Precision Electroweak Experiments at LEP

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Abstract

During the operation of the LEP e^+e^- collider at the Z resonance from 1989 to 1995 the four experiments ALEPH, DELPHI, L3 and OPAL have collected about 16 million decays of the Z into hadrons and charged leptons. The precise measurements of the total cross section allow an accurate determination of the properties of the Z. Including data up to 1994 one obtains for the mass, the total and partial widths:

$$\begin{array}{rclcrcl} m_Z & = & 91\,188.4 \pm 2.2 \text{ MeV} & & \Gamma_Z & = & 2\,496.3 \pm 3.2 \text{ MeV} \\ \Gamma_{\mathrm{had}} & = & 1\,744.8 \pm 3.0 \text{ MeV} & & \Gamma_\ell & = & 83.93 \pm 0.14 \text{ MeV}. \end{array}$$

The number of light neutrino families is deduced to be $N_\nu = 2.991 \pm 0.016$ leaving only little room for Z decays into unknown invisible particles.

Precise measurements of forward-backward asymmetries of leptons and quarks as well as the tau-polarization determine the effective weak mixing angle to $\sin^2\bar{\vartheta}_W = 0.2318 \pm 0.0004$. Electroweak observables studied at LEP are found to be in good agreement with the Standard Model and a top quark mass of

$$m_t = 170 \pm 10\,^{+17}_{-19}(m_H) \text{ GeV}.$$

can be derived from the measurements. This Standard Model prediction is now confirmed by the direct observation and mass measurement of the top quark in $p\bar{p}$ experiments.

year	$\int\mathcal{L}\,\mathrm{dt}$ [pb^{-1}]	center-of-mass energy
1990	7.6	m_Z, $m_\mathrm{Z} \pm$ 1, 2, 3 GeV
1991	17.3	m_Z, $m_\mathrm{Z} \pm$ 1, 2, 3 GeV
1992	28.6	m_Z
1993	40.0	m_Z, $m_\mathrm{Z} \pm$ 2 GeV
1994	64.4	m_Z
1995	39.7	m_Z, $m_\mathrm{Z} \pm$ 2 GeV

Table 1: Integrated luminosity delivered by LEP to each of the four experiments 1990–95. The approximate center-of-mass energies of the LEP runs are also indicated.

Introduction

The Standard Model (SM) of electroweak interaction [1] describes very successfully past and present experiments on charged and neutral current interactions. The experiments performed at LEP studying the production and decay of Z bosons have tremendously improved the precision of the neutral current sector of the SM. From the precise measurements of total cross sections one fundamental input parameter of the SM, the mass of the Z, is obtained with an unprecedented precision. The total and partial decay widths deduced from these measurements determine the number of light neutrino families.

The observed lepton forward-backward asymmetries and the tau-polarization measurements enable the experiments to determine the weak mixing angle and the coupling constants of the Z to charged leptons. Comparing these couplings among the three fermion generations tests one of the cornerstones of the SM: the concept of lepton universality. The precision measurements at the Z resonance are sensitive to weak radiative corrections originating from the large top quark mass. Comparing the value of m_t derived from this measurement with the result from the direct observation is a stringent test of the SM beyond the tree level.

In this article the experimental results on electroweak parameters of the LEP experiments based on the data accumulated from 1989 to 1994 are summarized. At the end the prospects for further improvements for tests of the SM of electroweak interactions at LEP are discussed.

The LEP collider and the detectors

The Large Electron Positron collider LEP at CERN [2] was commissioned in 1989 and has been very successfully operated ever since. As can be seen from tab. 1 the integrated luminosity has been continuously increased such that 200 pb^{-1} have been delivered to each experiment by the end of 1995. The first part of the physics program, running at the Z resonance to determine its properties, has been completed in October 1995. By then the four experiments ALEPH, DELPHI, L3 and OPAL have observed in total about 16 million decays of the Z into hadrons and charged leptons. Results on total cross section and forward-backward asymmetry measurements up to 1992 are published [3, 4, 5, 6]. Preliminary results of the 1993/94 runs are available and included here following reference [7].

