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Electroweak results from LEP

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1. Introduction

This is the first symposium in this series which is being held after the commissioning of SLC and LEP in 1989. During these 3 years the four LEP experiments Aleph, Delphi, L3 and Opal have provided a wealth of data and have determined electroweak parameters with unprecendented precision.

The structure of this talk will be

- Why LEP ?
- Accelerator, Detectors, Measurements.
- Methodology of determining EW Parameters.
- Results (Model Independent and in SM framework).
- Future, Conclusions.

2. Why LEP ?

Seminal theoretical work during the 60's and early 70's led to Electroweak Unification [1] and the prediction of a neutral current (Z°-mediated) in addition to the charged current ($W^\pm$-mediated) well known to be responsible for weak decays (β, μ). The existence of the neutral current was verified indirectly in the early 70's in bubble chamber experiments [2]. But due to their large masses the direct observation of $W^\pm$ and Z° was possible only in the early 80's with the advent of the CERN $p\bar{p}$ collider [3]. There followed a slow increase in world statistics of Z° events so that before LEP/SLC one had $\Delta M_Z = 2$ GeV, whereas today $\Delta M_Z = 7$ MeV, an obvious tribute to the efficacy of LEP.

A very clean way of producing Z°'s and studying their decays is by using e^+e^- colliders where the initial state is precisely known and the final state is overwhelmingly due to the production and decay of the Z°. In the Standard Model (SM) the production and decay characteristics of Z° are predicted 'exactly' ($\sim$ few per mille) modulo our knowledge of M_{top} and M_{Higgs}.

Thus the idea was to build a Z° factory, produce $n \times 10^6$ Z°'s, n being large,

⇒ Perform **Precision tests** of SM;

⇒ Search for **Predicted New particles** (e.g.,Higgs);

⇒ Look for the **UNEXPECTED**.

3. Accelerator, Detectors, Measurements

The LEP accelerator is a 27 km e^+e^- Storage Ring which functions as a Z° factory with $E_{cm} \leq 100$ GeV (88-94 GeV) during the LEP 1 phase (upto 1994). The nominal design luminosity ($\mathcal{L}$) was $1.7 \times 10^{31} cm^{-2}s^{-1}$ whereas the actual luminosity obtained upto now is lower. There are four detectors at the e^+e^- intersection regions : ALEPH, DELPHI, L3, OPAL. All attempt 4π coverage for detecting produced particles and they all consist of the following subdetector units (with different emphasis) : vertex detector, tracking chamber, calorimeters (em, hadron), muon detection, luminosity monitors.

Measurements at LEP consist of determining the number of e^+e^- interactions leading to the e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, hadrons final states. One then deduces

the cross sections $\sigma_i(s) = N_i(s)/L_{int}$, $L_{int} = \int \mathcal{L}dt$ (integrated luminosity), $i = e/\mu, \tau$,had;

lepton forward-backward (F/B) asymmetry : $A^i_{fb} = (\sigma^i_f - \sigma^i_b)/(\sigma^i_f + \sigma^i_b)$;

other Asymmetries : quark F/B, the τ polarisation $P(\tau)$, the $\cos\theta$ dependence of $P(\tau)$ (F/B), whose determination requires a knowledge also of the identity and momentum of the decay/fragmentation products.

4. Methodology of determining EW Parameters

LEP is run at a few (7) energy points around the Z° mass constituting an energy 'scan'. Each experiment determines the values of the cross sections and asymmetries mentioned above at each E_{cm} value.

- What do **cross section** measurements tell us ? The shape of the cross section variation around the Z° peak is described basically by a Breit-Wigner. The **three** main properties of this distribution, viz., the **position** of the peak, the **width** of the distribution and the **height** of the peak determine respectively the values of M_Z, Γ_Z and $\Gamma_e \times \Gamma_f$ where Γ_e, Γ_f are the electron and final state partial widths of the Z°. One explicitly takes into account the large (~30 %) initial state radiation effects by convoluting over a 'Radiator Function' $H(s, s')$. Thus

$$\sigma_f(s) = \int H(s,s')\, \sigma^\circ_f(s')\, ds',$$

$$\sigma^\circ_f(s) = \sigma^\circ_Z + \sigma^\circ_\gamma + \sigma^\circ_{\gamma Z},$$

$$\sigma^\circ_Z = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_f}{\Gamma_Z^2}\frac{s\,\Gamma_Z^2}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2},$$

