Results on the Tau at LEP

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Abstract

Data from the first three years of running at LEP, corresponding to about 18 pb^{-1} of integrated luminosity used per experiment, have led to precise measurements involving the tau lepton. Production and decay parameters of the tau, including the Z partial decay width to taus, the forward backward asymmetry, tau polarization, branching ratios and lifetime are reported.

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1 Introduction

The purpose of this lecture is to review the main results on the tau lepton from LEP, the Large Electron-Positron accelerator near Geneva, Switzerland. The four large experiments on the LEP ring (ALEPH, DELPHI, L3 and OPAL) have recorded data for the three years 1989-1991; and the 1992 run is well underway. All the data have been taken at center-of-mass energies within ± 3 GeV of the Z mass. The high center of mass energy presents opportunities for tau physics not found at lower energies. At the Z resonance both the neutral current character (couplings to the Z) and the charged current character (decays) of the tau may be measured. This paper is organized such that the measurements concerning production (tau lineshape, forward-backward asymmetry, and polarization) come first, in sections 3, 4, and 5. Sections 6, 7, and 8, are on tau decays (topological and exclusive branching ratios, and tau lifetime).

The data for this review have been gathered from the LEP experiments in the last days preceding this Summer Institute. Some of the results are from published data for the 1989 and 1990 running of LEP. Other results, on the same topic, may be from preliminary 1991 data only. The nature of the result (preliminary or final) will be indicated on the figures, which also give the LEP averages. There are no results from the present (1992) LEP run and in many cases the 1989 data have been dropped. All the averages were calculated by the lecturer and all contain preliminary results. Some interesting analyses were completed in the weeks between the SLAC Summer Institute and the date of this report. I have included here the later results. The experiments each use about 1 pb^{-1} of integrated luminosity from running in 1989; about 7 pb^{-1} from 1990 , and about 11 pb^{-1} from 1991.

2 Tau selection at the Z resonance

Taus produced through e^+e^- annihilation at the Z resonance are very energetic and collinear. Each tau carries nearly the beam energy and the angle between the two final state charged particles when both taus decays give one charged particle is typically about 175 degrees. There is always at least one neutrino in each hemisphere of a $Z \to \tau^+\tau^-$ event so there is always missing energy. All of these properties are exploited by the experiments to select $Z \to \tau^+\tau^-$ events and reject background. Radiation, either from the initial-state beam particles or from the taus, can lower the tau energy and change the angle between the decay products. All four of the LEP experiments use the KORALZ Monte Carlo event generator [1] to simulate the kinematics of $e^+e^- \to Z \to \tau^+\tau^-$. A full simulation of the detectors approximates the response of the apparatus to the tau decay products. Overall selection efficiencies (defined as the total number of taus used in the analysis divided by the total number produced) vary from about 70% for the lineshape analysis, to 50% for some channels in polarization measurements, and lower for some branching ratio analyses.

The backgrounds to $Z \to \tau^+\tau^-$ at LEP, and the characteristics which distinguish them from $Z \to \tau^+\tau^-$ are:

- $Z \to q\bar{q}$. Hadronic Z decays generally have much higher multiplicity than tau events. The mean charged multiplicity in hadronic Z decays at LEP is about 21 [2]. Most tau events have two or four charged particles. Hadronic Z decays are also much more spherical than tau events. Thus if a $Z \to q\bar{q}$ event results in just a few charged particles detected those particles will probably not be as highly collimated as the particles from a $Z \to \tau^+\tau^-$ event. Background in tau samples from hadronic Z decays varies depending on the analysis but is usually less than 1% of the tau sample, and in some cases a smaller fraction.

- $e^+e^- \to e^+e^- f\bar{f}$. The two-photon processes are characterized by low multiplicity, low energy, and balanced momentum perpendicular to the beam direction. Additionally, the center-of-mass system of the particles which are detected (i.e., not the original electron and positron, which usually escape down the beam pipe) is often boosted along the beam direction. Background from two-photon processes in tau samples is very low at LEP, typically a few picobarn. For comparison, the tau production cross section at the Z peak is about a nanobarn.

