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PRECISION TESTS OF THE STANDARD MODEL AT LEP

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1. Introduction

I present a short review on the precision tests of the Standard Model from the averaged LEP results until 1993.

Since Neutrino 92 the experimental breakthroughs on the LEP accelerator and on the detectors have been so important that the 'harvest of data' in terms of statistics and quality is quite impressive. Because of number of pages limitation I will make a strong selection of the arguments. For sure, some of the issues that I leave out, like the α_{strong} determination, the heavy flavour forward-backward asymmetries and the $\Gamma_{b\bar{b}}$ measurement would have deserved a better treatment.

2. The LEP Data

Between 1990 and 1993 the LEP machine has delivered around 94 pb^{-1} of integrated luminosity per experiment. The results presented here are based on the data taken during the energy scans in 1990 and 1991 with centre of mass energies in a range $\sqrt{s} = M_z \pm 3$ Gev (24.9 pb^{-1}/exp.), the high statistics data collected at the Z peak in 1992 (28.6 pb^{-1}/exp.), and a preliminary analysis of the high precision scan in 1993 (40.0 pb^{-1}/exp.). During this scan more than 18 pb^{-1} were recorded by each experiment at two centre of mass energy points roughly 1.8 Gev above and below the Z mass while the remainder was within 200 MeV of M_z.

Considerable progress has been made since 'Neutrino 92' in reducing the experimental systematic errors, thanks to better performances and understanding of the detectors, to keep pace with the growing statistical precision. For instance the present systematic errors are 0.13% for σ_h and from 0.3% to 0.5% for σ_ℓ, where σ_h and σ_ℓ are the hadronic and leptonic Z decay cross sections respectively. The total statistics of the individual LEP collaborations are given in Table 1. Details of the individual analysis can be found in [1].

Furthermore since then there have been two experimental breakthroughs:
i) The precision on the Z mass, M_z, and width, Γ_Z, depends crucially on the absolute and point to point energy calibration of the machine. A three point energy scan was performed in 1993 with energy calibration by resonant depolarization done for all the three beam energies [2]. An improvement of the errors on the Z mass and width by a factor 2 has been obtained with respect to the 1991 energy scan.

Table 1
The LEP statistics in units of 10^3 events.

		ALEPH	DELPHI	L3	OPAL	LEP
$q\bar{q}$	'90–'91	451	356	423	454	1684
	'92	680	697	677	733	2787
	'93 prel.	653	677	658	653	2641
	total	1784	1730	1758	1840	7112
$\ell^+\ell^-$	'90–'91	55	37	40	58	190
	'92	82	69	58	88	297
	'93 prel.	79	71	62	81	293
	total	216	177	160	227	780

ii) In all four experiments the luminosity is measured using small angle Bhabha events and the corresponding theoretical cross section. The four LEP apparatus have upgraded their luminosity detectors having $\Delta\mathcal{L}/\mathcal{L} < 0.1\%$ as final goal for the experimental systematic error. Figure 1 shows the precision of the LEP experiments on luminosity from 1990 till today. The improvement looks spectacular. However the theoretical Bhabha cross section uncertainty gives an extra contribution of 0.25% which is thus the present limit. Work is in progress and there is hope to decrease it to 0.1% [3].

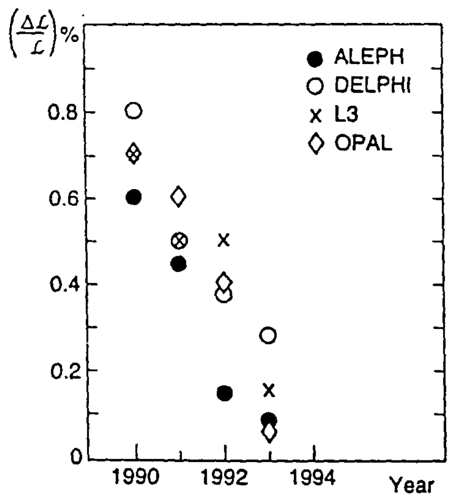

Fig. 1. $\Delta\mathcal{L}/\mathcal{L}$, the luminosity experimental systematic error, for the four LEP experiments from 1990 to 1993.