The large number of accumulated events enables the experiments to study the detectors in great detail and to make full use of the their capabilities. The systematic error, excluding the

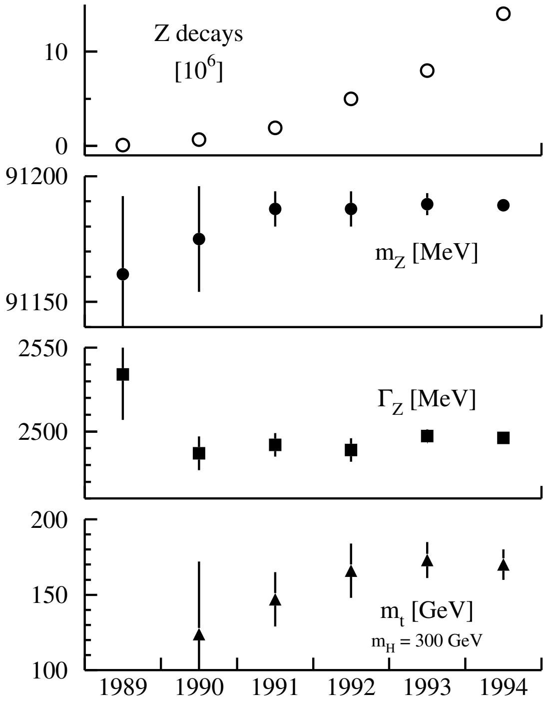

Figure 1: Progress in precision achieved by the LEP experiments from 1989 to 1994. Shown are the accumulated total number of Z decays together with the combined preliminary results for m_Z, Γ_Z and m_t (for fixed $m_H = 300$ GeV) as quoted at summer conferences.

contribution from luminosity, on the cross section $e^+e^- \to$ hadrons is as low as 0.1% and $0.2-0.4\%$ for leptonic Z decays. In the leptonic channels the systematic and statistical errors match nicely as the typical number of events for each species and experiment is 100–150 thousand. Due to the installation of second generation luminometers, e.g. [8], the experimental error on the luminosity is typically 0.1% to which a theoretical error (0.16%) common to all experiments from the calculation of the low angle Bhabha scattering [9] cross section must be added.

The steady increase in statistics and improvement in performance of the LEP machine and the detectors is reflected in a continuous improvement in the precision of Z parameters. Fig. 1 shows together with the accumulated number of events the measurements of the mass, the total width and the weak radiative corrections expressed as an estimate for the mass of the top quark [10, 7].

An important item for the measurement of the mass and total width of the Z is the precise knowledge of the LEP beam energy. The technique successfully used at LEP is the energy measurement by resonant depolarization [11]. In 1993 the beam energy has been calibrated 24 times at the end of luminosity runs at both energies $m_Z \pm 2$ GeV [12]. The contribution to the error on the Z mass and total width from the knowledge of the LEP beam energy is estimated to be:

$$\Delta m_Z = 1.5 \text{ MeV} \qquad \Delta\Gamma_Z = 2.0 \text{ MeV} \tag{1}$$

The error on Γ_Z includes the uncertainty due to the beam energy spread [7]. These errors are correlated among the four LEP experiments which has to be taken into account when averaging the results.

Results derived from the measurement of total cross sections

The LEP experiments measure the total cross sections of the four reactions

$$\begin{array}{ll} e^+e^- \to \text{hadrons} & e^+e^- \to e^+e^- \\ e^+e^- \to \mu^+\mu^- & e^+e^- \to \tau^+\tau^- \end{array}$$

as a function of the center-of-mass energy around the Z resonance. In a common fit to this set of cross section measurements six quantities are derived:

- The peak position yields the mass m_Z
- The width of the resonance curve yields the total widths Γ_Z
- The peak cross sections determine the partial widths of the Z decaying into hadrons, electrons, muons and taus:

$$\sigma_f^0(m_Z^2) = \frac{12\,\pi}{m_Z^2}\,\frac{\Gamma_e\,\Gamma_f}{\Gamma_Z^2} \qquad \text{(lowest order)} \tag{2}$$

If lepton universality is assumed the leptonic cross sections are fitted to a common leptonic width and the number of fit parameters reduces to four.

Since about 90% of the observed Z's decay into hadrons the hadronic cross sections dominate the results on the mass and the total width of the Z. As an example, fig. 2 shows the hadronic cross sections obtained by the L3 experiment. The solid line is the result of the Breit-Wigner fit to all cross sections and at the bottom the ratios of the measurements and the fit are shown.

The results obtained for the mass of the Z by the four LEP experiments are summarized in fig. 3[1]. The errors given include the uncertainty from the LEP energy calibration. The χ^2 is estimated from the uncorrelated part of the errors.

Now the mass of the Z is known very precisely:

$$m_Z = 91\,188.4 \pm 2.2 \text{ MeV}. \tag{3}$$

The relative precision $\Delta m_Z/m_Z = 2.4 \cdot 10^{-5}$ is about the same as for the Fermi constant G_F measured from the muon lifetime [13].