- $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$. Z decays to electrons and muons are generally the main background in tau event samples at LEP. These events usually result in two high energy back-to-back particles both of which are identified as electrons or muons. The $e^\pm$ or $\mu^\pm$ may sometimes be misidentified as a pion, particularly if it is well below beam energy or has gone into an insensitive area in the detector or into a region of overlap between the barrel and endcap part of the detector. The sum backgrounds from Z decays to electrons or muons is typically 1-2% of the tau sample.

3 Z lineshape from tau decays

The most simple measurement with taus at LEP is the lineshape, i.e., the tau production cross section as a function of center-of-mass energy. In general the tau lineshape is not published separately from those of the hadrons and other leptons. The main parameter to result from the measurement is the Z partial decay width to taus $\Gamma_{Z\to\tau^+\tau^-}$, although the taus do contribute to knowledge of the Z mass and width. The dominant term in the cross section for production of tau leptons at the Z resonance may be written[1]

$$\sigma(e^+e^- \to Z \to \tau^+\tau^-) = \frac{12\pi s}{M_Z^2}\frac{\Gamma_{Z\to e^+e^-}\Gamma_{Z\to\tau^+\tau^-}}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \quad (1)$$

where s is the square of the center of mass energy, Γ_Z is the Z full width, and M_Z is the Z mass. If the four LEP experiments were to publish results on the tau lineshape alone (for data through 1991) the combined statistical errors on the Z mass and width would be about 15 MeV and 28 MeV, respectively. Figure 1 shows a preliminary tau lineshape from L3. Figure 2 shows the present LEP results for $\Gamma_{Z\to\tau^+\tau^-}$. The average from the four LEP experiments [4] is

$$\Gamma_{Z\to\tau^+\tau^-}(LEP) = 83.88 \pm 0.67 \text{ MeV}. \quad (2)$$

The result is still statistically limited.

The Z partial decay width to taus provides some information on both the vector and axial vector coupling constants of the tau to the Z. $\Gamma_{Z\to\tau^+\tau^-}$ may be written [5]

$$\Gamma_{Z\to\tau^+\tau^-} = \frac{G_F M_Z^3}{6\sqrt{2}\pi}\cdot(g_{V\tau}^2 + g_{A\tau}^2)(1+\frac{3}{4}\frac{\alpha}{\pi}). \quad (3)$$

Since the vector coupling is much smaller than the axial vector coupling, $\Gamma_{Z\to\tau^+\tau^-}$ essentially determines $g_{A\tau}$. Information on $g_{V\tau}$ will come from the forward-backward asymmetry and the tau polarization.

4 Tau forward-backward asymmetry

The forward-backward asymmetry is defined as

$$A_{FB}^{\tau} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \quad (4)$$

where σ_F and σ_B are the cross sections for production of taus in the forward and backward directions, respectively. A τ^+ (τ^-) has gone forward if the angle between the τ^+ (τ^-) and the direction of the beam positron (electron) is less than $\frac{\pi}{2}$. In principle the A_{FB}^{τ} measurement consists simply of counting the $\tau^{\pm}$ in the forward and backward hemispheres. The asymmetry is a function of center-of-mass energy. At each energy the differential cross section for $\tau^{\pm}$ production may be written [6]

$$\frac{d\sigma}{d\cos\theta} = C(1+\cos^2\theta + \frac{8}{3}A_{FB}^{\tau}(\sqrt{s})\cos\theta). \quad (5)$$

[1] Here we neglect photon exchange, photon-Z interference, and initial state radiation. For the complete treatment of calculations used by the experiments see [3] and references therein.