$$\sigma^\circ_\gamma = \frac{4\pi\alpha^2(s)}{3s} Q_f^2 N_c^f,$$

$$\sigma^{\circ}_{\gamma Z} = -\frac{2\sqrt{2}\alpha(s)}{3}(Q_f G_F N_c^f g_{Ve} g_{Vf}) \frac{(s - M_Z^2)M_Z^2}{(s - M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2},$$

$$\Gamma_f = \frac{G_F M_Z^3}{6\sqrt{2}\pi}(g_{Vf}^2 + g_{Af}^2)\, N_c^f(1 + \frac{3\alpha Q_f^2}{4\pi})(1 + \delta_{QCD}),$$

with
$N_c^f = 3(1)$ for quarks (leptons),
$g_{Vf} = I_3^f - 2Q_f \sin^2\theta_w$, $g_{Af} = I_3^f$,
$\delta_{QCD} = 0$ for leptons,
$\delta_{QCD} = 1.05(\alpha_s/\pi) + 0.9(\alpha_s/\pi)^2 + 13(\alpha_s/\pi)^3$ for quarks.

Note that σ°_{γ} and $\sigma^{\circ}_{\gamma Z} \ll \sigma^{\circ}_{Z}$
In Practice one uses the full formula with best known values of g_V or $\sin^2\theta_w^{eff}$
Thus $\sigma_f^{th}(s) = \mathcal{F}(M_Z, \Gamma_Z, \Gamma_e, \Gamma_f)$, i.e., the calculated cross sections are functions of M_Z,Γ_Z,Γ_e,Γ_f. These are treated as **floating parameters** in fitting the measured cross sections using the usual χ^2 minimising procedure :

$$\chi^2 = \Delta^T V^{-1} \Delta,$$

where $\Delta = (\sigma^{th} - \sigma^{exp})$ and V is the N × N error correlation matrix between measurements. Thus **cross section measurements alone** lead to a determination of M_Z, Γ_Z and other Z°decay partial widths and eventually to N_ν, the number of light neutrino species.

- What do **asymmetry** measurements tell us ? They allow us to determine $\mathbf{g_A}$ and g_V (or $\sin^2\theta_w$) **separately**. One should remember the conventional 'on-shell' definition of $\sin^2\theta_w = 1 - M_W^2/M_Z^2$ whereas LEP I measures 'radiatively corrected' $\sin^2\theta_w^{eff}(M_Z)$

  In the **Improved Born Approximation** [4] it is sufficient to replace the quantity by its 'effective' values at M_Z. Thus the tree level expression for Γ_{lept} :

$$\Gamma_{lept} = \frac{G_F M_Z^3}{6\sqrt{2}\pi}(g_{Vf}^2 + g_{Af}^2)(1 + \frac{3\alpha}{4\pi})$$

which one can rewrite as

$$\Gamma_{lept} = \frac{G_F M_Z^3}{6\sqrt{2}\pi}\rho_{tree}(1 + g_{Vf}^2/g_{Af}^2)(1 + \frac{3\alpha}{4\pi})$$

and then recast as

$$\Gamma_{lept} = \frac{G_F M_Z^3}{6\sqrt{2}\pi}\rho_{eff}(1 + g_{Vf}^2/g_{Af}^2)(1 + \frac{3\alpha}{4\pi}),$$

where, henceforth g_A, g_V refer to radiatively corrected 'effective' quantities.

Expressions for Various Asymmetries studied at LEP

$$A^{\circ}_{FB}(lept) = \frac{3}{4}A_e A_f,$$

$$P(\tau) = -A_\tau,$$
$$P(\tau)^{FB} = -\frac{3}{4}A_e,$$
$$A^{o}_{FB}(b\bar{b}) = \frac{3}{4}A_e A_b,$$

where $A_f = 2g_{Vf}.g_{Af}/(g^2_{Vf} + g^2_{Af})$; $\sin^2\theta^{eff}_W = 0.25(1 - g_{Vf}/g_{Af})$.
Thus, the inclusion of asymmetry measurements in the fit leads to the determination of all the basic EW parameters. The various fits are :

use 5 parameter fit to determine

$M_Z, \Gamma_Z, \Gamma_{had}, \Gamma_{lept}, A^{o}_{fb}$ or $M_Z, \Gamma_Z, \sigma^{o}_{had}, R_{lept}, A^{o}_{fb}$,

where $R_{lept} = \Gamma_{had}/\Gamma_{lept}$, $\sigma^{o}_{had} = 12\pi\Gamma_e\Gamma_f/M^2_Z\Gamma^2_Z$.