3. Z Parameters

At LEP the Z properties are studied, among others, from the following measurements:
i) cross sections as a functions of $\sqrt{s}$ for all the detected decay modes. That is, $e^+e^- \to$ hadrons and $e^+e^- \to$ leptons (e, μ, τ);
ii) charge and polarization asymmetries.
To fit the data the key points are:
- a model independent expression for [4]:
a) the Z line-shape
b) the charge asymmetry
c) the τ polarization
- a radiator function which takes care of initial state radiation corrections
- weak radiative corrections

The last two points have to be calculated to a sufficient precision to match the experimental performances.

Then the set of parameters determined from the fit are:
i) $M_z, \Gamma_z, \sigma_h^0$, the hadronic peak cross section, $R_\ell = \Gamma_h/\Gamma_\ell$, where Γ_h and Γ_ℓ are respectively the hadronic and leptonic Z partial width, from the lineshapes;
ii) A_{FB}^ℓ, the forward and backward leptonic asymmetries, from the charge asymmetries;
iii) A_τ, A_e, the τ polarization and τ polarization asymmetry, from the polarizations.

These parameters are convenient for fitting and averaging since they have minimal correlations amongst them. Here I present the averaged results of the four LEP experiments from a procedure, outlined in common publications of the four collaborations [1], which takes properly into account common systematic errors.

3.1. Z Lineshapes Results

The cross sections are fitted to an energy dependent expression

$$\sigma_{f\bar{f}}(s) = \sigma_h^0 \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} + \gamma \text{ terms} + \text{Interference terms}$$

$$\sigma_h^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2} \quad (1)$$

The QED gamma term is well known from the theory and the observed cross section results from a convolution of the 0^{th} order cross section above, with a spectral function which accounts for the effect of radiative corrections [4]. The interference term remains as an additional undetermined parameter unless it is fixed to its Standard model expectations value. Its uncertainty increases the total error on M_z (by almost 8 MeV for a single LEP experiment) compared to the situation where it is taken from the Standard Model [5]. The results presented here have the interference term fixed to its Standard Model value and work is in progress to implement this term as an input parameter in the fit.

The 9 parameters set from the simultaneous fit to the combined hadronic and leptonic cross sections and leptonic forward-backward asymmetries, is given in Table 2. The values of the individual leptonic widths are consistent with leptonic universality. From the previous parameters one can then derive other observables of physical importance like $\Gamma_h, \Gamma_\ell, \Gamma_{INV}$, the invisible partial width, g_{A_ℓ} and g_{V_ℓ}, the axial and vector couplings of the neutral current, etc. Table 3 provides a number of commonly used parameters derived from the results of the 9-parameters and, with the assumption of leptonic universality, 5-parameters fits. Among this $\sin^2\theta_{eff}^{lept}$, the effective weak mixing angle, is defined as

$$\sin^2\theta_{eff}^{lept} \equiv \frac{1}{4}(1 - g_{V_\ell}/g_{A_\ell}) \quad (2)$$

and derived from $A_{FB}^{0,\ell}$ (see below).

Table 2
Average line shape and asymmetry parameters from the data of the four LEP experiments given in Table 1, without the assumption of lepton universality. The $\chi^2/(d.o.f.)$ of the average is 26.8/27.

Parameter	Average Value
M_Z (GeV)	91.1888±0.0044
Γ_Z (GeV)	2.4974±0.0038
σ_h^0 (nb)	41.49±0.12
R_e	20.850±0.067
R_μ	20.824±0.059
R_τ	20.749±0.070
$A_{FB}^{0,e}$	0.0156±0.0034
$A_{FB}^{0,\mu}$	0.0141±0.0021
$A_{FB}^{0,\tau}$	0.0228±0.0026

The new experimental results worth to be mentioned are:

• The Z mass is the most precise single measurement at LEP. Figure 2 shows how this measurement has improved through the years. The intrinsic precision of the energy calibration via resonant depolarization is a fraction of an MeV. Thus the bulk of the 4 MeV error comes from the fluctuations of the energy correlated with deformation of the LEP ring. These are due to temperature variations, tidal deformation, rainfalls

Table 3
Average values of some derived parameters.