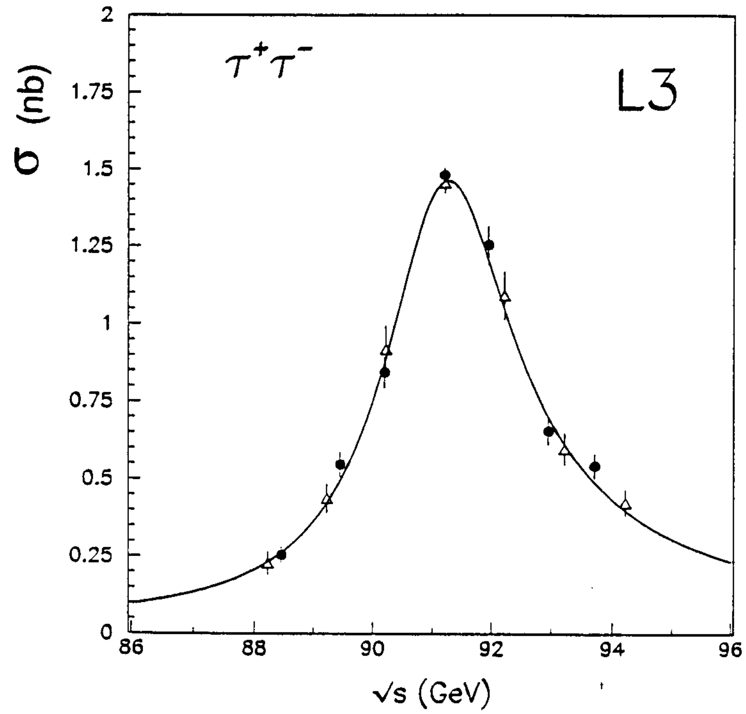
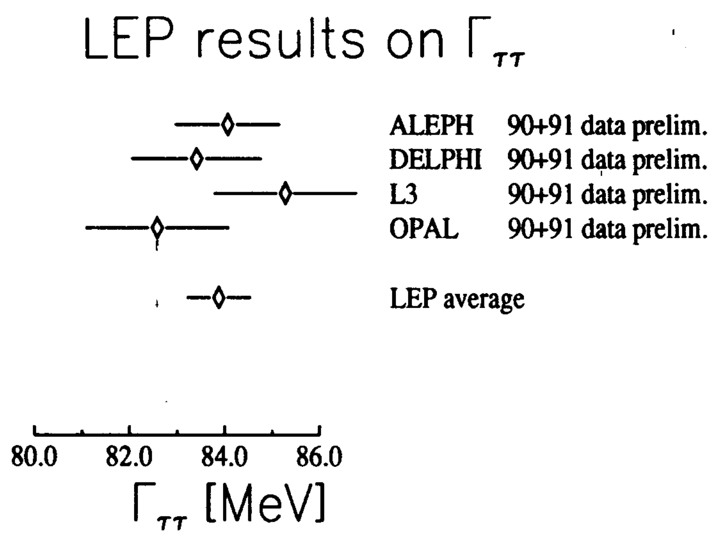


Figure 1: Tau lineshape from preliminary results from L3 for 1990 (open points) and 1991 (solid points).



ALEPH	84.09 ± 1.10
DELPHI	83.43 ± 1.36
L3	85.3 ± 1.5
OPAL	82.6 ± 1.5
LEP	83.88 ± 0.67 [MeV] (χ^2 = 1.8)

Figure 2: LEP results on Z partial decay width to taus.

ALEPH	0.0269	±	0.0082
DELPHI	0.033	±	0.010
L3	0.028	±	0.016
OPAL	0.0165	±	0.0082
LEP	0.0249	±	0.0048

Table 1: Measurements of the tau forward backward asymmetry at LEP [4].

