NEUTRAL CURRENT PHYSICS WITH THE τ LEPTON AT LEP

Invited Talk at the XVI Kazimierz Meeting on Elementary Particle Physics,
"New Physics with New Experiments", Kazimierz, 24 - 28 May 1993

STEFAN KIRSCH
DESY Institut für Hochenergiephysik Zeuthen
Zeuthen, 15738, Germany

ABSTRACT

During the operation of LEP, 138 000 $e^+e^- \longrightarrow \tau^+\tau^-$ events have been collected up to the end of 1992. In the following, the measurements of the total cross section, σ_{tot}, the forward-backward asymmetry, $\mathcal{A}_{fb}$, and the two polarization asymmetries, $\mathcal{A}_{pol}$ and $\mathcal{A}_{fb-pol}$, are reviewed. The partial width of the Z boson to τ leptons is measured to be $\Gamma_\tau = 83.28 \pm 0.49$MeV. The results for the asymmetries at $\sqrt{s} = m_Z$ are: $\mathcal{A}^\tau_{fb} = 0.0210 \pm 0.0034, \mathcal{A}_{pol} = -0.142 \pm 0.017, \mathcal{A}_{fb-pol} = -0.098 \pm 0.019$. The process $e^+e^- \longrightarrow \tau^+\tau^-$ is the channel with the highest sensitivity to the neutral current couplings at LEP. The τ couplings determined to be $v_\tau = 0.0389 \pm 0.0037$ and $a_\tau = 0.4999 \pm 0.0015$. A model independent measurement of the helicity amplitudes was performed for the first time. All the measurements of the process $e^+e^- \longrightarrow \tau^+\tau^-$ confirm the Standard Model.

1. Introduction

By analysing the decay of the Z boson into τ lepton pairs at LEP, one has the unique possibility to measure all four helicity amplitudes that contribute to the process $e^+e^- \longrightarrow \tau^+\tau^-$. By measuring the total cross section, σ_{tot}, the forward-backward asymmetry, $\mathcal{A}_{fb}$, the polarization asymmetry, $\mathcal{A}_{pol}$, and the forward-backward polarization asymmetry, $\mathcal{A}_{fb-pol}$, a complete analysis of the neutral current can be performed only in the τ channel.
The polarization asymmetries in particular allow to measure the couplings of the Z boson to the initial and final state fermions independently. That means that e $-$ τ universality can be tested in one single decay mode of the Z boson. Furthermore, independent precise measurements of the weak mixing angle, $\sin^2\theta_W^{\rm eff}$, are possible.
In the following sections the measurements of the four LEP experiments (ALEPH, DELPHI, L3 and OPAL) for the total cross section and the three asymmetries in the τ channel are reviewed. The results for the 1990-91 data are final, if not stated otherwise, and have been published [1−11]. The results presented for 1992 data are preliminary. The LEP experiments are described elsewhere [12−15].

2. The process $e^+e^- \longrightarrow \tau^+\tau^-$

Assuming the Z boson couples to fermions only via vector and axial-vector couplings, the process $e^-e^+ \rightarrow Z \rightarrow \tau^-\tau^+$ can be subdivided into the following four subprocesses [16]:

$$
\begin{array}{lllll}
R_Z^0 & = & R_Z(e_L^- e_R^+ \longrightarrow \tau_L^- \tau_R^+) & = & \kappa(v_e + a_e)(v_\tau + a_\tau)\,, \\
R_Z^1 & = & R_Z(e_L^- e_R^+ \longrightarrow \tau_R^- \tau_L^+) & = & \kappa(v_e + a_e)(v_\tau - a_\tau)\,, \\
R_Z^2 & = & R_Z(e_R^- e_L^+ \longrightarrow \tau_R^- \tau_L^+) & = & \kappa(v_e - a_e)(v_\tau - a_\tau)\,, \\
R_Z^3 & = & R_Z(e_R^- e_L^+ \longrightarrow \tau_L^- \tau_R^+) & = & \kappa(v_e - a_e)(v_\tau + a_\tau)\,,
\end{array}
\tag{1}
$$

with

$$
\kappa = \frac{G_\mu m_Z^2}{2\sqrt{2}\pi\alpha}\,, \tag{2}
$$

where the upper index of the fermions is for the charge and the lower for the helicity. The right part of Eq. 1 shows the helicity amplitudes R_Z^i as a function of effective vector and axial-vector couplings. Each helicity amplitude, R_Z^i, corresponds to a cross section σ^i. There are four linear independent combinations of these cross sections, which are observable at LEP:

$$
\begin{array}{lll}
\sigma_{tot}(s) & = & +\sigma^0 + \sigma^1 + \sigma^2 + \sigma^3\,, \\
\sigma_{fb}(s) & = & +\sigma^0 - \sigma^1 + \sigma^2 - \sigma^3\,, \\
\sigma_{pol}(s) & = & +\sigma^0 - \sigma^1 - \sigma^2 + \sigma^3\,, \\
\sigma_{fb-pol}(s) & = & +\sigma^0 + \sigma^1 - \sigma^2 - \sigma^3\,.
\end{array}
\tag{3}
$$

Experimentally one determines these four cross sections by measuring the total cross section and the three asymmetries:

$$
\mathcal{A}_A(s) = \frac{\sigma_A(s)}{\sigma_{tot}(s)}\,; \quad A = fb, pol, fb - pol. \tag{4}
$$

As defined below, at a center-of-mass energy equal to the mass of the Z boson, these quantities can be expressed as a function of the couplings :

$$
\begin{array}{lll}
\sigma_{tot}(s = M_Z^2) & \sim & (a_e^2 + v_e^2)(a_\tau^2 + v_\tau^2) \sim \Gamma_e \Gamma_\tau\,, \\
\mathcal{A}_{fb}(s = M_Z^2) & = & \frac{3}{4}\mathcal{A}_e \mathcal{A}_\tau\,, \\
\mathcal{A}_{pol}(s = M_Z^2) & = & -\mathcal{A}_\tau\,, \\
\mathcal{A}_{fb-pol}(s = M_Z^2) & = & -\frac{3}{4}\mathcal{A}_e\,,
\end{array}
\tag{5}
$$

with

$$
\mathcal{A}_l = 2\frac{a_l v_l}{a_l^2 + v_l^2}\,. \tag{6}
$$

3. τ Events at LEP

Until the end of 1992 the four LEP experiments had collected a sample of 138 000 $e^+e^- \longrightarrow \tau^+\tau^-$ events. Tab. 1 shows the number of collected events for

Table 1: The number of $\tau^+\tau^-$ events collected until the end of 1992 by the four LEP experiments.