Without Lepton Universality:	
Γ_{ee} (MeV)	83.85±0.21
$\Gamma_{\mu\mu}$ (MeV)	83.95±0.30
$\Gamma_{\tau\tau}$ (MeV)	84.26±0.34
With Lepton Universality:	
Γ_{ℓ} (MeV)	83.96±0.18
Γ_{had} (MeV)	1745.9±4.0
Γ_{inv} (MeV)	499.8±3.5
$g^2_{V_\ell}$	0.00144±0.00014
$g^2_{A_\ell}$	0.25118±0.00056
$\sin^2\theta^{lept}_{eff}$	0.23107±0.00090

and some effects not yet understood. More experiments are planned and a final error below 2 MeV seems feasible [2].

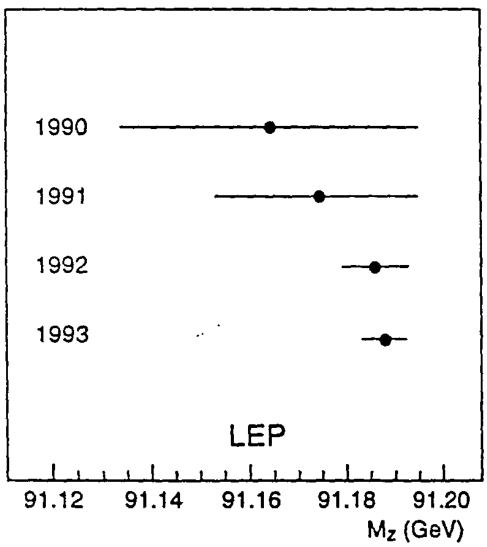

Fig. 2. The Z mass measurement from the LEP combined data through the years.

• For the total width the main error comes from the uncertainty on the point to point energy calibration. The absolute calibration done in 1993 in all the scan points has brough the error down to 2.7 MeV. Again with more studies there is the hope to reduce it to less than 2 MeV.

• For σ_h^0, and through it for Γ_h, Γ_ℓ and Γ_{INV}, the main systematic error comes from the luminosity determination. Therefore, when the theoretical precision will meet the experimental one, there will be a sizable improvement on all these measurements.

• Under the assumption of lepton universality, the Z^0 invisible width, Γ_{INV}, is deduced, from the 'Indirect Method', as:

$$\Gamma_{INV} = \Gamma_z - \Gamma_h - 3\Gamma_\ell$$

which gives for the LEP experiments $\Gamma_{INV} = 499.8 \pm 3.5$ MeV.
An expression for the number of light neutrino species, N_ν, is then

$$N_\nu = \frac{\Gamma_{INV}}{\Gamma_{\nu\bar{\nu}}} = \left(\frac{\Gamma_\ell}{\Gamma_{\nu\bar{\nu}}}\right)_{SM} \left\{\sqrt{\frac{12\pi R_\ell}{M_z^2\sigma_h^0}} - R_\ell - 3\right\}$$

where $(\Gamma_\ell/\Gamma_{\nu\bar{\nu}})_{SM}$ is taken from the Standard Model and it is almost independent of M_t, the quark top mass. The result is

$$N_\nu = 2.988 \pm 0.023 \ .$$

As said the main contribution to the systematic error comes from the luminosity measurement.

3.2. Lepton Forward-Backward Asymmetries Results

The leptonic forward-backward asymmetries can be defined as

$$A^l_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \ .$$

where F and B indicate whether the positively charged lepton goes into the forward or backward hemisphere. They are measured by fitting the lepton angular distributions of $\tau^+\tau^-, \mu^+\mu^-, e^+e^-$

(subtracting the t channel contribution in this last case). Then they are corrected for QED effects and initial state radiation to provide the peak asymmetries:

$$A_{FB}^{0,l} = \frac{3}{4} A_e A_l$$
$$A_f = \frac{2 g_V^f / g_A^f}{1 + (g_V^f / g_A^f)^2} .$$

Again the results are summarized in Table 2. The event selections, with the extra requirement of the charge determination, are similar to those for the Z lineshape sample. However the absolute normalization here is not needed and the statistical errors still dominate the measurements. Experimental systematics can only come from simultaneous charge and forward backward asymmetries in the detector which are therefore very small (about 0.2%). Theoretical error will become important in the future.