The experiments fit the angular dependence of the tau cross section at each center-of-mass energy to determine $A^{\tau}_{FB}(\sqrt{s})$. Figure 3 shows the forward-backward asymmetry as a function of $\sqrt{s}$ as measured by L3. Having determined $A^{\tau}_{FB}(\sqrt{s})$, another fit is made using a formulation which takes the energy dependence of the asymmetry into account [3] to determine the tau couplings to the Z. The data on A^{τ}_{FB} are usually fit simultaneously with the forward-backward asymmetries for electrons and muons. Additionally the lineshape data for hadrons and leptons either constrain the A^{τ}_{FB} fit or are fit at the same time.

At tree level A^{τ}_{FB} is a simple function of the vector and axial vector couplings of the electron and tau to the Z [7]:

$$A^{\tau}_{FB} = \frac{3}{4} A_e A_\tau \tag{6}$$

where

$$A_e = 2g_{Ve}g_{Ae}/(g^2_{Ve} + g^2_{Ae}) \text{ and } A_\tau = 2g_{V\tau}g_{A\tau}/(g^2_{V\tau} + g^2_{A\tau}). \tag{7}$$

The tau forward backward asymmetry is sensitive to the ratios $g_{V\tau}/g_{A\tau}$ and g_{Ve}/g_{Ae}. The combinations of couplings, A_e and A_τ, will be seen again in the tau polarization measurement. The LEP [4] measurements on A^{τ}_{FB} are summarized in table 4.

5 Tau polarization

The tau polarization, like the partial width and the forward-backward asymmetry, provides information on the tau couplings to the Z. In addition, the polar angle dependence of the tau polarization yields a measure of the electron couplings to the Z.

At LEP the beams are unpolarized and the tau polarization is defined as the fractional difference in production of right- and left-handed taus:

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}. \tag{8}$$

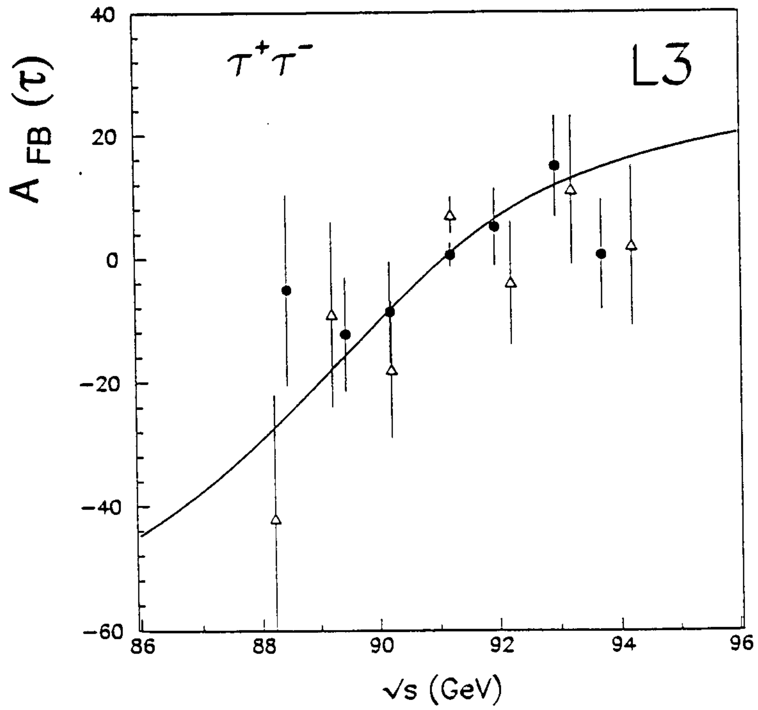


Figure 3: Tau forward-backward asymmetry as a function of center-of-mass energy measured by L3. The result is preliminary. The plot shows 1990 (open points) and 1991 (solid points).