ALEPH	DELPHI	L3	OPAL
47k	25k	25k	46k

the single experiments. Due to the high center-of-mass energy at LEP an $e^+e^- \longrightarrow \tau^+\tau^-$ event is characterized by two highly collimated back-to-back jets, with low multiplicity. One observes also a certain amount of invisible energy, because the neutrinos from the τ decay escape detection. Furthermore, certain decay modes of the τ are characterized by the presence of neutral particles. The main background sources are:

- $e^+e^- \longrightarrow q\bar{q}$, can be easily identified by the high track multiplicity in the jets;
- $e^+e^- \longrightarrow e^+e^-$, characterized by a high energy deposition in the electromagnetic calorimeter ($E_{ECAL} \approx 2E_{BEAM}$) and two back-to-back tracks;
- $e^+e^- \longrightarrow \mu^+\mu^-$, which has typically two tracks in the muon chambers with a momentum close to the beam energy;
- $e^+e^- \longrightarrow e^+e^-X$, characterized by low energy deposition and low momentum tracks, which are highly acollinear.

In contradiction to the selection of the other leptonic decay modes of the Z boson, one has to be aware of possible selection biases in the polarization measurements of the τ lepton. One must avoid direct cuts on variables which are sensitive to the polarization, like the energy of the decay particle or the acollinearity of the event.

4. The Total Cross Section

The total cross section is defined as the number of selected $e^+e^- \longrightarrow \tau^+\tau^-$ events, $N^{(sel)}_{\tau^+\tau^-}$, corrected for the expected number of background events, BG, and divided by the selection efficiency, ϵ, the luminosity, $\mathcal{L}$, and the acceptance of the detector, A:

$$\sigma_{tot} = \frac{N^{(sel)}_{\tau^+\tau^-} - BG}{\epsilon \mathcal{L} A}\,. \tag{7}$$

The acceptance, the selection efficiency and the background contamination have to be determined by Monte Carlo studies. As an example in Tab. 2 a breakdown of systematic errors for these measurements with the OPAL detector are given [7]. In 1990 and 1991, LEP was running at seven different energy points in the vicinity of the Z pole. In 1992 data were taken only at the pole. For all these points a measurement of the total cross section was performed. Fig. 1 shows the cross

Table 2: Systematic errors for the measurement of the 1991 total cross section $e^+e^- \longrightarrow \tau^+\tau^-$ with the OPAL detector.

	Uncertainity [%]
Acceptance/Efficiency:	
$e^+e^- \longrightarrow \tau^+\tau^-$ Monte Carlo	0.19
τ pair selection cuts	0.42
Definition of $\mid cos\theta \mid$	0.39
Trigger efficiency	0.06
Uncertainty of τ branching fraction	$<$0.05
Other sources	0.10
Background	0.45
Overall (without Luminosity)	0.75
Luminosity	0.60

section as a function of the center-of-mass energy measured by the L3 collaboration for the 1990, 1991 and 1992 data. The results for the 1990 and 1991 data are published [4,5].
The partial width approach is a model independent parametrization of the total cross section [16],

$$\sigma_{tot} \sim \frac{12\pi\Gamma_e\Gamma_\tau}{m_Z}\frac{s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}\,. \tag{8}$$

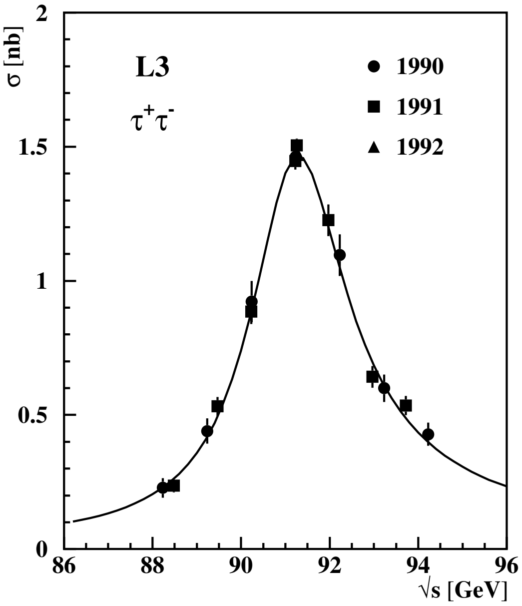
The free parameters are the mass of the Z boson, m_Z , its total width, Γ_Z, and the partial widths for electrons, Γ_e, and τ leptons, Γ_τ. Because of the larger branching ratio, the precision in determining m_Z and Γ_Z is given by the hadron cross section measurement. Furthermore, the precision for Γ_e depends on all total cross sections, measured for e^+e^- annihilation, because the electrons are in the initial state. Therefore, a global fit to hadron and the three lepton total cross sections is performed, with an additional free parameter Γ_μ, the partial widths for the muons. Fig. 3 shows the values for Γ_τ for all four experiments and the LEP average for the lepton channels. The LEP mean value for Γ_τ is

$$\Gamma_\tau = 83.28 \pm 0.49 \text{ MeV}\,.$$

Comparing Γ_τ with the LEP average for the other lepton channels confirms the validity of lepton universality.

