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 $\alpha_{\text{strong}}$ determination, the heavy flavour forward-backward asymmetries and the $\Gamma_{\text{had}}$ 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 $\sigma_{H}$ and from 0.3% to 0.5% for $\sigma_{L}$, where $\sigma_{H}$ and $\sigma_{L}$ 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, $\Gamma_{Z}$, 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.
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 $\Delta L/L < 0.1\%$ 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].

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, $e^+e^- \rightarrow$ hadrons and $e^+e^- \rightarrow$ leptons ($e, \mu, \tau$);

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 $\tau$ 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) $M_Z, \Gamma, \sigma_h^0$, the hadronic peak cross section, $R_\ell = \Gamma_h/\Gamma_\ell$, where $\Gamma_h$ and $\Gamma_\ell$ are respectively the hadronic and leptonic Z partial width, from the lineshapes;

ii) $A_{FB}$, the forward and backward leptonic asymmetries, from the charge asymmetries;

iii) $A_\tau, A_e$, the $\tau$ polarization and $e$ 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

$$\sigma_{\ell f}(s) = \frac{s \Gamma_{Z}^{2}}{(s - M_{Z}^{2})^{2} + s \Gamma_{Z}^{2}/M_{Z}^{2}}$$

+ $\gamma$ terms

+ Interference terms

$$\sigma_{K}^{0} = \frac{12\pi \Gamma_{K} \Gamma_{f}}{M_{Z}^{2} \Gamma_{Z}^{2}}$$ (1)

The QED gamma term is well known from the theory and the observed cross section results from a convolution of the 0th 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 $\Gamma_{h}, \Gamma_{e}, \Gamma_{INV}$, the invisible partial width, $g_{A}$, and $g_{V}$, 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 $\sin^{2}\theta_{\text{eff}}$, the effective weak mixing angle, is defined as

$$\sin^{2}\theta_{\text{eff}} = \frac{1}{4}(1 - g_{V}/g_{A})$$ (2)

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

![Table 2](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{Z}$ (GeV)</td>
<td>91.1888±0.0044</td>
</tr>
<tr>
<td>$\Gamma_{Z}$ (GeV)</td>
<td>2.4974±0.0038</td>
</tr>
<tr>
<td>$\sigma_{Z}^{0}$ (nb)</td>
<td>41.49±0.12</td>
</tr>
<tr>
<td>$R_{e}$</td>
<td>20.850±0.067</td>
</tr>
<tr>
<td>$R_{\mu}$</td>
<td>20.824±0.059</td>
</tr>
<tr>
<td>$R_{\tau}$</td>
<td>20.749±0.070</td>
</tr>
<tr>
<td>$A_{FB}^{0}$</td>
<td>0.0156±0.0034</td>
</tr>
<tr>
<td>$A_{FB}^{0,\mu}$</td>
<td>0.0141±0.0021</td>
</tr>
<tr>
<td>$A_{FB}^{0,\tau}$</td>
<td>0.0228±0.0026</td>
</tr>
</tbody>
</table>

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

Table 3
Average values of some derived parameters.

<table>
<thead>
<tr>
<th>Without Lepton Universality:</th>
<th>( \Gamma_{ee} ) (MeV)</th>
<th>83.85±0.21</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_{e\mu} ) (MeV)</td>
<td>83.95±0.30</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{e\tau} ) (MeV)</td>
<td>84.26±0.34</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>With Lepton Universality:</th>
<th>( \Gamma_{l} ) (MeV)</th>
<th>83.96±0.18</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_{had} ) (MeV)</td>
<td>1745.9±4.0</td>
<td></td>
</tr>
<tr>
<td>( \Gamma_{inv} ) (MeV)</td>
<td>499.8±3.5</td>
<td></td>
</tr>
<tr>
<td>( g_{L} )</td>
<td>0.0014±0.00014</td>
<td></td>
</tr>
<tr>
<td>( g_{R} )</td>
<td>0.2511±0.00056</td>
<td></td>
</tr>
<tr>
<td>( \sin^{2} \theta_{eff} )</td>
<td>0.2310±0.00090</td>
<td></td>
</tr>
</tbody>
</table>

- 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 brought the error down to 2.7 MeV. Again with more studies there is the hope to reduce it to less than 2 MeV.
- For \( \sigma_{h} \), and through it for \( \Gamma_{h} \) and \( \Gamma_{inv} \), 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, \( \Gamma_{inv} \), is deduced, from the 'Indirect Method', as:

\[
\Gamma_{inv} = \Gamma_{l} - \Gamma_{h} - 3\Gamma_{t}
\]

which gives for the LEP experiments \( \Gamma_{inv} = 499.8 \pm 3.5 \text{ MeV} \).