The next quantity extracted from the measured cross sections is the total width Γ_Z. In fig. 4 the results of the LEP experiments are summarized. The four experiments agree very well and the combined value is

$$\Gamma_Z = 2\,496.3 \pm 3.2 \text{ MeV}. \tag{4}$$

Knowing m_Z the total width of the Z can be calculated in the SM framework. The width of the Z as a function of the top quark mass obtained from the ZFITTER [14] program is shown at the bottom of fig. 4. For the unknown Higgs mass a value of $m_H = 300$ GeV is assumed, and the hatched band shows the shift of the central value if m_H is varied between its experimental (60 GeV) and theoretical (1 000 GeV) limits [15, 16]. For the strong coupling constant $\alpha_s = 0.123 \pm 0.006$ [17] is used. Comparing the experimental result to the SM expectation one observes a very good agreement for top quark masses around 170 GeV.

The results for the leptonic widths, averaged over the four experiments, are:

$$\Gamma_e = 83.92 \pm 0.17 \text{ MeV} \quad \Gamma_\mu = 83.92 \pm 0.23 \text{ MeV} \quad \Gamma_\tau = 83.85 \pm 0.29 \text{ MeV} \tag{5}$$

[1]The results presented here emerge from a fit to cross sections and forward-backward asymmetries [7]. However, the latter do not contribute significantly to the mass and widths measurements.

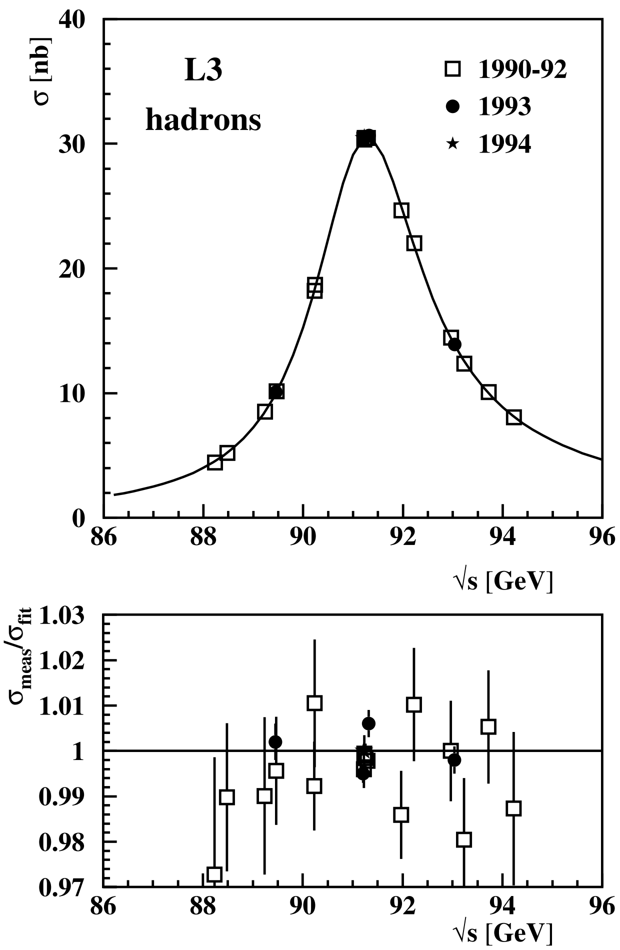

Figure 2: The cross section $e^+e^- \rightarrow$ hadrons at the Z resonance measured by the L3 experiment. The lower plot shows the ratio of the measured cross sections and the fit result together with the statistical error.

Within the errors the partial widths are the same for all three lepton species.

Imposing lepton universality the lepton cross sections are fitted to a common partial width Γ_ℓ. From these fits one obtains the combined values for the leptonic and hadronic width of the Z:

$$\Gamma_\ell = 83.93 \pm 0.14 \text{ MeV} \quad \Gamma_{\text{had}} = 1\,744.8 \pm 3.0 \text{ MeV} \tag{6}$$

Both values are well compatible with the SM expectation.

From the total and partial decay widths into hadrons and leptons the decay width of the Z into invisible particles is derived:

$$\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - 3\,\Gamma_\ell \;= 499.9 \pm 2.5 \text{ MeV} \tag{7}$$

In the SM the Z decays invisibly into neutrino-antineutrino pairs. The experimental result for Γ_{inv} can be converted into a number of neutrino species:

$$N_\nu = 2.991 \pm 0.016 \tag{8}$$

This result firmly proves the existence of three and only three light ($m_\nu \leq m_Z/2$) neutrino species. The small error does not leave much room for the Z to decay into other invisible particles. The

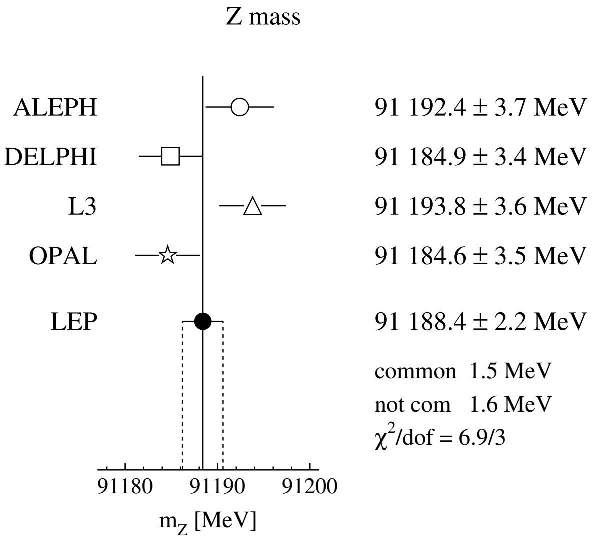

Figure 3: The mass of the Z as determined by the LEP experiments together with the combined result.