5. The Forward-Backward Asymmetry

The forward-backward asymmetry is defined as the difference of the cross section measured in the forward region of the detector ($\cos\theta > 0$) and the cross



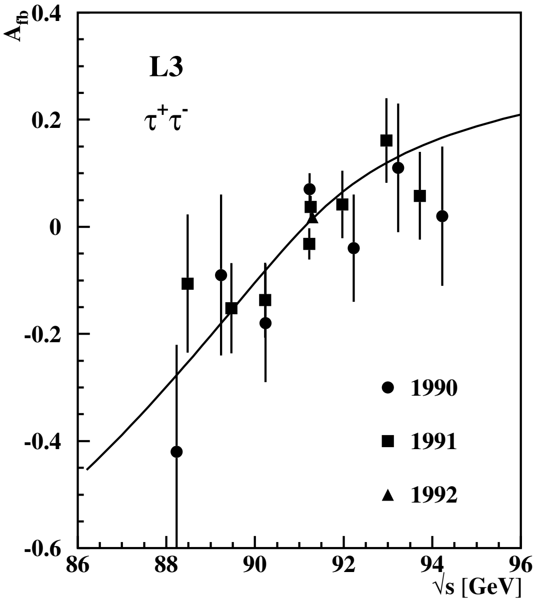


Figure 1: The total cross section as function of $\sqrt{s}$ for the data taken 1990, 1991 and 1992 measured with the L3 detector.

Figure 2: The forward-backward asymmetry as function of $\sqrt{s}$ for the data taken 1990, 1991 and 1992 measured with the L3 detector.

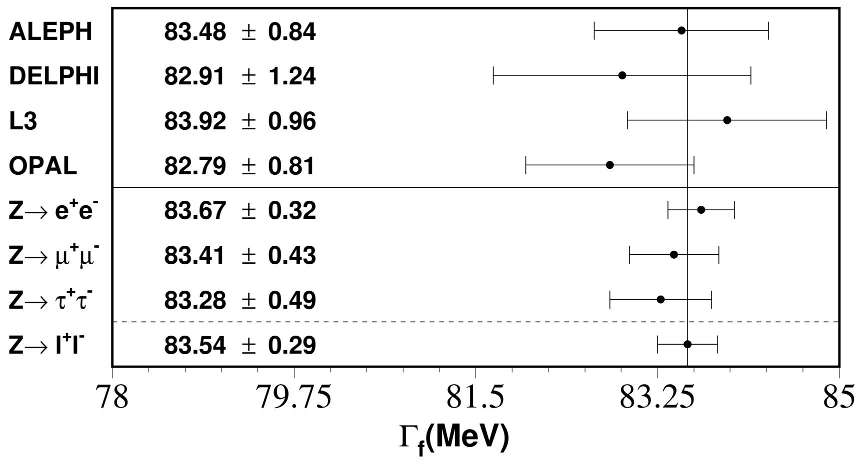


Figure 3: The measurement of Γ_τ for all four experiments and the LEP average of the partial widths for the lepton channels.

Table 3: Systematic errors for the $\mathcal{A}_{fb}$ measurement with the L3 detector.

Systematic Error of $\mathcal{A}_{fb}$ measurement	
Source	Systematic Error $\delta\mathcal{A}_{fb}$
Charge Confusion	$< 0.001 \cdot \mathcal{A}_{fb}$
Background Subtraction	0.003
Cosmic Contamination	< 0.001
Total Systematic Error	0.003

section in the backward region ($\cos\theta < 0$) divided by the total cross section, where θ is the angle between the electron and the negatively charged τ^-:

$$\mathcal{A}_{fb} = \frac{\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)}{\sigma_{tot}} . \tag{9}$$

The differential cross section can be expressed in Born approximation as follows:

$$\frac{1}{\sigma_{tot}(s)} \frac{d\sigma(s)}{d\cos\theta} = \frac{3}{8}(1 + \cos^2\theta) + \mathcal{A}_{fb}(s)\cos\theta . \tag{10}$$

A maximum likelihood fit according to Eq. 10 allows a measurement of $\mathcal{A}_{fb}$. That has to be corrected for charge confusion, because to measure θ one needs the charge of the τ. Systematic errors for the 1992 $\mathcal{A}_{fb}$ measurement are given in Tab. 3 for the L3 experiment. All systematic errors which are related to the normalization of the cross section cancel for asymmetries.
Fig. 2 shows the measurement of $\mathcal{A}_{fb}$ for the 1990,1991 and 1992 data as function of $\sqrt{s}$ for the L3 experiment.
Fig. 4 shows the measurements of $\mathcal{A}_{fb}$ for all experiments for the τ channel and the LEP average for the lepton channels. The LEP average for $\mathcal{A}^{\tau}_{fb}$ is

$$\mathcal{A}^{\tau}_{fb} = 0.0210 \pm 0.0034 .$$

6. The Polarization Asymmetries

The τ lepton decays inside the detector at LEP energies. If one assumes V–A couplings in the τ decay vertex, one can measure the polarization of the τ's by analyzing the decay distribution of each τ decay mode. The polarization of the τ as a function of $\cos\theta$ is given by:

$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1 + \cos^2\theta) + \mathcal{A}_e(2\cos\theta)}{(1 + \cos^2\theta) + \mathcal{A}_\tau\mathcal{A}_e(2\cos\theta)} , \tag{11}$$

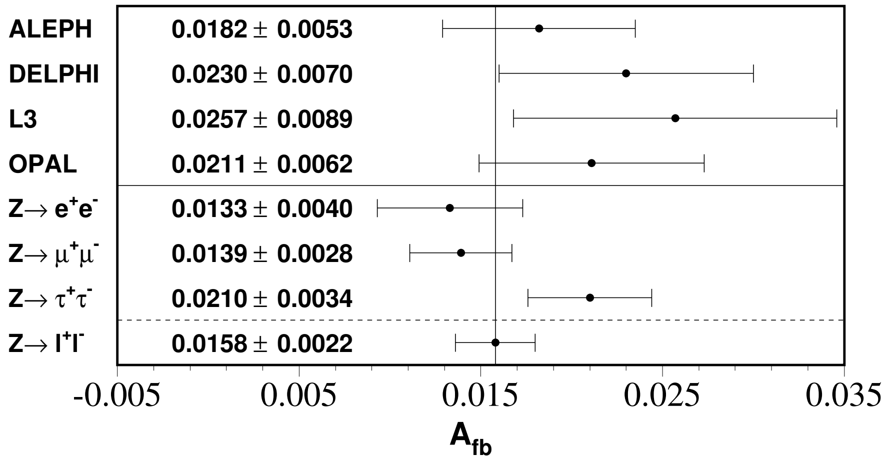


Figure 4: The measurement of $\mathcal{A}^{\tau}_{fb}$ for all four experiments and the LEP average of $\mathcal{A}_{fb}$ for the lepton channels.