The τ^+ and τ^- from Z decays have opposite helicity and $P_\tau \equiv P_{\tau^-} = -P_{\tau^+}$. The energies of the tau decay products reflect the helicity of the tau. For example, in the decay $\tau^- \to \pi^-\nu$, pions from the decay of positive helicity τ^- tend to be higher in energy in the lab than pions from negative helicity τ^-. This dissimilarity in energy distribution for the decay products from positive and negative helicity taus may be exploited to deduce the fraction of each in the data. For some tau decay modes other kinematic quantities are more sensitive to the polarization than just the energy of decay products [8]. For the decay $\tau \to \rho\nu$, for example, the difference in energy between the charged and neutral pions from rho decay carries information on the tau helicity.

One implicit assumption in these measurements is the pure $V-A$ structure of the weak charged current which governs tau decay. This assumption enters in the use of the KORALZ Monte Carlo to simulate tau decays. A discrepancy between the polarization measured using two different decay modes might indicate that the pure $V-A$ assumption was not a good one.

The LEP experiments have so far concentrated mostly[2] on four decay modes for the polarization analysis: $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, and $\rho\nu$. The experiments do not distinguish pions from kaons for these analyses, so the pion mode also includes the decays $\tau \to K\nu$.

For the leptonic modes $e\nu\bar{\nu}$ and $\mu\nu\bar{\nu}$ the electron or muon energy, scaled by the beam energy, x, is the quantity which exhibits sensitivity to the polarization. For $e\nu\bar{\nu}$ and $\mu\nu\bar{\nu}$ the scaled energy spectrum is a cubic in x

$$\frac{1}{N_{e\nu\bar{\nu}(\mu\nu\bar{\nu})}}\frac{dN_{e\nu\bar{\nu}(\mu\nu\bar{\nu})}}{dx} = \frac{1}{3}[5 - 9x^2 + 4x^3 + P_\tau(1 - 9x^2 + 8x^3)] \tag{9}$$

where $N_{e\nu\bar{\nu}(\mu\nu\bar{\nu})}$ is the number of tau to electron (muon) decays detected. $P_\tau = -1$ gives the spectrum for left-handed taus, while $P_\tau = +1$ is for right-handed taus. The presence of two neutrinos in the leptonic decays reduces the sensitivity of these decay modes to the polarization.

The scaled energy spectrum is also used in the pion decay mode. It is linear in x

$$\frac{1}{N_{\pi\nu}}\frac{dN_{\pi\nu}}{dx} = 1 + P_\tau(2x - 1). \tag{10}$$

The pion decay mode is much more sensitive than the lepton modes. The helicity of the tau in $\tau \to \pi\nu$ strongly constrains the neutrino direction in the tau rest frame, and thus the pion energy in the lab frame.

The rho decay mode is more complicated than the lepton or pion modes. The rho itself has unit spin and decays to $\pi\pi^0$. The spin state of the rho must be unfolded before the helicity of the tau can be deduced. As mentioned above,

[2] ALEPH has also analysed the mode $\tau \to a_1\nu$, but with present techniques it is far less sensitive than the other modes.

the $\pi\pi^0$ energy difference

$$Y_{\rho^\pm} = \frac{|E_{\pi^\pm} - E_{\pi^0}|}{E_{beam}} \quad (11)$$

may be used to differentiate positive and negative helicity taus. In the more complete formulation [8], the decay angles in the tau decay to $\rho\nu$ and the rho decay to $\pi\pi^0$ are reconstructed from the measured charged pion and neutral pion. The angles are

$$\cos\theta_\rho = \frac{2E_\rho/E_{beam} - 1 - m_\rho^2/m_\tau^2}{1 - m_\rho^2/m_\tau^2} \quad (12)$$

and

$$\cos\psi = \frac{m_\rho}{\sqrt{m_\rho^2 - 4m_\pi^2}} \frac{E_{\pi^\pm} - E_{\pi^0}}{p_\rho}, \quad (13)$$

where $E_\rho = E_{\pi^\pm} + E_{\pi^0}$ and $m_\rho = m_{\pi^0\pi^\pm}$. The sensitivity to the polarization is slightly enhanced by using the two decay angles instead of just the energy difference.