3.3. τ polarization results

The τ polarization, P_τ, is determined by measuring the longitudinal polarization of tau pairs produced in Z decays. It is defined as

$$\langle P_\tau \rangle = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_\tau ,$$

where $\sigma_{R(L)}$ is the cross section for the production of a right(left) handed τ. The helicity of the τ is measured through a fit of the momentum distributions of the τ decay products (e, μ, π, ρ, A_1). Table 4 provides the results for A_τ obtained by the four experiments and their combination [6]. On most results the systematic errors are about equal to the statistical errors. For the π channel they come both from the energy dependence of the selection efficiency and from the $\pi - \pi^0$ background. In the ρ channel the key point is to separate correctly the neutral π^0 in presence of a nearby charged pion. This is a very demanding measurement for the calorimeters and progress will be difficult in the coming years.

Table 4
LEP results for A_τ. The $\chi^2/(d.o.f.)$ for the average is 0.4/3 d.f.

ALEPH	('90–'92), prel.	$0.137 \pm 0.012 \pm 0.008$
DELPHI	('90–'92), prel.	$0.144 \pm 0.018 \pm 0.016$
L3	('90–'93), prel.	$0.144 \pm 0.013 \pm 0.015$
OPAL	('90–'92), final	$0.153 \pm 0.019 \pm 0.013$
LEP Average		0.143 ± 0.010

As function of $\cos\theta$, θ being the τ production polar angle, the τ polarization is given as

$$P_\tau(\cos\theta) = \frac{\frac{d\sigma_R}{d\cos\theta} - \frac{d\sigma_L}{d\cos\theta}}{\frac{d\sigma_R}{d\cos\theta} + \frac{d\sigma_L}{d\cos\theta}} = -\frac{A_\tau + A_e \cdot \frac{2\cos\theta}{1+\cos^2\theta}}{1 + A_e A_\tau \cdot \frac{2\cos\theta}{1+\cos^2\theta}} .$$

Averaging over $\cos\theta$ one gets A_τ whereas from the angular distribution of P_τ one can fit A_e. Table 5 provides the results for A_e from the four experiments [6]. The sensitivity of the method depends on the acceptance in $\cos\theta$. The error is still mainly statistical because here most systematic effects cancel out. The values of A_τ and A_e are compatible with the lepton universality.

Table 5
LEP results for A_e. The $\chi^2/(d.o.f.)$ for the average is 1.1/3 d.f.

ALEPH	('90–'92), prel.	$0.127 \pm 0.016 \pm 0.005$
DELPHI	('90–'92), prel.	$0.140 \pm 0.028 \pm 0.003$
L3	('90–'93), prel.	$0.154 \pm 0.020 \pm 0.012$
OPAL	('90–'92), final.	$0.122 \pm 0.030 \pm 0.012$
LEP Average		0.135 ± 0.011

Table 6
Comparison of several determinations of $\sin^2\theta_{eff}^{lept}$ from asymmetries. Averages are obtained as weighted averages assuming no correlations.

	$\sin^2\theta_{eff}^{lept}$	average by group of observations	$\chi^2/(d.o.f.)$	cumulative average	$\chi^2/(d.o.f.)$
$A_{FB}^{0,\ell}$	0.2311 ± 0.0009				
$\mathcal{A}_\tau$	0.2320 ± 0.0013				
$\mathcal{A}_e$	0.2330 ± 0.0014	0.2317 ± 0.0007	1.4/2	0.2317 ± 0.0007	1.4/2
$A_{FB}^{0,b}$	0.2327 ± 0.0007				
$A_{FB}^{0,c}$	0.2310 ± 0.0021	0.2325 ± 0.0006	0.6/1	0.2321 ± 0.0005	2.8/4
$\langle Q_{FB}\rangle$	0.2320 ± 0.0016	0.2320 ± 0.0016	–	0.2321 ± 0.0004	2.8/5
A_{LR} (SLC)	0.2294 ± 0.0010	0.2294 ± 0.0010	–	0.2317 ± 0.0004	9.0/6