where $P_{\tau}(\cos\theta)$ is the difference of the cross section for left and right handed τ's divided by the total cross section. $\cos\theta$ is defined in the same way as for $\mathcal{A}_{fb}$. The two polarization asymmetries, introduced in Eq. 5, are defined as follows:

$$\begin{aligned} \mathcal{A}_{pol} &= \int_{1}^{-1} \mathcal{P}_{\tau}(\cos\theta) d(\cos\theta) \, , \\ \mathcal{A}_{fb-pol} &= \int_{1}^{0} \mathcal{P}_{\tau}(\cos\theta) d(\cos\theta) - \int_{0}^{-1} \mathcal{P}_{\tau}(\cos\theta) d(\cos\theta) \, . \end{aligned} \tag{12}$$

The measurement of $\mathcal{A}_{pol}$ and $\mathcal{A}_{fb-pol}$ allows a study of parity violation in the weak neutral current more sensitively than with $\mathcal{A}_{fb}$, because the polarization asymmetries are linear in the vector and axial-vector couplings and depend only on the couplings of one flavor. This allows a test of e–τ universality in the process $e^+e^- \longrightarrow \tau^+\tau^-$. Furthermore, these measurements are independent determinations of the weak mixing angle, $\sin^2\theta_W^{\text{eff}}$. Eq. 13 shows the sensitivities of the three asymmetries to $\sin^2\theta_W^{\text{eff}}$:

$$\begin{aligned} \triangle \sin^2\theta_w^{\text{eff}} &= \frac{1}{8} \triangle \mathcal{A}_{pol} \, , \\ \triangle \sin^2\theta_w^{\text{eff}} &= \frac{1}{6} \triangle \mathcal{A}_{fb-pol} \, , \\ \triangle \sin^2\theta_w^{\text{eff}} &= \frac{1}{2} \triangle \mathcal{A}_{fb} \, . \end{aligned} \tag{13}$$

Details of the polarization analysis can be found elsewhere [8–11]. All experiments have analysed the $\tau \rightarrow e, \mu, \pi$ decay mode, some of them also the modes $\tau \rightarrow \rho\nu$ and $\tau \rightarrow a_1\nu$.
Experimentally the polarization is inferred from the energy spectra of the τ decay

products. Generally, the two body decay modes $\tau \rightarrow \pi\nu$, $\tau \rightarrow \rho\nu$, $\tau \rightarrow a_1\nu$ are more sensitive to $\mathcal{A}_{pol}$, than the three body decays $\tau \rightarrow e\nu\nu$ and $\tau \rightarrow \mu\nu\nu$, because only one neutrino escapes detection. But in case the hadron is a spin-1 meson (ρ, a_1), one also has to analyze the decay of this meson itself. Otherwise the sensitivity in this particular channel is reduced by a factor

$$\alpha = \frac{{m_\tau}^2 - 2{m_{\rho,a_1}}^2}{{m_\tau}^2 + 2{m_{\rho,a_1}}^2}\,, \tag{14}$$

because one averages over the two possible spin states of the meson.
In cases, where the charged decay product is not a spin-1 meson ($\tau \rightarrow e, \mu, \pi$), one has only one variable, normally defined as $x = E_{e,\mu,\pi}/E_{beam}$, to measure $\mathcal{P}_\tau$. The variable x is equivalent to a determination of the angle between the τ and the charged decay product in the τ rest frame.
If the τ decays into spin-1 mesons instead of x one uses the angle between the τ and the vector meson $\cos\theta^*$ and in addition further information to analyse the decay of the spin-1 meson, in order to treat its different spin states. For the $\tau \rightarrow \rho\nu$ decay one has two additional variables, $\cos\psi^*$, the angle between the ρ and the π, and $m_{\pi\pi^0}$, the invariant mass of the $\pi - \pi^0$ system.
A new method was introduced [17] in order to construct a variable with maximal sensitivity to $\mathcal{P}_\tau$.
For any decay mode $\tau \rightarrow X\nu(\nu)$ the probability distribution has the general form:

$$W(\vec{\xi}) = f(\vec{\xi}) + P_\tau g(\vec{\xi})\,, \tag{15}$$

where $\vec{\xi}$ is a set of variables, which describe the decay of the τ itself and for the ρ and a_1 also subsequent decays. The true polarization maximizes the likelihood for the probability distribution $W(\vec{\xi})$:

$$\frac{\delta}{\delta P_\tau}\log\mathcal{L} = \sum_i \frac{g(\vec{\xi_i})}{f(\vec{\xi_i}) + P_\tau g(\vec{\xi_i})} = \sum_i \frac{\omega_i}{1 + P_\tau\omega_i} = 0\,. \tag{16}$$

The likelihood function $\mathcal{L}$ thus depends only on one variable

$$\omega = g(\vec{\xi})/f(\vec{\xi})\,, \tag{17}$$

which contains the whole information about the τ decay and can be determined for each event.
For all the decay modes $\tau \rightarrow e, \mu, \pi, \rho$ the new method is equivalent to the standard technique. But in the $\tau \rightarrow \rho\nu$ channel the three dimensional distribution in $\cos\theta^*$, $\cos\psi^*$,$m_{\pi\pi^0}$ is transformed into a one dimensional distribution ω, without any loss in sensitivity. For the $\tau \rightarrow a_1\nu$ decay one gets substantial improvement, because the new technique allows to take into account all the information to reconstruct $a_1 \rightarrow \pi\pi\pi$.
Tab. 4 shows the sensitivities and the weights for the polarization measurement,

Table 4: Sensitivity of different τ decay modes for the measurement of $\mathcal{P}_\tau$. In columns 2 and 3 the sensitivities are shown, where the number of variables, N_{var}, to measure $\mathcal{A}_{pol}$, is 1 or 3. Column 4 corresponds to the new technique. Here all variables are taken into account, but not the τ direction of flight. The τ direction of flight is not measurable, because the neutrinos are not detected. In Column 5 also the τ direction is also used. Than all two body decay modes are equivalent. The weight in column 6 is given for the sensitivities in column 4.