The experiments use full simulation Monte Carlo to generate the detected energy distribution for positive helicity taus and negative helicity taus separately. The average tau polarization can be measured by fitting a linear combination of these histograms to the energy distribution from the data. The relative amount of positive and negative helicity taus from the Monte Carlo is the quantity varied in the fit, this being essentially the tau polarization. Alternately, the data distributions can be unfolded for detector and acceptance and QED effects; then the theoretical x distribution can be fit to the corrected data.

The tau polarization measurement places tough demands on the detectors, particularly in the $\rho\nu$ mode where photon/π^0 reconstruction is crucial. In fact, in $\rho\nu$ the main systematic uncertainty comes from knowledge of photon and π^0 reconstruction efficiencies. In the lepton and pion decay modes it is clear that any uncertainty in overall energy scale will induce a false polarization. Similarly an uncertainty in selection efficiency as a function of x will systematically affect the extracted polarization. The energy measurements are the main sources of systematic uncertainty in the lepton and pion decay modes. Background in the $\pi\nu$ mode, principally from tau decays with a pion and one or more π^0's, also contributes to the systematic uncertainty.

For the $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, and $\pi\nu$ channels the experiments have sources of kinematically identifiable electrons, muons, and pions in the data with which to check sources of systematic error. Clean samples of electrons and muons come from Z decays. The kinematics of the event, together with the identification of a lepton in one hemisphere, can be used as a tag for high energy leptons. Leptons at lower energies are available from two-photon interactions, which can be selected either by the kinematics and identities of the tracks in the central detector or by presence of energy in the low-angle electromagnetic calorimeter. Converted photons can also be used as a clean source of electrons. Tracks in three-prong tau decays are a source of hadrons for testing particle identification. Also the single track accompanied by a clear π^0 is almost always a pion if the track and π^0 invariant mass is consistent with the rho. All these sources, along with test beam data, have been used by the experiments to measure systematic uncertainties. There is no clean source of kinematically identifiable π^0s in the LEP data. The experiments must rely upon Monte Carlo simulation and comparisons with data to evaluate the systematic effects from π^0 reconstruction. Table 2 lists the systematic uncertainties quoted by the experiments in the four main decay modes.

	$e\nu\bar{\nu}$	$\mu\nu\bar{\nu}$	$\pi\nu$	$\rho\nu$
ALEPH 90+91 prelim.	0.052	0.032	0.020	0.030
DELPHI 90 final	0.08	0.07	0.07	0.07
L3 90+91 prelim.	0.059	0.072	0.033	0.029
OPAL 90+91 prelim.	0.08	0.10	0.07	0.08

Table 2: Total systematic errors quoted by the LEP experiments on tau polarization measurements in the four main decay modes. The years in which the data were collected, and whether the result is preliminary or final, are indicated in the first column.

Figures 4 through 7 show the LEP results for each channel. The uncertainties quoted on the figures are the total uncertainties including statistics and systematics. The values from the four channels are consistent with each other. The LEP [9] averages are

$$P_\tau(LEP \text{ from } \tau \to e\nu\bar{\nu}) = -0.087 \pm 0.066, \quad (14)$$

$$P_\tau(LEP \text{ from } \tau \to \mu\nu\bar{\nu}) = -0.128 \pm 0.057, \quad (15)$$