4. Determinations of the Z couplings for charged leptons

The various asymmetries measured at LEP yield the ratio of the neutral couplings af the leptons g_{V_ℓ}/g_{A_ℓ} and, from the tau polarization, the determination of their relative sign. The absolute sign is derived from neutrino-electron scattering [7]. The measured ratio of the e, μ and τ couplings from the LEP experiments provide a test of universality:

$$g_{A_\mu}/g_{A_e} = 1.0014 \pm 0.0021 ,$$
$$g_{A_\tau}/g_{A_e} = 1.0034 \pm 0.0023 ,$$
$$g_{V_\mu}/g_{V_e} = 0.83 \pm 0.16$$
$$g_{V_\tau}/g_{V_e} = 1.044 \pm 0.091 .$$

The various asymmetries can all be related to the effective electroweak mixing angle. Table 6 provides the results from LEP [8]. The comparison with the left-right asymmetry measurement from SLC is also given [9].

5. Comparison between LEP observables and Standard Model Predictions

In the Standard Model one starts from the input parameters: α, G_f, and M_z (from LEP) known very precisely (to better than $10^{-7}, 2\cdot10^{-5}$ and $5\cdot10^{-5}$ respectively), M_{flight}, the fermion-light masses, and $\alpha_s(M_z^2)$ only approximately determined, M_t from CDF [10] known to better than $1\cdot10^{-1}$ and M_H, the Higgs mass, largely unknown.

Every electroweak observables can then be computed as a function of the input parameters. Finally one compares the theoretical predictions for all the observables which have been measured and derives constraints on M_t and hopefully on M_H.

Figures 3a,b,c,d show such a comparison as a function of M_t, in the range of M_H and α_s quoted there, for $\Gamma_Z, \Gamma_\ell, A_\tau$ and $\sin^2\theta_W$. The various measurements are all consistent with the Standard Model for a top mass around 160 GeV.