An expression for the number of light neutrino species, \( N_{\nu} \), is then

\[
N_{\nu} = \frac{\Gamma_{inv}}{\Gamma_{\nu\nu}} = \left( \frac{\Gamma_{l}}{\Gamma_{\nu\nu}} \right)_{SM} \left\{ \sqrt{\frac{12\pi e_{l}}{M_{t}^{2}g_{R}^{4}}} - R_{l} - 3 \right\}
\]

where \( \left( \Gamma_{l}/\Gamma_{\nu\nu} \right)_{SM} \) 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

\[
A_{FB} = \frac{\sigma_{F} - \sigma_{B}}{\sigma_{F} + \sigma_{B}} .
\]

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:

\[ A^0_{FB} = \frac{3}{4} A_e A_L \]

\[ A_f = \frac{2 g'_f / g'_A}{1 + (g'_f / g'_A)^2} \]

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. \( \tau \) polarization results

The \( \tau \) polarization, \( P_\tau \), is determined by measuring the longitudinal polarization of tau pairs produced in \( Z \) decays. It is defined as

\[ (P_\tau) = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_\tau \]

where \( \sigma_R(L) \) is the cross section for the production of a right(left) handed \( \tau \). The helicity of the \( \tau \) is measured through a fit of the momentum distributions of the \( \tau \) decay products (\( e, \mu, \pi, \rho, A_1 \)). Table 4 provides the results for \( A_\tau \) obtained by the four experiments and their combination [6]. On most results the systematic errors are about equal to the statistical errors. For the \( \pi \) channel they come both from the energy dependence of the selection efficiency and from the \( \pi - \pi^0 \) background. In the \( \rho \) channel the key point is to separate correctly the neutral \( \pi^0 \) 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

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( A_\tau ) (d.o.f.)</th>
<th>( \chi^2/(d.o.f.) )</th>
<th>Average (d.o.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH ('90-'92), prel.</td>
<td>0.137 ± 0.012 ± 0.008</td>
<td>0.143 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>DELPHI ('90-'92), prel.</td>
<td>0.144 ± 0.018 ± 0.015</td>
<td>0.144 ± 0.013 ± 0.015</td>
<td>0.143 ± 0.010</td>
</tr>
<tr>
<td>L3 ('90-'93), prel.</td>
<td>0.153 ± 0.019 ± 0.013</td>
<td>0.143 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>OPAL ('90-'92), final</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEP Average</td>
<td>0.143 ± 0.010</td>
<td>0.143 ± 0.010</td>
<td></td>
</tr>
</tbody>
</table>

As function of \( \cos \theta \), \( \theta \) being the \( \tau \) production polar angle, the \( \tau \) polarization is given as

\[ P_\tau(\cos \theta) = \frac{\frac{d \sigma}{d \cos \theta} - \frac{d \sigma}{d \cos \theta}}{\frac{d \sigma}{d \cos \theta} + \frac{d \sigma}{d \cos \theta}} = -\frac{A_\tau + A_e A_L}{1 + A_e A_L} \cdot \frac{2 \cos \theta}{1 + 2 \cos \theta} \]

Averaging over \( \cos \theta \) one gets \( A_\tau \) whereas from the angular distribution of \( P_\tau \) 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 \( A_\tau \) and \( A_e \) are compatible with the lepton universality.

Table 5

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( A_e ) (d.o.f.)</th>
<th>( \chi^2/(d.o.f.) )</th>
<th>Average (d.o.f.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALEPH ('90-'92), prel.</td>
<td>0.127 ± 0.016 ± 0.005</td>
<td>0.135 ± 0.011</td>
<td></td>
</tr>
<tr>
<td>DELPHI ('90-'92), prel.</td>
<td>0.140 ± 0.028 ± 0.003</td>
<td>0.154 ± 0.020 ± 0.012</td>
<td>0.135 ± 0.011</td>
</tr>
<tr>
<td>L3 ('90-'93), prel.</td>
<td>0.122 ± 0.030 ± 0.012</td>
<td>0.135 ± 0.011</td>
<td></td>
</tr>
<tr>
<td>OPAL ('90-'92), final</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison of several determinations of $\sin^2 \theta_{\text{eff}}^{\text{lep}}$ from asymmetries. Averages are obtained as weighted averages assuming no correlations.

<table>
<thead>
<tr>
<th></th>
<th>$\sin^2 \theta_{\text{eff}}^{\text{lep}}$</th>
<th>average by group of observations</th>
<th>cumulative average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\chi^2/(\text{d.o.f.})$</td>
<td>$\chi^2/(\text{d.o.f.})$</td>
<td></td>
</tr>
<tr>
<td>$A_{FB}$</td>
<td>0.2311 ± 0.0009</td>
<td>0.2317 ± 0.0007</td>
<td>0.2317 ± 0.0007</td>
</tr>
<tr>
<td>$A_{T}$</td>
<td>0.2320 ± 0.0013</td>
<td>0.2325 ± 0.0006</td>
<td>0.2321 ± 0.0005</td>
</tr>
<tr>
<td>$A_{*}$</td>
<td>0.2310 ± 0.0014</td>
<td>0.2320 ± 0.0016</td>
<td>0.2321 ± 0.0004</td>
</tr>
<tr>
<td>($Q_{FB}$</td>
<td>0.2320 ± 0.00016</td>
<td>0.2320 ± 0.00016</td>
<td>0.2321 ± 0.0004</td>
</tr>
<tr>
<td>$A_{LR}$ (SLC)</td>
<td>0.2294 ± 0.0010</td>
<td>0.2294 ± 0.0010</td>
<td>0.2317 ± 0.0004</td>
</tr>
</tbody>
</table>