use 9 parameter fit to determine

$M_Z, \Gamma_Z, \Gamma_{had}, \Gamma_e, \Gamma_\mu, \Gamma_\tau, A^{o}_{fb}(e), A^{o}_{fb}(\mu), A^{o}_{fb}(\tau)$ or

$M_Z, \Gamma_Z, \sigma^{o}_{had}, R_e, R_\mu, R_\tau, A^{o}_{fb}(e), A^{o}_{fb}(\mu), A^{o}_{fb}(\tau)$.

- **Systematic Errors**

  In addition to the **statistical** errors, there exist **systematic** errors due mainly to **selection procedures**, and theoretical uncertainties. The values of these errors on the various cross sections are given in Table 1 for LEP 1990 + 1991 data [5]

Table 1: Systematic Errors for LEP Experiments

90 + 91 data	ALEPH	DELPHI	L3	OPAL
$\Delta\sigma_{sys}(had)$	0.2%	0.3%	0.2%	0.2%
$\Delta\sigma_{sys}(ee)$	0.4%	0.5%	0.5%	0.4%
$\Delta\sigma_{sys}(\mu\mu)$	0.5%	0.4%	0.5%	0.3%
$\Delta\sigma_{sys}(\tau\tau)$	0.5%	0.9%	0.7%	0.8%
$\Delta\sigma_{sys}(lumi)$	0.45%	0.55%	0.6%	0.7% (90)

The value of integrated luminosity (L_{int}) is obtained by counting the number of small angle e^+e^- events and normalizing to the calculated theoretical cross section. Thus the systematic error on luminosity measurement affects the errors on all cross sections. There are two main contributions to this error : one coming from the uncertainty in the geometry of the luminosity monitor (the value of the inner radius being the critical factor) and the second coming from the theoretical uncertainty due to ignoring higher order terms etc in the Monte Carlo programs. The most recent, BHLUMI [6], gives a theoretical uncertainty of $\sim$ 0.3 %.

For the large angle e^+e^- final state one has a contribution not only due to s-channel but also due to t-channel and s-t interference. The full amplitude is not amenable to fast calculation which is essential if one has to carry out minimisation fits within reasonable computer time. Thus the standard procedure is to calculate the non-s channel part of the cross section separately using the SM program ALIBABA [7] and add it by hand to the s-channel cross section. As the calculation in ALIBABA itself has some inherent error (~ 0.5 %) this introduces a theoretical systematic error into $\Delta\sigma_{sys}(ee)$. The non-s channel contribution decreases with E_{cm} being about 15 % on the peak. The average theoretical systematic error used by the LEP experiments is 0.3 %.

- **LEP machine errors [8]**

  The Working Group on LEP energy measurements has determined the overall energy uncertainty in the values of E_{cm} which leads to a value of $\Delta\ M_Z = 6.3$ MeV. Point-to-point energy setting errors lead to an uncertainty in Γ_Z which is estimated to be $\Delta\ \Gamma_Z = 4.5$ MeV.

- **Program Package Used**

  - DELPHI, L3, OPAL $\Rightarrow$ ZFITTER [9] (Dubna Zeuthen);
  - ALEPH $\Rightarrow$ MIZA [10] (Hollik, ALEPH);

  ZFITTER Model Independent Mode :

  Input parameters $\rightarrow M_Z, \Gamma_Z, \Gamma_{lept}{}^i, \Gamma_{had}$.

  Output $\rightarrow \sigma_i(s)$, i = e, μ, τ, hadrons

  or

  Input parameters $\rightarrow M_Z, \Gamma_Z, \Gamma_{had}, g_A{}^i, g_V{}^i$.

  Output $\rightarrow \sigma_i(s)$, i = e, μ, τ, hadrons, $A^i_{fb}(s)$, $P(\tau)$, etc.

  ZFITTER Standard Model Mode :

  Input parameters $\rightarrow M_Z, M_{top}, M_{Higgs}, \alpha_S$.