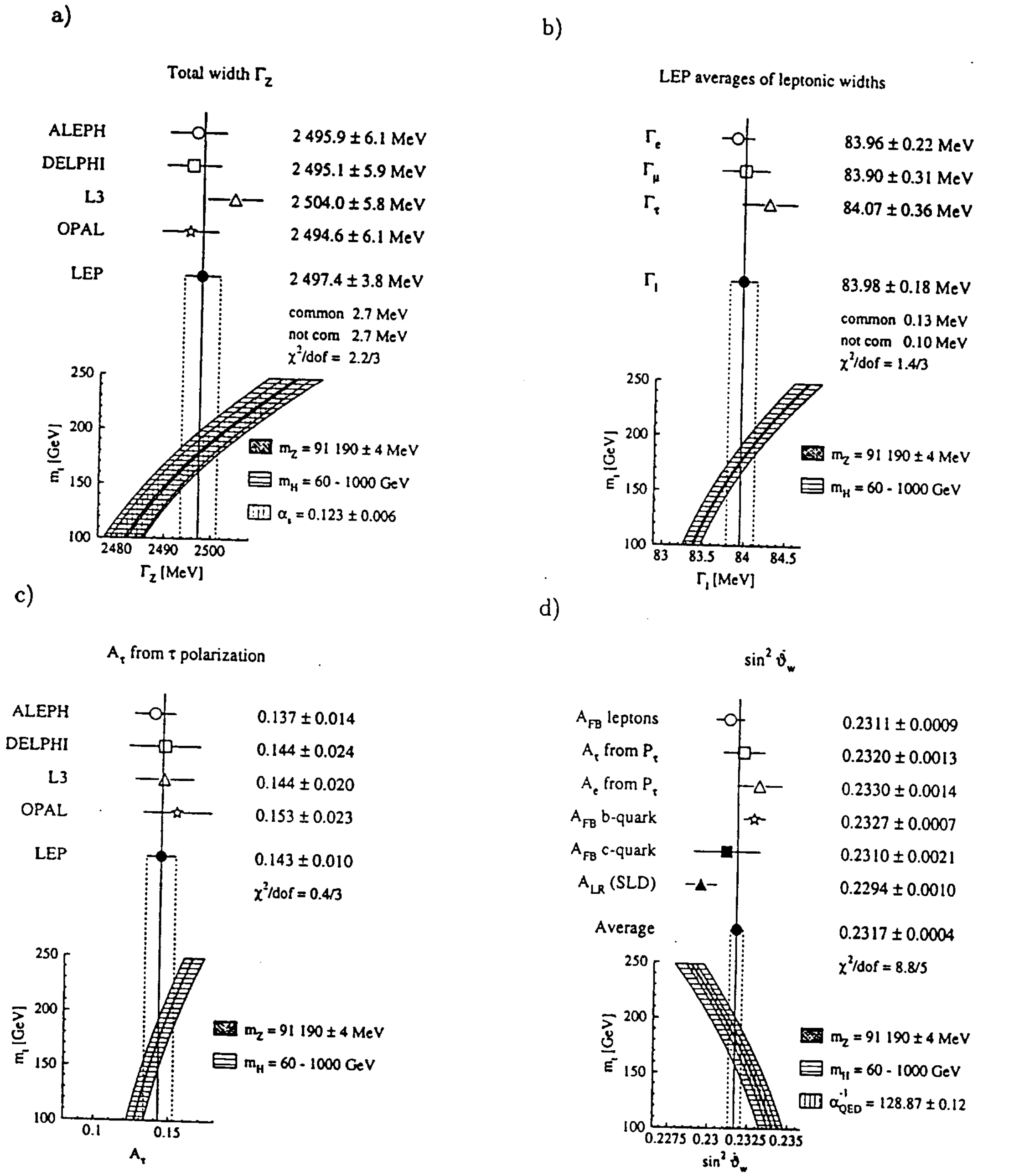

Fig. 3. Comparison between LEP observables and Standard Model predictions for: a) Γ_Z, b) Γ_ℓ, c) A_τ and d) $\sin^2\theta_W$.

6. Minimal Standard Model fits

As illustrated in Fig. 3 the Standard Model predictions for the electroweak parameters are dependent, through radiative corrections, on the values of M_t and M_H. Conversely, from a global fit of LEP observables one can estimate M_t and M_H. Table 7 shows the constraints obtained on M_t and $\alpha_s(M_z^2)$, with $M_H = 300$ GeV, using only LEP data [8], as well as those obtained by including the measurements of M_W from UA2 [11], CDF and D0 [12], and measurements of the neutrino neutral to charged current ratios from CDHS [13], CHARM [14] and CCFR [15]. Finally also the SLC results for the left-right asymmetry, A_{LR} [9] is added. The χ^2/d.o.f. is always acceptable. The fits have been repeated for $M_H = 60$ and 1000 GeV and the differences in the fitted parameters are quoted as an uncertainty.

The value of M_t from these fits is in excellent agreement with the one from the CDF direct search: $M_t = 174 \pm 17$ GeV [10]. This is a strong evidence that the quantum effects on the electroweak observables are indeed due to the top quark. Moreover the fitted $\alpha_S(M_z^2)$ value turns out to be in very good agreement with the one from event shape measurements at LEP [16].

Figure 4 shows the top mass result from the Minimal Standard Model fits through the years.

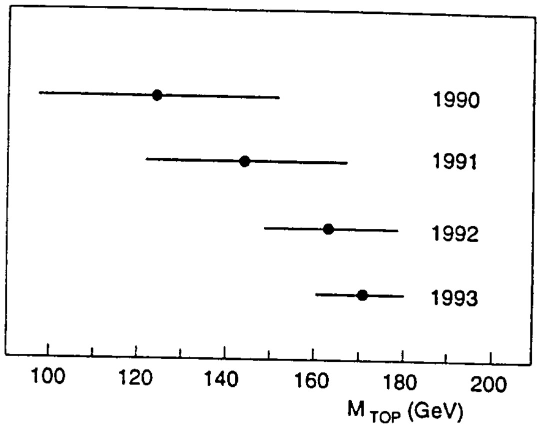

Fig. 4. The top mass determination from the Minimal Standard Model fits through the years.