Channel	Sensitivity				Weight
	$N_{var}=1$	$N_{var}=3$	all but τ	with τ	
$\tau \to \pi\nu$	0.58	-	0.58	0.58	0.32
$\tau \to \rho\nu$	0.26	0.49	0.49	0.58	0.48
$\tau \to a_1\nu$	0.10	0.23	0.45	0.58	0.12
$\tau \to l\nu\nu$	0.22	-	0.22	0.27	0.08

which are defined as follows [17]:

$$S = \frac{1}{\sigma(P_\tau)\sqrt{N}} = \sqrt{\langle \frac{\omega^2}{(1+P_\tau\omega)^2} \rangle}\,, \tag{18}$$

$$W \sim S^2 \times Branching Ratio\,,$$

for the different decay modes.
Fig. 5 shows the distribution of the optimal variable ω for the $\tau \to \rho\nu$ and $\tau \to a_1\nu$ channel for the ALEPH collaboration, which applied this new method for the first time [8]. The results can be found in Fig. 7.
If the τ polarization $\mathcal{P}_\tau$ is measured as a function of $\cos\theta$ according to Eq. 11, one can fit $\mathcal{A}_e$ and $\mathcal{A}_\tau$ simultaneously and has therefore a test of e–τ universality in a single measurement. Fig. 6 shows this fit assuming e–τ universality and no e–τ universality as performed by the ALEPH collaboration [8]. The results for $\mathcal{A}_\tau$ and $\mathcal{A}_e$ can be found in Fig. 8 and Fig. 9, respectively. The second LEP experiment, which has measured $\mathcal{A}_{fb-pol}$ ($\mathcal{A}_e$) is the OPAL collaboration[11]. For the result see Fig.9. Fig. 7 gives an overview of the $\mathcal{A}_{pol}$ measurements in the different τ decay channels for all four experiments.
An alternative way to measure $\mathcal{P}_\tau$ was proposed [18], which takes advantage of the correlation between both τ leptons. At energies near the Z resonance the mass of the τ lepton is negligible. Assuming vector and axial-vector couplings for the neutral current, helicity is conserved in the scattering process $e^+e^- \longrightarrow \tau^+\tau^-$. That implies, that the helicities of the τ's are opposite. Hence, the decay angular distributions are correlated. Because of this correlation the acollinearity between the charged decay products of the τ's is sensitive to the polarization.
This measurement relies on information from both τ leptons. For the case of an acollinearity measurement from an exclusive decay channel for both τ leptons, the statistics are very low and an inclusive or semi-inclusive measurement is prefered.

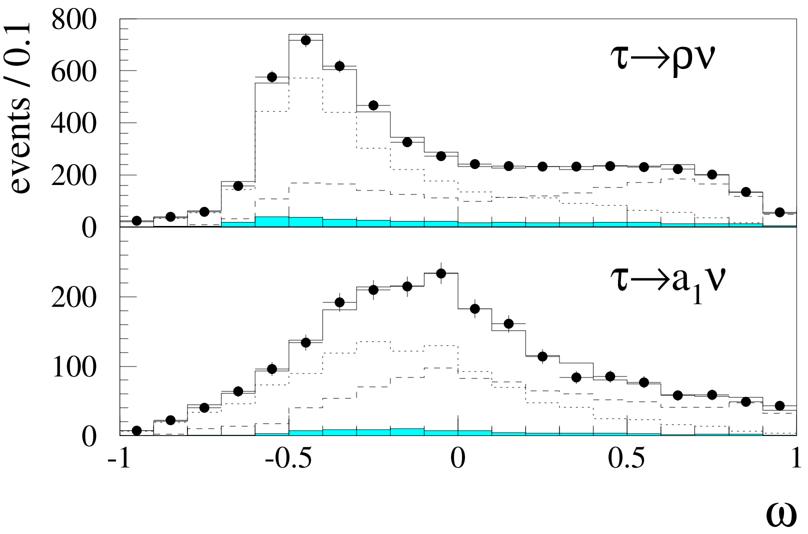


Figure 5: The ω distribution for the $\tau \to \rho\nu$, $\tau \to a_1\nu$ channel for the ALEPH collaboration.

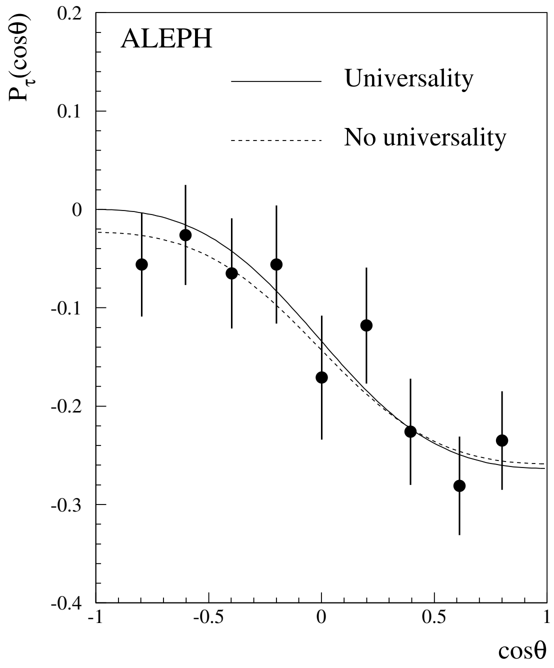


Figure 6: A fit to $P_\tau(\cos\theta)$ assuming e–τ universality and no e–τ universality done by the ALEPH collaboration.