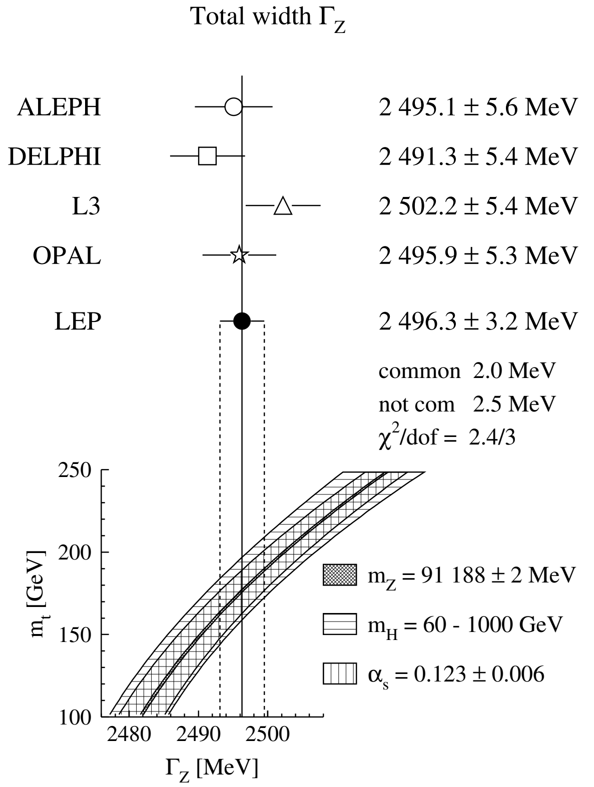

Figure 4: The total width of the Z determined by the LEP experiments together with the combined result and the SM calculation.

invisible width can be measured in an independent way from the study of $e^+e^- \to \nu\bar{\nu}\gamma$ events where only a photon radiated from an electron is observed in the detector. The result [18], even though not as precise as eq. 7, rules out the existence of a fourth light neutrino generation.

From the ratio of hadronic to leptonic width $R_\ell = \Gamma_{\text{had}}/\Gamma_\ell$ a quite precise value for the strong coupling constant at the Z mass $\alpha_s = \alpha_s(m_Z)$ can be derived. In this ratio many experimental and theoretical uncertainties cancel to large extend. Due to QCD corrections in the hadronic final state it depends on α_s [19] and from the LEP average $R_\ell = 20.788 \pm 0.032$ one obtains

$$\alpha_s = 0.124 \pm 0.005 \pm 0.004 \tag{9}$$

in very good agreement with other α_s measurements at LEP [20].

In the SM special vertex corrections from virtual top quark exchange modify the coupling of the Z to the b-quark [21]. Also, new physics with mass dependent couplings might change the partial width of the Z into b-quarks. Experimentally $Z \to b\bar{b}$ decays are best identified through the relatively long lifetime of B-hadrons. Clean samples are obtained from exploiting the silicon micro vertex detectors. For example, fig. 5 shows the distance of reconstructed primary and secondary vertices, divided by the estimated error, for hadronic Z decays in the OPAL detector. Clear enrichment of b-quarks is seen on the right hand side of the distribution.

In the ratio $R_b = \Gamma_b/\Gamma_{\text{had}}$ the universal dependences on m_H and α_s cancel. The preliminary combined result of the LEP experiments