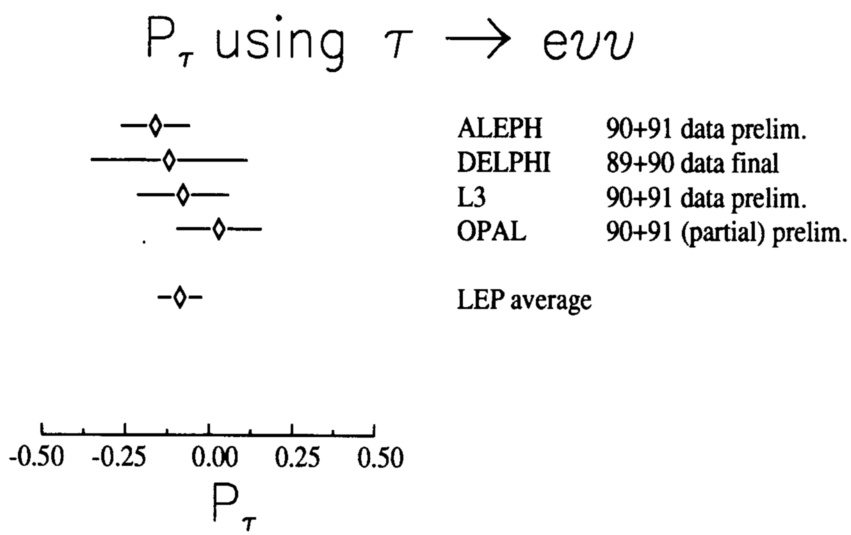
$$P_\tau(LEP \text{ from } \tau \to \pi\nu) = -0.153 \pm 0.030, \quad (16)$$

$$P_\tau(LEP \text{ from } \tau \to \rho\nu) = -0.147 \pm 0.030. \quad (17)$$

The experiments also each quote an overall tau polarization, which is either an average of the polarization values from the individual channels or, in the case of ALEPH, the result of a fit to the angular dependence of the tau polarization (see below). The LEP average is

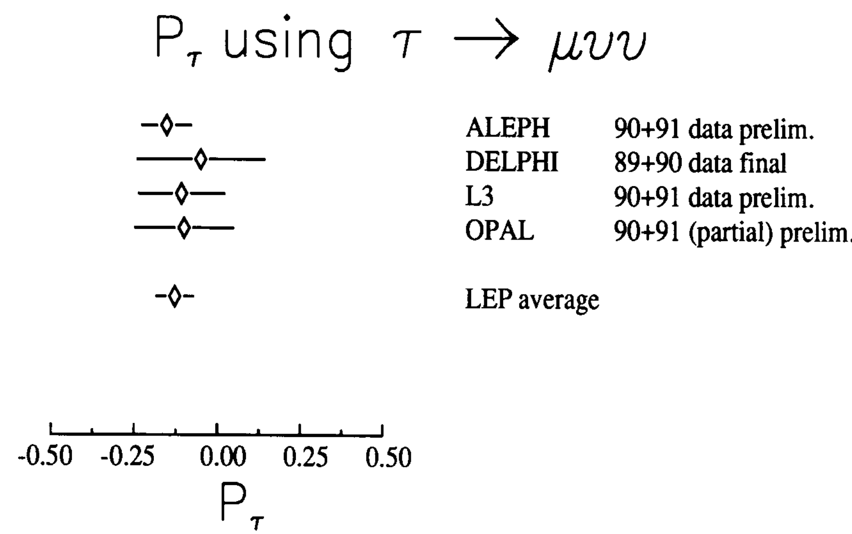
$$P_\tau(LEP) = -0.137 \pm 0.019. \quad (18)$$

Figure 8 summarizes the results on overall average tau polarization.