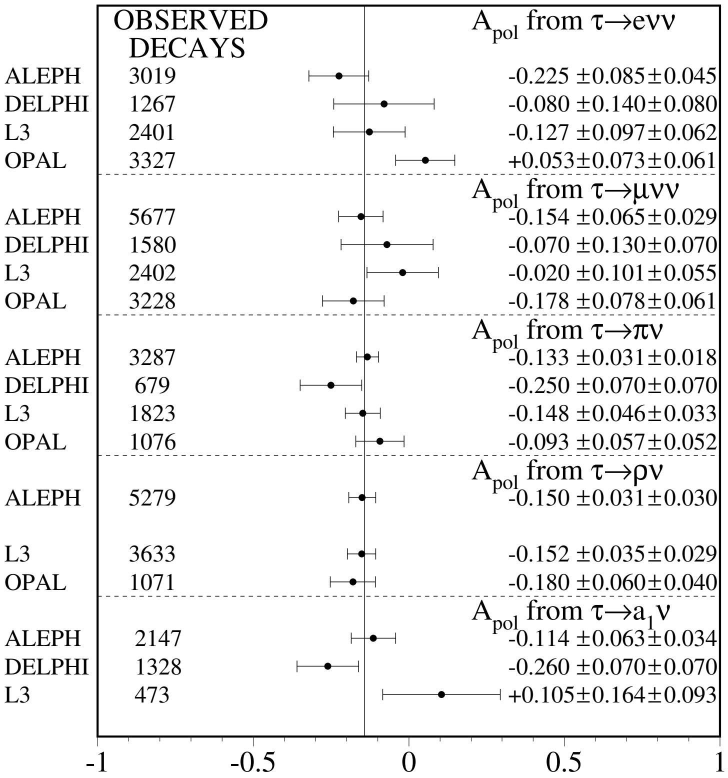


Figure 7: The results of the $\mathcal{A}_{pol}$ measurements in the different τ decay channel for all four LEP experiments.

ALEPH published final results[8] of the 1990 and 1991 data for the π–X and lepton–lepton decay modes. The combined results of both final states are:

$$\begin{aligned} \mathcal{A}_\tau &= 0.147 \pm 0.059 \pm 0.011\,, \\ \mathcal{A}_e &= 0.154 \pm 0.079 \pm 0.002\,. \end{aligned}$$

L3 has a preliminary result for $\mathcal{A}_\tau$ in the π–X channel for 1991:

$$\mathcal{A}_\tau = 0.13 \pm 0.14 \pm 0.03\,.$$

An overview of the measurements of $\mathcal{A}_\tau$ and $\mathcal{A}_e$ at LEP are given in Fig. 8 and Fig. 9, respectively. Here $\mathcal{A}_\tau$ and $\mathcal{A}_e$ are averaged over all analysed decay channels of the τ. The LEP mean values for $\mathcal{A}_\tau$ and $\mathcal{A}_e$ are:

$$\begin{aligned} \mathcal{A}_\tau &= 0.142 \pm 0.017\,, \\ \mathcal{A}_e &= 0.130 \pm 0.025\,, \end{aligned}$$

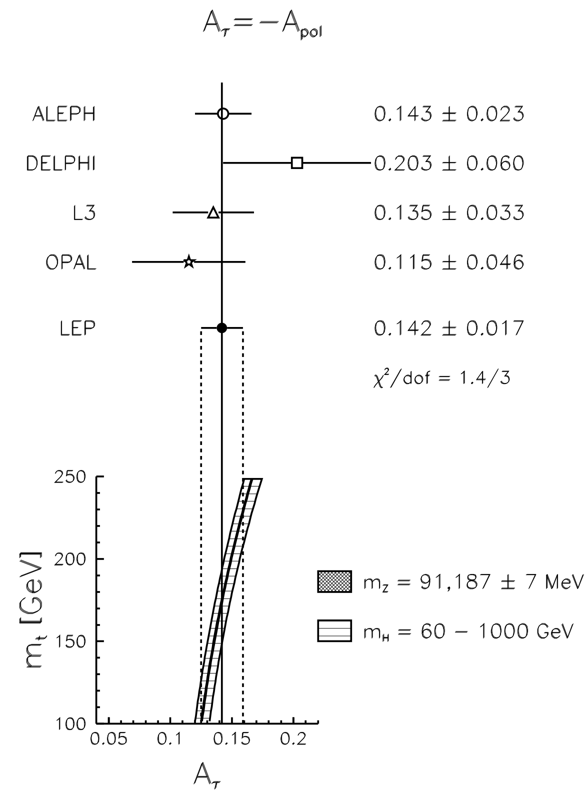


Figure 8: The measurement of $\mathcal{A}_\tau$ at LEP. For comparison the Standard Model expectation for $\mathcal{A}_\tau$ as a function of the top quark mass m_t is ploted.

which confirm the e–τ universality also by polarization measurements. Both measurements are in very good agreement with the Standard Model.

7. The Determination of the Effective Weak Mixing Angle and the Effective Vector and Axial-Vector Couplings

The LEP collaborations use the following definition of the effective weak mixing angle:

$$\frac{v_f}{a_f} = 1 - 4 \mid Q_f \mid \sin^2\theta_W^{\text{eff}} . \tag{19}$$

The conversion of $\mathcal{A}_{pol}$ and $\mathcal{A}_{fb-pol}$ into $\sin^2\theta_W^{\text{eff}}$ according to Eq. 5,6,19 gives two independent possibilities to measure $\sin^2\theta_W^{\text{eff}}$. The LEP averages for $\sin^2\theta_W^{\text{eff}}$ from $\mathcal{A}_{pol}$ and $\mathcal{A}_{fb-pol}$ are:

$$\begin{aligned} \sin^2\theta_W^{\text{eff}} &= 0.2323 \pm 0.0021; \text{ from } \mathcal{A}_{fb} , \\ \sin^2\theta_W^{\text{eff}} &= 0.2338 \pm 0.0031; \text{ from } \mathcal{A}_{fb-pol} . \end{aligned}$$