$$R_b = 0.2205 \pm 0.0016 \tag{10}$$

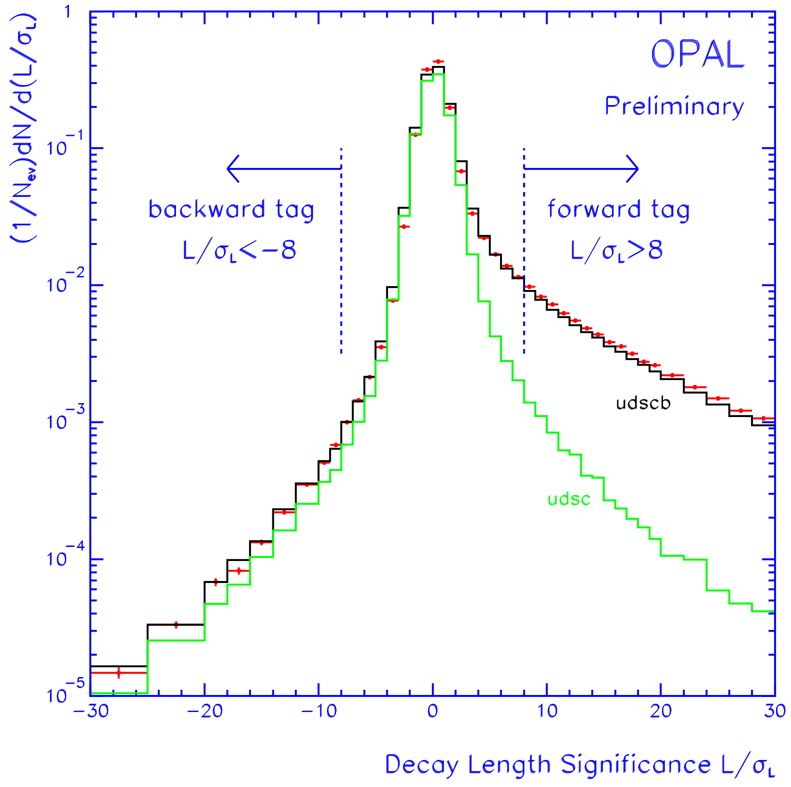

Figure 5: Distance of primary to secondary vertex in unit of the estimated error (decay length significance) for hadronic Z decays from OPAL.

is three standard deviations away from the SM prediction $R_{\mathrm{b}}^{\mathrm{SM}} = 0.2157$ (for $m_{\mathrm{t}} = 175$ GeV). However, further experimental studies in particular on possible correlation of errors are necessary before definite conclusions can be drawn from this result [21].

Measurements of asymmetries

Information on electroweak parameters, in particular the coupling constants of leptons and the weak mixing angle, is derived from the measurements of various asymmetries at the Z pole. LEP experiments measure forward-backward asymmetry of leptons, b- and c-quarks and the tau polarization.

The forward-backward asymmetry A_{FB} is obtained from a fit to the measured polar angle distribution:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} \propto 1 + \cos^2\theta + \frac{8}{3} A_{\mathrm{FB}} \cos\theta \tag{11}$$

where θ is the angle of the incoming electron and the final state particle. As an example fig. 6 shows the differential cross section for $\mathrm{e}^+\mathrm{e}^- \rightarrow \mu^+\mu^-$ as measured at three different center-of-mass energies in 1993 by DELPHI.

The measured A_{FB} values contain QED radiative corrections which depend on the experimental cuts (angular acceptance, acolinearity and minimum momentum cuts) and hence cannot directly be compared among each other. The LEP experiments extract from a fit to the observed asymmetries and total cross sections pole asymmetries $A_{\mathrm{FB}}^{0,\mathrm{f}}$ which are defined by the effective vector and axial-

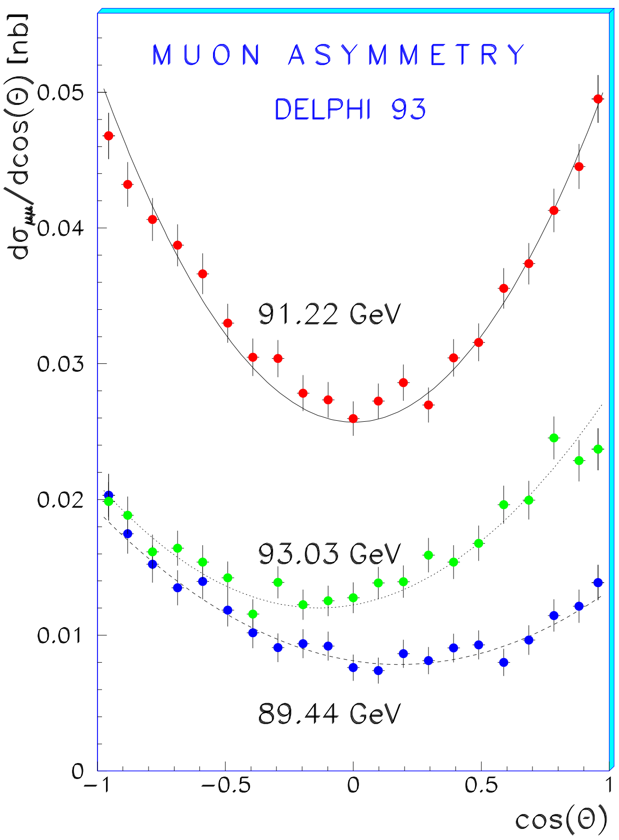

Figure 6: Differential cross section $e^+e^- \rightarrow \mu^+\mu^-$ for the three center-of-mass energies in 1993 obtained by DELPHI.

vector couplings:

$$A_{\rm FB}^{0,\rm f} \equiv \frac{3}{4} A_{\rm e} A_{\rm f} \qquad \text{with } \mathrm{A_f} = \frac{2\,\bar{\rm g}_{\rm A}^{\rm f}\bar{\rm g}_{\rm V}^{\rm f}}{(\bar{\rm g}_{\rm A}^{\rm f})^2 + (\bar{\rm g}_{\rm V}^{\rm f})^2} \tag{12}$$

The results for the three charged lepton species and for heavy (b and c) quarks are all in agreement with the SM (see below).