4. Determinations of the $Z$ couplings for charged leptons

The various asymmetries measured at LEP yield the ratio of the neutral couplings of the leptons $g_{\nu}/g_{A_{*}}$ 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 $e, \mu$ and $\tau$ couplings from the LEP experiments provide a test of universality:

$g_{A_{e}}/g_{A_{\tau}} = 1.0014 ± 0.0021$

$g_{A_{\mu}}/g_{A_{\tau}} = 1.0034 ± 0.0023$

$g_{\nu}/g_{\tau} = 0.83 ± 0.16$

$g_{\nu}/g_{\tau} = 1.044 ± 0.091$

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: $\alpha, G_f$, and $M_z$ (from LEP) known very precisely (to better than $10^{-7}, 2 \cdot 10^{-5}$ and $5 \cdot 10^{-5}$ respectively), $M_{\text{flight}}$, the fermion-light masses, and $\alpha_s(M_\tau^2)$ only approximately determined, $M_t$ from CDF [10] known to better than $1 \cdot 10^{-4}$ 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 $\alpha_s$ quoted there, for $\Gamma_Z, \Gamma_\ell, A_T$ 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) $\Gamma_z$, b) $\Gamma_{\ell}$, c) $A_{\tau}$ 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 [9], 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 \( \chi^2/d.o.f. \) 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.](image-url)

<table>
<thead>
<tr>
<th>( M_t ) (GeV)</th>
<th>( \alpha_s(M_Z^2) )</th>
<th>( \chi^2/(d.o.f.) )</th>
<th>( \sin^2\theta_{eff} )</th>
<th>( 1-M_Z^2/M_W^2 )</th>
<th>( M_W ) (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>173^{+15}_{-13} \pm 20</td>
<td>0.126 \pm 0.005 \pm 0.002</td>
<td>7.6/9</td>
<td>0.2322 \pm 0.0004 \pm 0.0002</td>
<td>0.2249 \pm 0.0013 \pm 0.0003</td>
<td>80 \pm 0.07 \pm 0.02</td>
</tr>
<tr>
<td>171^{+11}_{-12} \pm 19</td>
<td>0.126 \pm 0.005 \pm 0.002</td>
<td>7.7/11</td>
<td>0.2233 \pm 0.0003 \pm 0.0002</td>
<td>0.2250 \pm 0.0013 \pm 0.0003</td>
<td>80.27 \pm 0.06 \pm 0.01</td>
</tr>
<tr>
<td>178^{+11}_{-11} \pm 19</td>
<td>0.125 \pm 0.005 \pm 0.002</td>
<td>15/12</td>
<td>0.2242 \pm 0.0012 \pm 0.0003</td>
<td>0.2242 \pm 0.0013 \pm 0.0003</td>
<td>80.32 \pm 0.06 \pm 0.01</td>
</tr>
</tbody>
</table>

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 pp experiments UA2 [11], CDF and D0 [12]; \( M_W = 80.22 \pm 0.16 \) GeV and from the neutrino experiments, CDHS [13], CHARM [14] and CCFR [15]; \( 1-M_Z^2/M_W^2 = 0.2256 \pm 0.0047 \) are included. The fourth column gives the result when also the SLD measurement of the left-right asymmetry at SLC [9], \( \sin^2\theta_{eff} = 0.2294 \pm 0.0010 \), 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] \( \leq 1000 \).
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 $\chi^2$ 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].

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 $\Gamma_{INV}$. Therefore it would not be possible to explain a deviation of $N_\nu$ from 3 as an excess in $\Gamma_{INV}$ or as a defect in the visible width. Hence we need to measure 'Directly' $\Gamma_{INV}$.

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 $\theta$ 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 $N_\nu$ 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 \( N_e \) 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 \( N_e \) better than 2%.

\[ 2 \times 10^{-3} \]

The Minimal Standard Model fits, through virtual radiative effects, allow a determination of the top quark mass of \( 178 \pm 11 \pm 18 \text{ GeV} \); 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 foresees 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 \( \pm 2 \text{ MeV} \) on \( \Gamma \) seems reachable.

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

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 \( 5 \times 10^{-5} \), the number of neutrinos to 2% of a family, the \( Z \) width with a precision of \( 1.5 \times 10^{-3} \) and the weak mixing angle with a precision of \( 2 \times 10^{-3} \).

\[ \text{Fig. 5. Energy spectrum of the L3 single photon candidates along with the Monte Carlo predictions.} \]

Acknowledgements

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References


A. Martinez et al., Z. Phys. C49 (1991) 645;


CDF and DO Collaboration, preliminary results, by Y. Ducros, La Thuile, March 6-12, 1994.