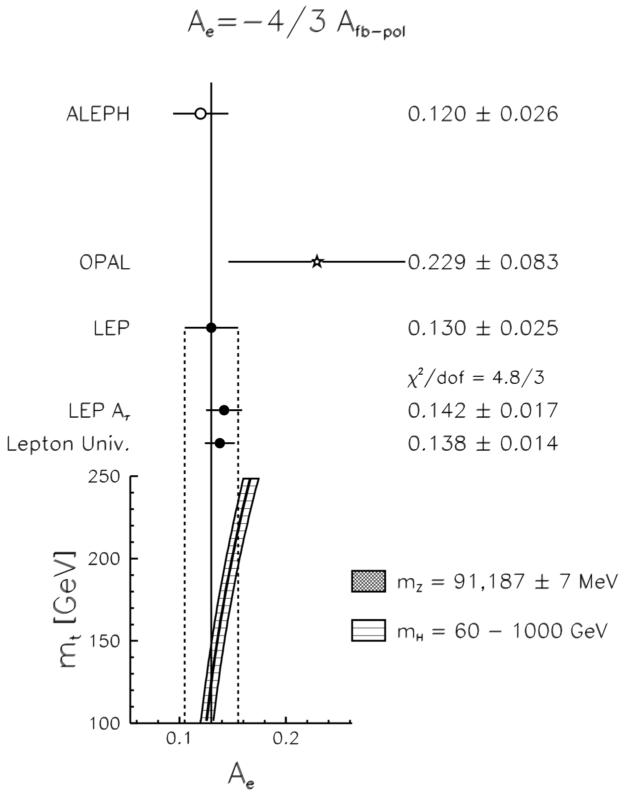


Figure 9: The measurement of $\mathcal{A}_e$ at LEP. For comparison the Standard Model expectation for $\mathcal{A}_e$ as a function of the top quark mass m_t is ploted.

The LEP results from other measurements of $\sin^2\theta_W^{\mathrm{eff}}$ are summarized in Fig. 10. All measurements are in agreement with the Standard Model.
The effective vector and axial vector couplings of the τ to the Z Boson can be determined using Γ_τ, $\mathcal{A}_{fb}$ and $\mathcal{A}_{pol}$, referring to Eq. 5. This results in the following LEP mean values for the τ couplings:

$$
\begin{aligned}
v_\tau &= 0.0389 \pm 0.0037\,, \\
a_\tau &= 0.4999 \pm 0.0015\,.
\end{aligned}
$$

8. The Helicity Amplitudes

The S matrix approach [19, 20] is a rigorously model independent approach to describe the cross sections and asymmetries in e^+e^- annihilation. In the framework of the S matrix only the existence of a massless and massive vector boson is assumed

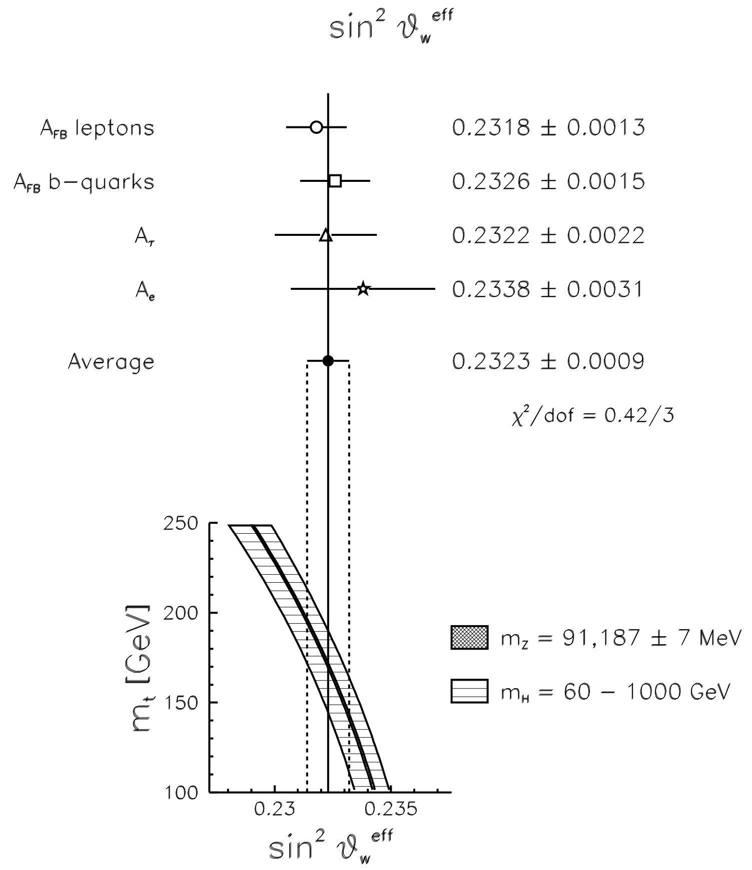


Figure 10: The measurement of $\sin^2\theta_W^{\mathrm{eff}}$ at LEP. For comparison the Standard Model expectation for $\sin^2\theta_W^{\mathrm{eff}}$ as a function of the top quark mass m_t is ploted.

and the matrix element can be written as:

$$\mathcal{M}^{\mathrm{f}i}(s) = \frac{R_\gamma^{\mathrm{f}}}{s} + \frac{R_{\mathrm{Z}}^{\mathrm{f}i}}{s - s_{\mathrm{Z}}}\,, \tag{20}$$

with $\sqrt{s}$ the center-of-mass energy, and $s_{\mathrm{Z}} = \overline{m}_Z^2 - i\overline{m}_Z\overline{\Gamma}_Z$. R_γ^{f} is the residual for the photon exchange and $R_{\mathrm{Z}}^{\mathrm{f}i}$ are the helicity amplitudes, introduced in Eq. 1, describing the Z exchange. As mentioned in the introduction of this paper one needs the total cross section and three asymmetries to measure all four helicity amplitudes. This is only possible at LEP for the process $e^+e^- \longrightarrow \tau^+\tau^-$.