The tau polarization P_τ is defined as the difference of the production cross sections for right and left handed taus normalized to the total cross section. On the Z peak it can be written (apart from small radiative corrections) as:

$$P_{\tau^-} \equiv \frac{\sigma^R_{\tau^-} - \sigma^L_{\tau^-}}{\sigma^R_{\tau^-} + \sigma^L_{\tau^-}} \approx -A_\tau \tag{13}$$

Experimentally the tau helicity states are interfered from the energy spectra of the tau decay products. All main tau decay channels are exploited: $\tau^- \rightarrow e^-\nu\bar{\nu}$, $\mu^-\nu\bar{\nu}$, $\pi^-\nu$, $\rho^-\nu$, $a_1^-\nu$. The most sensitive final states are the decays into pions and rhos. Generally very good agreement is observed among the different channels. See references [22] for details of the analysis.

Additional information on electroweak couplings is contained in the angular dependence of the tau polarization:

$$P_{\tau^-}(\cos\theta) = -\frac{(1+\cos^2\theta)\,A_\tau + 2\cos\theta\,A_{\rm e}}{(1+\cos^2\theta) + 2\cos\theta\,A_\tau A_{\rm e}} \tag{14}$$

	$\bar{g}_\mathrm{A}$	$\bar{g}_\mathrm{V}$
e^+e^-	-0.5011 ± 0.0005	-0.0368 ± 0.0018
$\mu^+\mu^-$	-0.5011 ± 0.0008	-0.0370 ± 0.0041
$\tau^+\tau^-$	-0.5015 ± 0.0009	-0.0371 ± 0.0018
$\ell^+\ell^-$	-0.5012 ± 0.0004	-0.0369 ± 0.0010

Table 2: The effective axial-vector and vector coupling constants $\bar{g}_\mathrm{A}$ and $\bar{g}_\mathrm{V}$ for charged leptons obtained from LEP total cross section and asymmetry measurements.

Since the electron and tau coupling constants can be obtained from one single measurement this provides an important test of lepton universality. The combined LEP results are:

$$A_\mathrm{e} = 0.1390 \pm 0.0089 \qquad A_\tau = 0.1418 \pm 0.0075 \tag{15}$$

The effective weak mixing angle $\sin^2\bar{\vartheta}_\mathrm{W}$ and the coupling constants of charged leptons

A quantitative comparison of asymmetries can be made in terms of the weak mixing angle. LEP experiments use the effective weak mixing angle defined by the ratio of the effective couplings of the leptons:

$$\frac{\bar{g}_\mathrm{V}}{\bar{g}_\mathrm{A}} \equiv 1 - 4\,\sin^2\bar{\vartheta}_\mathrm{W} \tag{16}$$

The asymmetries described above, corrected only for QED effects, can be converted into $\sin^2\bar{\vartheta}_\mathrm{W}$ independent of the validity of the SM. It should be noted that the b-quark asymmetry is not affected by the special vertex corrections at the $\mathrm{Z} \rightarrow \mathrm{b\bar{b}}$ vertex as is it mainly sensitive to the coupling of the electron [23].

The $\sin^2\bar{\vartheta}_\mathrm{W}$ measurements from LEP are shown in fig. 7. The results obtained from very different processes are all in good agreement and one obtains an overall LEP average of 0.2318 ± 0.0004. Also shown in fig. 7 is the result of the SLD experiment derived from the measurement of the left-right asymmetry [24] which is the most precise single measurement of $\sin^2\bar{\vartheta}_\mathrm{W}$. It is compatible with the LEP results and the overall average yields $\sin^2\bar{\vartheta}_\mathrm{W} = 0.2314 \pm 0.0003$. The comparison with the SM calculation shows that the asymmetries at the Z pole point to the same value for the top quark mass as the measurement of the total width.

The vector and axial vector coupling constants of electrons, muons and taus are determined from the asymmetries at the Z pole and the partial widths (eq. 5): $\Gamma_\ell \propto (\bar{g}^\ell_\mathrm{A})^2 + (\bar{g}^\ell_\mathrm{V})^2$. The results are listed in tab. 2 and fig. 8 shows the allowed in the $\bar{g}_\mathrm{A}$-$\bar{g}_\mathrm{V}$ plane for electrons, muons and taus. The contours are compared to SM predictions for different top and Higgs masses and excellent agreement is found for the three channels.

