are the predictions in the case of an extra Z' under various scenarios (χ model, $M_{z'} = 500Gev, \theta_{mix} = -0.01, -0.005, 0.005, 0.01$).

8 Variables sensitive to new physics: R_{inv} and ϵ_3

There are many variables in the literature which disentangle the effects of unknown Standard Model quantities from the possible effects of new physics (σ^{had}_{pole} mentioned earlier goes some way to being such a quantity). The two presented here happen to be the favorite of the author.

It is well known that the m_t,m_H dependences of Γ_l and Γ_{inv} are large, but almost equal. Hence the ratio $R_{inv} = \Gamma_{inv}/\Gamma_l$ is almost constant in the SM. Similarly, the quantity ϵ_3 ([14]) cancels the top dependence of Γ_l against that of A^{pole}_{FB}. Both of these quantities therefore have a rather small allowed range within the Standard Model . Figure 6 shows the 1 σ contour ellipse for the best fit in this plane. The result is perfectly consistent with the Standard Model . The fit values are:

$$R_{inv} = 5.947 \pm 0.046 \quad (7)$$

$$\epsilon_3 = 0.0033 \pm 0.0031 \quad (8)$$

In the Standard Model this value of R_{inv} corresponds to the number of light neutrinos being $N_\nu = 2.985 \pm 0.024$.

For comparison, the figure shows some ranges of these quantities in the case of extended gauge model scenarios (points generated using ZEFIT [15]).

9 Conclusion

The 1993 LEP running period was very successful. The off peak data sample was increased by a factor of 4, leading to substantially improved errors on the measurement of the mass and width of the Z^0.

Other quantities have also benefitted from the statistics. Translated into a Standard Model fit for m_t at fixed m_H this leads to an error of ± 19Gev from lineshape precision alone. Variables sensitive to new physics are currently fully compatible with the Standard Model .

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References

[1] Talk by J.Wenniger on LEP energy measurement, these proceedings.

[2] Talk by M.Merk on L3 Luminosity measurement, these proceedings.

[3] Talk by B.Pietrzyk on lepton asymmetries, these proceedings

[4] M.Martinez and B.Pietrzyk, CERN PPE/93-222, Phys. Lett. B324(1994)492 and references contained therein.

[5] The ALEPH collabn., D.Decamp et al., Z.Phys C53(1992)1. D.Buskulic et al., Z.Phys C60(1993)71.

[6] The OPAL collabn., R.Akers et al., CERN PPE/93-146 Z.Phys C61(1994)19. P.D.Acton et al., Z.Phys C58(1993)219.

[7] The L3 collabn., CERN-PPE/94-45, submitted to Z.Phys C.

[8] The DELPHI collabn., CERN PPE/94-31. CERN PPE/94-08, to be published in Nuclear Phys. B

[9] Lineshape program ZFITTER, version 4.60, Dubna-Zeuthen radiative correction group, D.Bardin et al., Comp. Phys. Comm. 59(1990)303, Z.Phys C44(1989)493, Nucl. Phys. B351(1991)1

CPHCB

[10] M.Martinez, L.Garrido, R.Miquel, J.Harton, R.Tanaka, Z.Phys C49(1991)323.

[11] W.Beenakker et al., Nucl. Phys. B349 (1991)323

[12] The LEP collaborations ALEPH, DELPHI, L3, OPAL and the LEP electroweak working group, Updated parameters of the Z^0 resonance from combined preliminary data of the LEP experiments, CERN PPE/93-157.

[13] SLD collabn, K.Abe et al., SLAC-PUB-6456, submitted to Phys. Rev. Lett.

[14] G.Altarelli, R.Barbieri, F.Caravaglios, CERN TH/6770/93 and references contained therein. Note that the definition of ϵ_3 adopted here is the old one, and not the new one of the above authors whereby they apply offsets such that the Standard Model is at the origin.

[15] The ZEFIT program, A.Leike, S.Riemann, T.Riemann, Univ. Munich prepr. LMU-91/06.