Table 7

Results of fits to LEP and other data for M_t and $\alpha_s(M_Z^2)$. No external constraint on $\alpha_s(M_Z^2)$ has been imposed. In the third column also the combined data from the $p\bar{p}$ experiments UA2 [11], CDF and DO [12]: $M_W = 80.22 \pm 0.16$ GeV and from the neutrino experiments, CDHS [13], CHARM [14] and CCFR [15]: $1 - M_W^2/M_Z^2 = 0.2256 \pm 0.0047$ are included. The fourth column gives the result when also the SLD measurement of the left-right asymmetry at SLC [9], $\sin^2\theta_{eff}^{lept} = 0.2294 \pm 0.0010$, is added. The central values and the first errors quoted refer to $M_H = 300$ GeV. The second errors correspond to the variation of the central value when varying M_H in the interval $60 \leq M_H$ [GeV] ≤ 1000.

	LEP	LEP + Collider and ν data	LEP + Collider and ν data + A_{LR} from SLC
M_t (GeV)	173^{+12+18}_{-13-20}	171^{+11+18}_{-12-19}	178^{+11+18}_{-11-19}
$\alpha_s(M_Z^2)$	$0.126 \pm 0.005 \pm 0.002$	$0.126 \pm 0.005 \pm 0.002$	$0.125 \pm 0.005 \pm 0.002$
$\chi^2/(d.o.f)$	7.6/9	7.7/11	15/12
$\sin^2\theta_{eff}^{lept}$	$0.2322 \pm 0.0004^{+0.0001}_{-0.0002}$	$0.2323 \pm 0.0003^{+0.0001}_{-0.0002}$	$0.2320 \pm 0.0003^{+0.}_{-0.0002}$
$1 - M_W^2/M_Z^2$	$0.2249 \pm 0.0013^{+0.0003}_{-0.0002}$	$0.2250 \pm 0.0013^{+0.0003}_{-0.0002}$	$0.2242 \pm 0.0012^{+0.0003}_{-0.0002}$
M_W (GeV)	$80 \pm 0.07^{+0.01}_{-0.02}$	$80.27 \pm 0.06^{+0.01}_{-0.01}$	$80.32 \pm 0.06^{+0.01}_{-0.01}$

Next, one can check if the data are sensitive to the Higgs mass. The limit on the Higgs mass of the direct search from the combined LEP data is 64.5 GeV [17]. The dependence of radiative corrections on M_H is logarithmic and correlated to the larger one on the Top mass. Therefore with the present data accuracy the interpretation in terms of M_H is still a delicate task. The χ^2 of the fit including LEP and non-LEP data increases of only 3.6 when the Higgs mass goes from 60 to 1000 GeV and, even though the CDF M_t determination makes more robust the Standard Model sensitivity to the data, no meaningful constraints can be derived on M_H. The only conclusion drawn so far by the LEP experiments is that the data seem to prefer a light Higgs [8].

7. The number of Neutrino families: the single photon counting method

The invisible width, $\Gamma_{\rm INV}$, of the Z is its partial decay width into long-lived, weekly interacting particles, e.g. neutrino pairs. $\Gamma_{\rm INV}$ is of interest because it is sensitive, as seen in section 3.1, to the existence of additional neutrino generations or any other pair of stable weekly interacting particles with mass less than $M_z/2$, non standard couplings of the known neutrinos to the Z and to phenomena such as the existence of right-handed neutrinos mixing with the left-handed ones.

From the so-called 'Indirect Method' we have seen that N_ν is today known from a single experiment with a precision of 2% which exludes a fourth generation with a significance of 20 σ. Furthermore this result indicates that eventual modifications of $\Gamma_{\rm INV}$ due to new phenomena have to be very small.

Thus precise measurements are needed to address the above models.

Moreover in the indirect approach non standard Z decays, not taken properly into account in the hadronic or in the leptonic selections, would give a contribution to $\Gamma_{\rm INV}$. Therefore it would not be possible to explain a deviation of N_ν from 3 as an excess in $\Gamma_{\rm INV}$ or as a defect in the visible width. Hence we need to measure 'Directly' $\Gamma_{\rm INV}$.

A 'Direct Measurement' at LEP, the so-called single-photon counting method, is to study the production of events, like $e^+e^- \rightarrow Z\gamma \rightarrow \nu\bar{\nu}\gamma$, in which the only detectable particle is a photon from the radiation of the initial state electron or positron.