In the calculation leading to tab. 2 the axial-vector coupling constant of the electron is constrained to negative values. The sign of $\bar{g}^\mathrm{e}_\mathrm{A}$ has been experimentally determined by the combination of neutrino-electron scattering results and forward-backward asymmetries at lower energies [25]. All other signs are unambiguously resolved by LEP measurements. Hence, lepton universality is confirmed in size and sign of the coupling constants to high accuracy by the experiments at the Z.

The test of lepton universality can be quantified by calculating the ratios of muon and tau

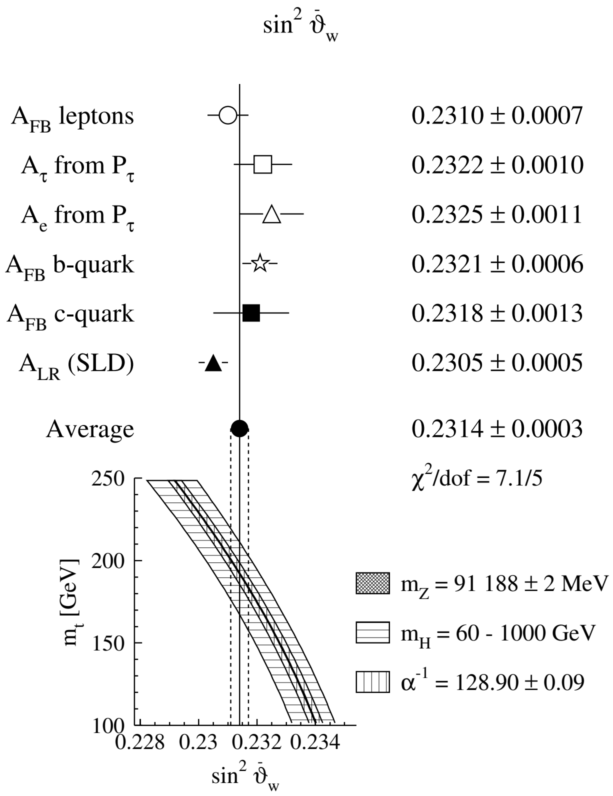

Figure 7: The effective weak mixing angle $\sin^2\bar{\vartheta}_{\mathrm{W}}$ determined from various asymmetries at LEP and from SLD.

coupling constants to those of the electron obeying their correlations:

$$\begin{array}{rclcrcl} \bar{g}_{\mathrm{A}}^{\mu}/\bar{g}_{\mathrm{A}}^{\mathrm{e}} & = & 1.0000 \pm 0.0018 & \qquad & \bar{g}_{\mathrm{V}}^{\mu}/\bar{g}_{\mathrm{V}}^{\mathrm{e}} & = & 1.01 \pm 0.14 \\ \bar{g}_{\mathrm{A}}^{\tau}/\bar{g}_{\mathrm{A}}^{\mathrm{e}} & = & 1.0007 \pm 0.0020 & & \bar{g}_{\mathrm{V}}^{\tau}/\bar{g}_{\mathrm{V}}^{\mathrm{e}} & = & 1.01 \pm 0.07 \end{array} \tag{17}$$

The numbers are all well compatible with unity and hence prove the universality of lepton couplings. In particular, the experimental accuracy on the ratios of axial-vector couplings is $\pm 0.2\%$.

Constraints on SM parameter

As it has been demonstrated in previous sections the precision measurements of electroweak parameters performed at LEP are in good agreement with the SM using a common value for the top quark mass. The experimental results can thus be used to determine m_{t} in the SM framework. The result obtained from a fit to all LEP measurements is

$$m_{\mathrm{t}} = 170 \pm 10\,^{+17}_{-19}(m_{\mathrm{H}})\ \mathrm{GeV} \tag{18}$$

Leaving out R_{b} which is the only measurement not compatible with the SM from the fit increases the central value by 4 GeV without changing the errors.

Using SM relations this result for m_{t} can be converted into other parameters. For instance, eq. 18 corresponds to a $\mathrm{W}^{\pm}$ mass of

$$m_{\mathrm{W}} = 80.295 \pm 0.057\,^{+0.011}_{-0.019}\ \mathrm{GeV} \tag{19}$$

which is in excellent agreement with the direct measurement $m_{\mathrm{W}} = 80.26 \pm 0.16$ GeV at $\mathrm{p\bar{p}}$ colliders [13, 26].