  Output $\rightarrow$ Everything $(\Gamma_Z, \Gamma_{lept}{}^i, g_A{}^i, g_V{}^i)$

  $\Rightarrow \sigma_i(s)$, i = e, μ, τ, hadrons, $A^i_{fb}(s)$, $P(\tau)$, etc.

  - One can put in $\theta_{acc}, \theta_{acol}, E_{min}$ cuts.

5. Results

5.1. Model Independent Fits

As mentioned in section 3, all LEP experiments carry out 5 and 9 parameter model independent fits to determine various Z° parameters. The results from such fits are shown in Table 2 [5]. In calculating the LEP averages care has been taken to take properly into account the common systematic errors (the theoretical errors in luminosity and in large angle e^+e^- cross sections and the LEP machine errors). An example of the L3 cross section and lepton asymmetry data is shown in Fig. 1 along with the fitted curves.

Thus one sees from Table 2 that both M_Z and Γ_Z are now determined with a 7 MeV error out of which 6.3 MeV and 4.5 MeV, respectively, is due to the LEP machine uncertainties.

Table 2: Number of Z° Events and Model Independent Results

Parameter	ALEPH	DELPHI	L3	OPAL	LEP avge
Z → hadron evts	452 K	368 K	425 K	454 K	
Z → lepton evts	53 K	35 K	41 K	54 K	
M_Z (MeV)	91187±9	91188±10	91195±9	91180±9	91187±7
Γ_Z (MeV)	2501±12	2488±12	2490±11	2483±12	2490±7
σ^o_{had} (nb)	41.60±.27	40.86±.28	41.34±.28	41.01±.41	41.25±.18
R_{lept}	20.78±.13	20.82±.16	21.00±.15	20.87±.13	20.86±.07
A^o_{fb}(%)	1.54±.48	2.02±.59	2.25±.66	0.76±.48	1.52±.27
R_e	20.69±.21	20.79±.28	21.09±.25	21.01±.26	20.87±.12
R_μ	20.88±.20	20.92±.22	21.13±.22	20.65±.18	20.88±.10
R_τ	20.77±.23	20.69±.30	20.67±.27	21.16±.25	20.83±.13
$A^o_{fb}(e)$(%)	1.40±.93	1.30±1.3	1.55±1.27	-0.20±1.2	1.05±.57
$A^o_{fb}(\mu)$(%)	0.74±.72	1.48±.83	2.37±.90	0.47±.76	1.14±.40
$A^o_{fb}(\tau)$(%)	2.69±.82	3.30±1.0	2.76±1.3	1.65±.82	2.50±.47
Γ_{lept} (MeV)					83.34±.30
Γ_e (MeV)	84.15±.59	83.02±.68	83.00±.61	82.56±.69	83.24±.36
Γ_μ (MeV)	83.38±.96	82.50±1.07	82.83±1.0	84.00±.99	83.27±.52
Γ_τ (MeV)	83.82±1.07	83.42±1.36	84.68±1.2	81.97±1.2	83.40±.62
Γ_{inv} (MeV)					505.0±7.0
N_ν	2.97±.05	3.10±.06	2.98±.06	3.06±.08	3.03±.04

• The number of light neutrinos is determined by using the relation

$$N_\nu = \left(\frac{\Gamma_{inv}}{\Gamma_{lept}}\right)_{meas} \left(\frac{\Gamma_{lept}}{\Gamma_\nu}\right)_{SM}$$

which eliminates its dependence on unknown values of M_{top} and M_{Higgs}. The value is now 24 standard deviations away from 4.

• Using $R_{lept} = R^{SM}_{lept}(\alpha_S = 0)(1 - \delta_{QCD})$
with $\delta_{QCD} = 1.05(\alpha_S/\pi) + 0.9(\alpha_S/\pi)^2 + 13(\alpha_S/\pi)^3$,
the measured value of $R_{lept} = 20.86 \pm 0.07$ leads to a determination of the strong coupling constant $\alpha_S = 0.130 \pm 0.011$.