The experimental key points of this approach are:

i) the capacity to trigger on low energy photons ($E\gamma \sim 0.9$ GeV for L3);

ii) very good knowledge of the absolute energy scale;

iii) a good hermeticity of the detector to the lowest possible θ angle;

iv) good photon identification.

The energy spectrum of the single photon candidates for L3 is shown in Fig. 5 together with the Monte Carlo prediction for the signal expected from 3 light neutrino family and the backgrounds.

There are today three LEP measurements [18] of N_ν from such a method:

OPAL	
(1990 + 1991 + 1992 data)	$N_\nu = 3.23 \pm 0.16 \pm 0.10$
L3	
(1992 data) :	$N_\nu = 3.00 \pm 0.16 \pm 0.08$
ALEPH	
(1990 + 1991 data)	$N_\nu = 2.68 \pm 0.20 \pm 0.20$

These results, agree with the Standard Model expectation for three light neutrinos and also with the indirect determinations. The statistical error still dominate the measurements. Even if a fourth family has been excluded, it has to be kept in mind that N_ν has not to be integer [19]. Therefore it is still quite important to have such a complementary approach. The final goal is to reach an error on N_ν better than 2%.

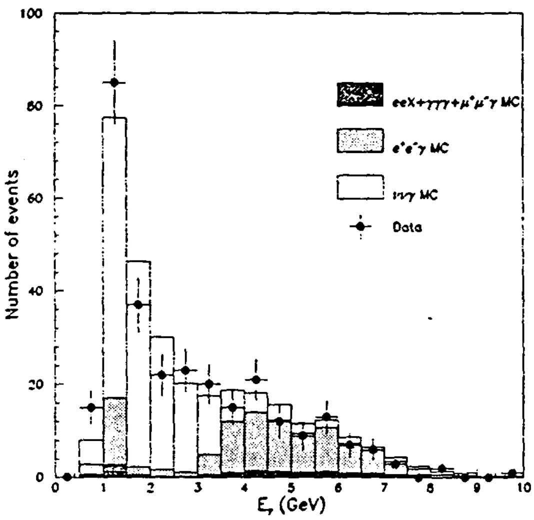

Fig. 5. Energy spectrum of the L3 single photon candidates along with the Monte Carlo predictions.

8. Conclusions and Outlook

The LEP experiments have brought new and very precise tests of the electroweak theory. No deviation from the minimal picture, has been found at 10^{-3} level. Each experiment, till the 1993 run, has collected around 1.8 million hadronic and 200 thousand leptonic Z decays. Because of the beam energy calibration by resonant depolarization and high precision luminosity monitors, the Z mass is now known with a precision of 5×10^{-5}, the number of neutrinos to 2% of a family, the Z width with a precision of 1.5×10^{-3} and the weak mixing angle with a precision of 2×10^{-3}.

The Minimal Standard Model fits, through virtual radiative effects, allow a determination of the top quark mass of $178 \pm 11 \pm 18$ GeV: right where it has possibly been seen by the CDF experiment. Yet the Higgs has not been found even though, with the help of a CDF better determination of the top mass, there is the hope to put more stringent constraints on its mass.

The continuation of the LEP program at the Z pole forsees to collect 60 pb^{-1} for the 1994 and, operating LEP with four trains of four bunches each, 90 pb^{-1} for the 1995. The measurements of the Z mass and width should then improve significantly by scanning again the Z resonance together with precise energy calibrations. An error of ± 2 MeV on Γ_z seems reachable.

In order to make full use of such a precision the present estimate of $\alpha(M_z^2)$ should also be improved, see Fig. 3d.

What next for the Electroweak measurements? LEP 200, from 1996 on, will allow a measurement of the W mass with a precision of about 40 MeV or better. This, together with a precision of 5 GeV on the top mass from CDF, will put a further constraint on the Higgs mass.

Of course the best would be to find the Higgs. LEP 200 can find it up to $M_H \cong (2E_{\rm beam} - 100)$ GeV. Otherwise the answer to the spontaneous symmetry breaking mechanism will wait for the LHC experiments.

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