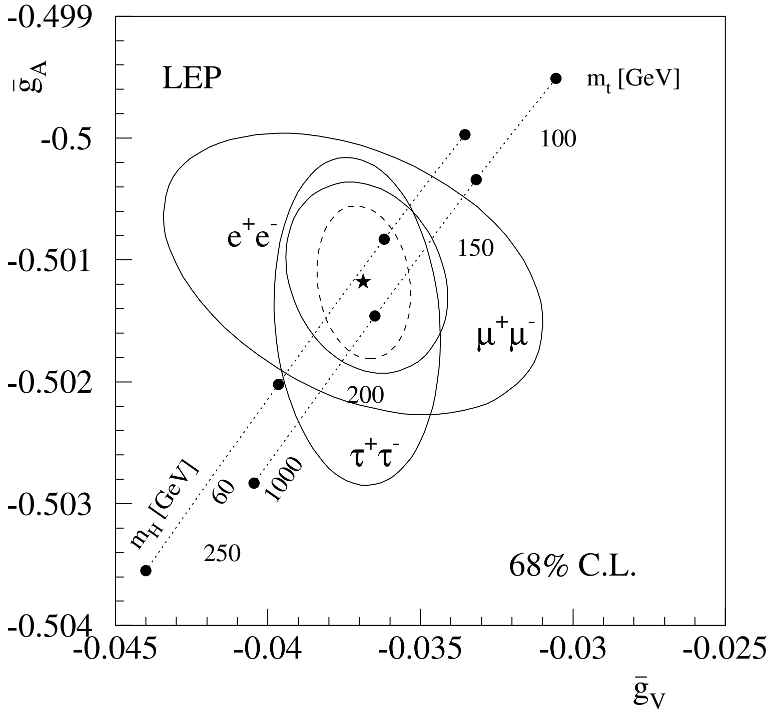

Figure 8: The contours (68% C.L.) in the $\bar{g}_A$-$\bar{g}_V$ plane for electrons, muons and taus from LEP experiments. The broken line is the combined contour for leptons and the star indicates the central value. The filled circles connected by dotted lines show the SM predictions for different m_t and m_H values.

The estimate of m_t in the SM can be improved if the result of SLD, the direct measurement of m_W and results from νN scattering are included in the fit [7]:

$$m_t = 178 \pm 8\,^{+17}_{-20}(m_H) \text{ GeV} \tag{20}$$

With increasing precision the accurate measurements of weak radiative corrections at LEP and SLC have provided predictions for the mass of the top quark (fig. 1). Now the top quark has been observed at Fermilab just at the mass derived from SM relations [27]:

$$\begin{aligned} m_t &= 176 \pm 8 \pm 10 \text{ GeV} \qquad \text{(CDF)} \\ m_t &= 199\,^{+19}_{-21} \pm 22 \text{ GeV} \qquad \text{(D0).} \end{aligned} \tag{21}$$

This discovery is a triumph for the SM since it proves that the major part of the weak radiative corrections does indeed originate from the large mass difference in the top-bottom weak isospin doublet. Non-trivial higher order diagrams like the vacuum polarization of heavy gauge bosons are thus experimentally established [28].

Knowing now the top mass from direct measurement one can try to use the experiments at the Z pole to get an estimate for the last unknown SM parameter: the mass of the Higgs boson [7, 23]. However, Z observables are not very sensitive to the Higgs as weak radiative corrections depend only weakly on the logarithm of m_H. Even though the data seem to favour a low Higgs mass one cannot rule out m_H values close to the theoretical limit of 1 000 GeV.

Outlook

The results on electroweak parameters obtained so far at LEP are much more precise as it was anticipated before the startup [29]. Yet, further improvement can be expected from the final analysis of all LEP data. In particular, the scan of the Z resonance performed in 1995 which has very comparable off-peak luminosity as the scan of 1993 will improve even further the precision on m_Z and Γ_Z and lead to a significant reduction of the error in other observables.

In November 1995 after installation of more superconducting cavities the energy of LEP is increased to $\sqrt{s} = 130 - 140$ GeV. This extends the kinematically accessible range for the search for new particles. The second phase of the LEP program will start in June 1996 with an energy close to the threshold of $e^+e^- \rightarrow W^+W^-$ production ($\sqrt{s} = 161$ GeV). From the cross section at the threshold the mass of the $W^\pm$ will be measured to approximately ± 100 MeV. Then the center-of-mass energy will be increased in steps up to 193 GeV. The goal is to deliver 500 pb^{-1} corresponding to 7 000 $W^\pm$ pairs to each experiment until 1999. At LEP the mass of the W will be determined to better than ± 50 MeV [30] thus adding another precision measurement of an electroweak parameter. The observation of the triple boson coupling and the determination of the W couplings to a few percent will test the gauge structure of the SM. And very importantly, the search for the Higgs boson will be extended to about $m_H \approx 90$ GeV.

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