Figs. 2-6 show the fitted values of M_Z, Γ_Z, σ^o_{had}, R_{lept} and A^o_{fb}. One sees that the LEP average values fall within the expectation from SM using reasonable values for M_{top}, M_{Higgs} and α_S. Figs. 5 and 6 also show that lepton universality is satisfied within errors. This is also shown in Fig. 7 using the g_A vs g_V contour plot for leptons. Recently the so called 'oblique parameters' ϵ_1 and ϵ_3 have also been used which show the effects of 'new physics' more directly [11]. Fig. 8 depicts the ϵ_1 vs ϵ_3 plot along with the SM prediction. Finally in Fig. 9 we summarize the LEP situation on $\sin^2\theta^{eff}_W$. The values obtained using different asymmetries are depicted in the top four points and their average is shown as the fifth point. These are model independent determinations. Next we show the value of $\sin^2\theta^{eff}_W$ determined using the SM relation

$$\Gamma_{lept} = \frac{K^{lept}_{eff}\,\alpha(M_Z)M_Z}{48\sin^2\theta^{eff}_W\cos^2\theta^{eff}_W}[1 + (1 - 4\sin^2\theta^{eff}_W)^2]\;(1 + \frac{3\alpha}{4\pi}).$$

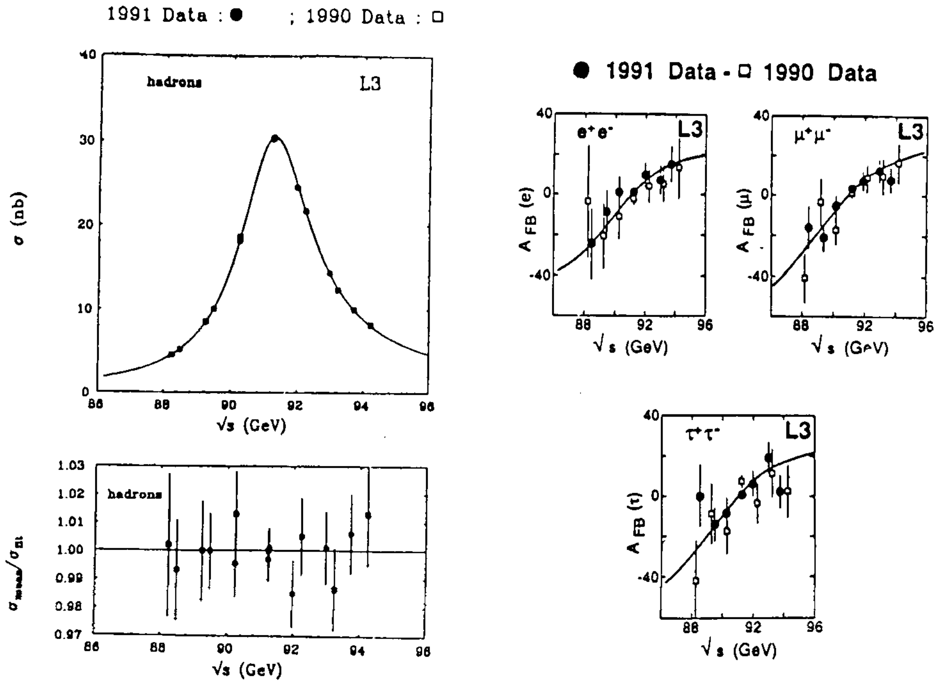

Figure 1. The L3 cross section and lepton asymmetry data along with the fitted curves.

The measured values of M_Z and Γ_{lept} from Table 2 and the Standard Model value of $K_{eff}^{lept} = 1.0070^{+0.0012}_{-0.0024}$ is used. The latter has been calculated for $M_{top} = 150^{+100}_{-60}$ and $M_{Higgs} = 300^{+700}_{-240}$ GeV respectively. Although the error on $\sin^2\theta_w^{eff}$ using this method is small it does involve the Standard Model relation given above which is why we list it separately. Finally, if one combines this measurement with the average $\sin^2\theta_w^{eff}$ obtained from asymmetry measurements the best LEP value for $\sin^2\theta_w^{eff} = 0.2330 \pm 0.0007$.

5.2. Fits in the Standard Model Framework

An input of the parameters M_Z, M_{top}, M_{Higgs} and α_S is sufficient to calculate all the Z° parameters within the Standard Model framework. In practice, since the dependence on Higgs mass is only logarithmic, one fixes the value of M_{Higgs} to a central (300 GeV), upper (1000 GeV) and lower (60 GeV) limiting values and floats the other parameters to obtain their best fitted values. Table 3 depicts the results so obtained. The fitted value of M_Z is not shown as it comes out to be exactly as from the model independent fits.