The L3 collaboration already published the results of an S matrix investigation [21]. Because L3 does not yet have a measurement of $\mathcal{A}_{fb-pol}$, lepton universality is assumed. This reduces by one the number of independent helicity amplitudes. The remaining three can be determined using σ_{tot}, $\mathcal{A}_{fb}$ and $\mathcal{A}_{pol}$. For σ_{tot} and $\mathcal{A}_{fb}$ the results of the other lepton channels are also taken into account.

The results for the helicity amplitudes are:

$$
\begin{aligned}
R_Z^0 &= 0.429 \pm 0.012\,, \\
R_Z^1 &= -0.370 \pm 0.003\,, \\
R_Z^2 &= 0.323 \pm 0.016\,.
\end{aligned}
$$

9. Summary

During the successful operation of LEP a data sample of 138 000 $e^+e^- \longrightarrow \tau^+\tau^-$ events was collected by the four LEP collaborations. To investigate the neutral current process $e^+e^- \longrightarrow \tau^+\tau^-$ the total cross section, σ_{tot}, the forward-backward asymmetry, $\mathcal{A}_{fb}$ and the two polarization asymmetries, $\mathcal{A}_{pol}$ and $\mathcal{A}_{fb-pol}$, are measured and give a complete description of the neutral current in the τ channel.
The partial width, Γ_τ, which is derived from σ_{tot}, is determined to be:

$$\Gamma_\tau = 83.28 \pm 0.49 \text{ MeV}.$$

The three asymmetries have the following values:

$$
\begin{aligned}
\mathcal{A}_{fb}^\tau & & &= 0.0210 \pm 0.0034\,, \\
\mathcal{A}_{pol} &= -\mathcal{A}_\tau & &= -0.1420 \pm 0.0170\,, \\
\mathcal{A}_{fb-pol} &= -\tfrac{3}{4}\mathcal{A}_{\rm e} & &= -0.0980 \pm 0.0190\,,
\end{aligned}
$$

and confirm parity violation in the neutral current. e–τ universality can be tested by the polarization asymmetries and is confirmed :

$$\mathcal{A}_{\rm e}/\mathcal{A}_\tau = 0.92 \pm 0.21\,.$$

The τ decay is the most sensitive channel to measure the neutral current couplings and also improves significantly the measurement of the electron couplings due to $\mathcal{A}_{\rm e}$. The couplings of the τ can be extracted from Γ_τ, $\mathcal{A}_{fb}^\tau$ and $\mathcal{A}_{pol}$:

$$
\begin{aligned}
v_\tau &= 0.0389 \pm 0.0037\,, \\
a_\tau &= 0.4999 \pm 0.0015\,.
\end{aligned}
$$

The helicity amplitudes of this process are measured in a model independent approach for the first time:

$$
\begin{aligned}
R_Z^0 &= 0.429 \pm 0.012\,, \\
R_Z^1 &= -0.370 \pm 0.003\,, \\
R_Z^2 &= 0.323 \pm 0.016\,.
\end{aligned}
$$

All the measurements of the process $e^+e^- \longrightarrow \tau^+\tau^-$ confirm the Standard Model.

10. Acknowledgements

I would like to thank Z. Ajduk and the organizers of the XVI Kazimierz Meeting for their hospitality. I acknowledge the cooperation of my collegues from the LEP experiments J. Harton, J. Mnich, G. Quast and D. Reid, who provide me with the latest results of their experiments. Furthermore I have to thank W. Lohmann for the discussions in preparation of the manuscript and I. Brock, T. Hebbeker and M. Pohl for the critical reading.

11. References

1. ALEPH Collab., D. Decamp et al., *Z. Phys.* **C 53** (1992) 1.
2. ALEPH Collab., D. Buskulic et al., *Update of Electroweak Parameters from Z Decays* , Preprint CERN-PPE/93-40, CERN, 1993, submitted to Zeitschrift für Physik C.
3. DELPHI Collab., P. Abreu et al., *Phys. Lett.* **B 367** (1991) 511.
4. L3 Collab., B. Adeva et al., *Z. Phys.* **C 51** (1991) 179.
5. L3 Collab., B. Adeva et al., *Results from the L3 Experiment at LEP*, Preprint CERN-PPE/93-31, CERN, 1993, to be published in Physics Reports.
6. OPAL Collab., G. Alexander et al., *Z. Phys.* **C 52** (1991) 175.
7. OPAL Collab., P. D. Acton et al., *Z. Phys.* **C 58** (1993) 219.
8. ALEPH Collab., D. Buskulic et al., *Z. Phys.* **C 59** (1993) 369.
9. DELPHI Collab., P. Abreu et al., *Z. Phys.* **C 55** (1992) 555.
10. L3 Collab., O. Adriani et al., *Phys. Lett.* **B 294** (1992) 466.
11. OPAL Collab., G. Alexander et al., *Phys. Lett.* **B 266** (1991) 201.
12. ALEPH Collab., D. Decamp et al., *Nucl. Inst. Meth.* **A 294** (1990) 121.
13. DELPHI Collab., P. Aarnio et al., *Nucl. Inst. Meth.* **A 303** (1991) 233.
14. L3 Collab., B. Adeva et al., *Nucl. Inst. Meth.* **A 289** (1990) 35.
15. OPAL Collab., K. Ahmet et al., *Nucl. Inst. Meth.* **A 305** (1991) 275.
16. F. Berends in "Z Physics at LEP", ed. G. Altarelli, R. Kleiss, C. Verzegnassi, CERN Yellow Book, 1989, Vol. 1, CERN 89-08, p. 89.
17. M. Davier, L. Duflot, F. Le Diberder, A. Rougé, *The Optimal Method for the Measurement of the Tau Polarization*, Preprint LAL 92-73 or X-LPNHE 92-22.
18. R.Alemany, N. Rius, J. Bernabeu, J.J. Gomez-Cadenas, A. Pich, *Nucl. Phys.* **B 379**, (1992), 3.
19. A. Leike, T. Riemann and J. Rose, *Phys. Letters* **B 273** (1991) 513.
20. T. Riemann, *Phys. Letters* **B 293** (1992) 451.
21. L3 Collab., O. Adriani et al.,*Phys. Lett.* **B 315** (1993) 494.