The first row of Table 3 corresponds to the use of the cross sections and F/B lepton asymmetry data in the SM fit. For the fit in the second row we include constraints on $\sin^2\theta_w^{eff}$ obtained from other LEP asymmetry measurements (F/B $b\bar{b}$, $P(\tau)$ and F/B $P(\tau)$. For the third row the $\sin^2\theta_w^{eff}$ constraint using lineshape (M_Z, Γ_{lept}, as mentioned above) is also included. Finally in the last row additional

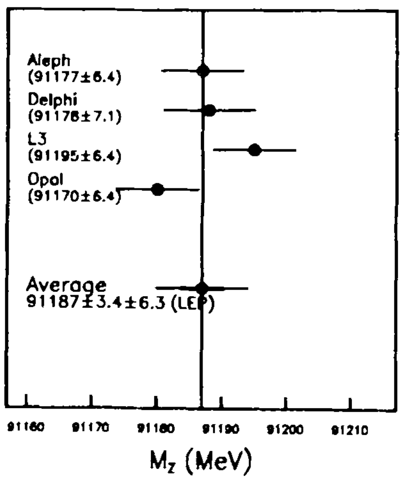

Figure 2. Fitted values of M_Z from the 4 LEP experiments.

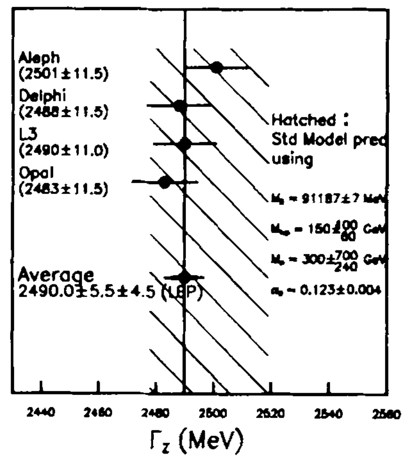

Figure 3. Fitted values of Γ_Z from the 4 LEP experiments along with the Standard Model expectation.

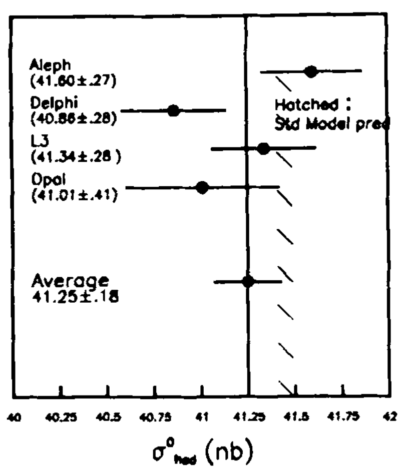

Figure 4. Fitted values of σ^0_{had} from the 4 LEP experiments along with the Standard Model expectation.

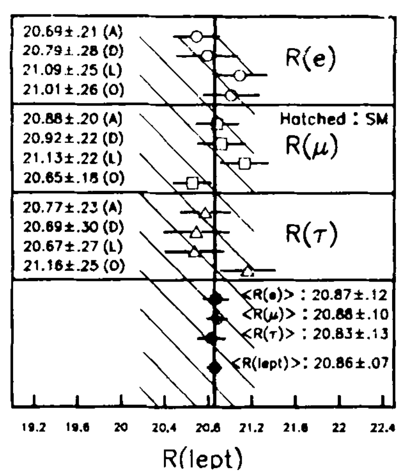

Figure 5. Fitted values of R_{lept} from the 4 LEP experiments along with the Standard Model expectation.

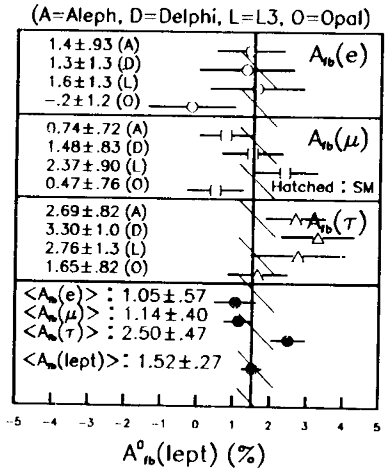

Figure 6. Fitted values of A°_{fb} from the 4 LEP experiments along with the Standard Model expectation.

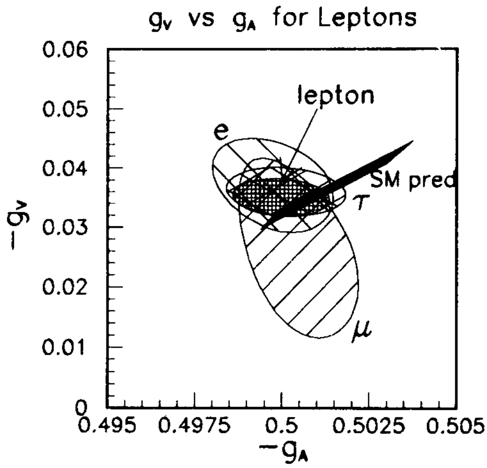

Figure 7. g_A vs g_V contour plot for leptons along with the Standard Model expectation.

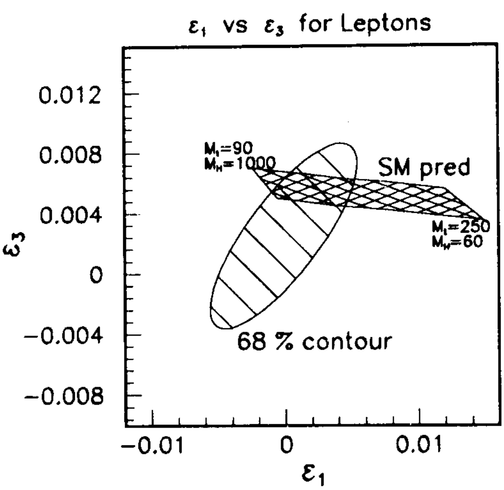

Figure 8. The ϵ_1 vs ϵ_3 plot along with the SM prediction.

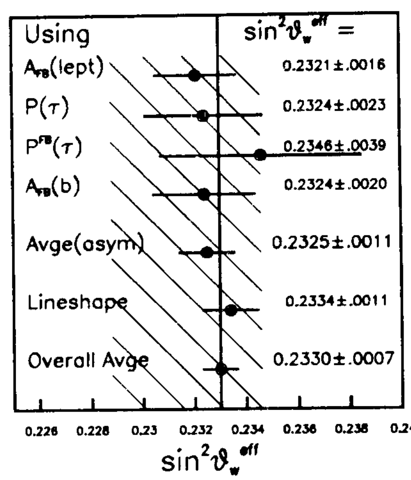

Figure 9. Measurements of $\sin^2\theta_w^{\rm eff}$ from different asymmetries and line shape data.

Table 3: Results in Standard Model Framework α_S unconstrained

Data Used	M_{top} fitted	α_S fitted
LEP 5 par. fit	134^{+30+18}_{-38-18}	$0.134 \pm 0.009 \pm 0.002$
$\sin^2\theta_w^{eff}$(LEP asym)	142^{+24+19}_{-29-21}	$0.133 \pm 0.009 \pm 0.002$
$\sin^2\theta_w^{eff}$(LEP line sh.)	140^{+21+20}_{-24-25}	$0.133 \pm 0.008 \pm 0.002$
Coll + CHARM	139^{+18+21}_{-20-23}	$0.133 \pm 0.008 \pm 0.002$

information on the ratio M_W/M_Z (from $p\overline{p}$ colliders) and $\sin^2\theta_w$ (from low energy ν scattering) is used. There is a correlation between the fitted values of M_{top} and α_S and this is depicted in the contour plot shown in Fig. 10 where 68 % and 95 % contours are shown.

In order to find the best possible value of M_{top} one constrains the value of α_S to that determined from methods other than lineshape : from the event shape variables and the energy-energy correlations. Then carrying out the same fits as shown in Table 3 , but now **constraining α_S = 0.123 ±0.004** [12] one obtains the results as shown in Table 4.

Table 4: Results in Standard Model Framework α_S constrained to 0.123 ± 0.004

Data Used	M_{top} fitted	α_S fitted
LEP 5 par. fit	146^{+26+20}_{-32-20}	0.125 ± 0.004
+ $\sin^2\theta_w^{eff}$(LEP asym)	150^{+22+19}_{-26-22}	0.125 ± 0.004
+ $\sin^2\theta_w^{eff}$(LEP line sh.)	145^{+19+21}_{-22-25}	0.125 ± 0.004
+ Coll + CHARM	143^{+17+20}_{-19-23}	0.125 ± 0.004

Thus, LEP has allowed the indirect determination of M_{top} via the radiative correction formulation in the SM framework : $M_{top} = 145^{+19+21}_{-22-25}$ from LEP data alone and $M_{top} = 143^{+17+20}_{-19-23}$ from all available data. **As one sees the situation has been reached where the additional use of non-LEP data does not significantly reduce the errors on M_{top}.**

Having carried out these SM fits, other quantities can also be derived : $\sin^2\theta_w^{eff} = 0.2331 \pm 0.0006$, $M_W = 80.14 \pm 0.12$ GeV from LEP data alone and $\sin^2\theta_w^{eff} = 0.2332 \pm 0.0005$, $M_W = 80.13 \pm 0.11$ GeV using all available data

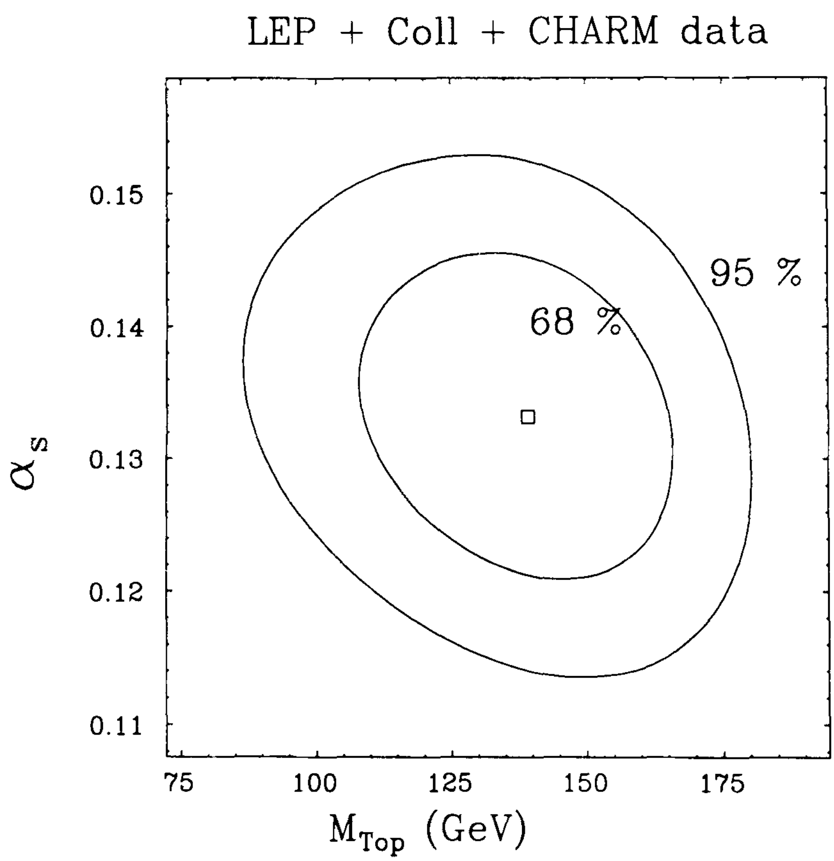

Figure 10. 68 % and 95 % contours of the Standard Model fit with M_{top} and α_S as free parameters.

6. Conclusions and Future

- Upto 1991 data fully analysed
  Z°, Standard Model parameters determined with HIGH PRECISION
  ⇒ **STANDARD MODEL HOLDS**
- Analysis of 1992 data awaited (~700 K evts/expt)
  1992 data taken ONLY on Z° PEAK,
  No improvement expected in ΔM_Z, $\Delta\Gamma_Z$
  EXPECT improvement in $\Delta\Gamma_i, \Delta\sin^2\theta_w^{eff}$, ΔM_{top}
- 1993, 1994 Data to be taken (expect ~1.5-2.0 M evts/expt)
  To match the future very high statistics data LEP experiments are going in for LUMINOSITY MONITOR upgrades to REDUCE syst err on cross sections due to luminosity uncertainty. A matching THEORETICAL effort is also going on.

- **SLC**

  With polarised beams and measurement of A_{LR} at SLC the value of $\sin^2\theta_w^{eff}$ will be much better constrained - even with a sample of 50 K Z^o's, since the sensitivity of $\sin^2\theta_w^{eff}$ to A_{LR} is very great.

- **The top quark**

  If the top quark is discovered in the near future in the Tevatron experiments, then the precision LEP data will be used to constrain the mass of the Higgs again within the Standard Model framework.

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