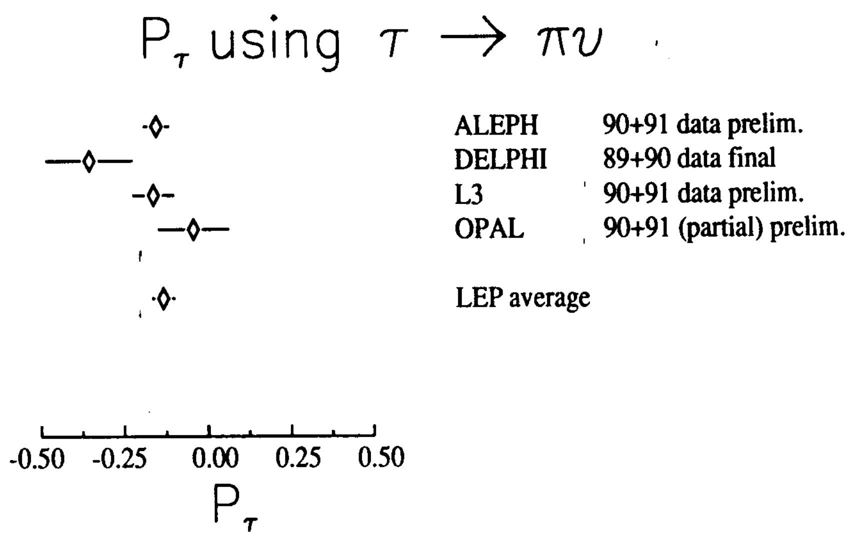
ALEPH	-0.161 ± 0.103
DELPHI	-0.12 ± 0.23
L3	-0.078 ± 0.137
OPAL	$+0.03 \pm 0.13$
LEP	-0.087 ± 0.066 ($\chi^2 = 1.4$)

Figure 4: Tau polarization measurements from the LEP experiments in the decay mode $\tau \rightarrow e\nu\bar{\nu}$.



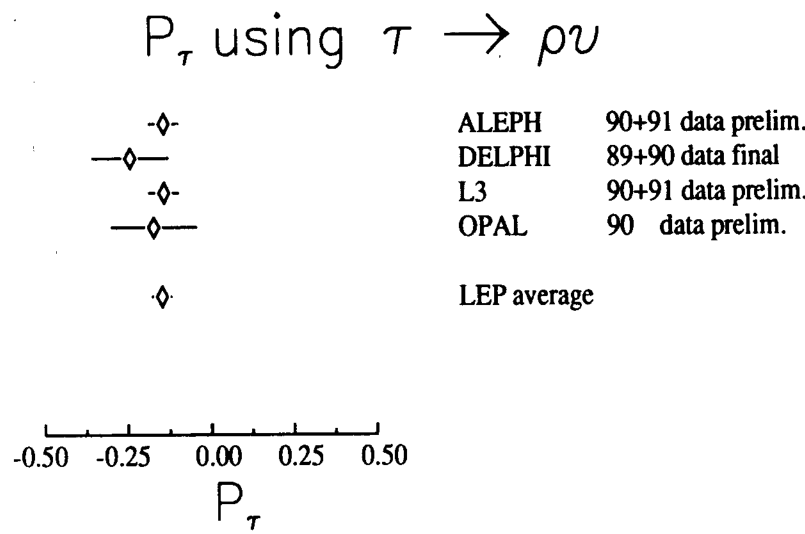
ALEPH	-0.153 ± 0.075
DELPHI	-0.05 ± 0.19
L3	-0.108 ± 0.131
OPAL	-0.10 ± 0.15
LEP	-0.128 ± 0.057 ($\chi^2 = 0.3$)

Figure 5: Tau polarization measurements from the LEP experiments in the decay mode $\tau \rightarrow \mu\nu\bar{\nu}$.



ALEPH	-0.149 ± 0.038
DELPHI	-0.350 ± 0.130
L3	-0.159 ± 0.061
OPAL	-0.040 ± 0.106
LEP	-0.153 ± 0.030 $(\chi^2 = 3.4)$

Figure 6: Tau polarization measurements from the LEP experiments in the decay mode $\tau \rightarrow \pi\nu$.



ALEPH	-0.139 ± 0.044
DELPHI	-0.240 ± 0.114
L3	-0.139 ± 0.045
OPAL	-0.170 ± 0.128
LEP	-0.147 ± 0.030 $(\chi^2 = 0.8)$

Figure 7: Tau polarization measurements from the LEP experiments in the decay mode $\tau \rightarrow \rho\nu$.

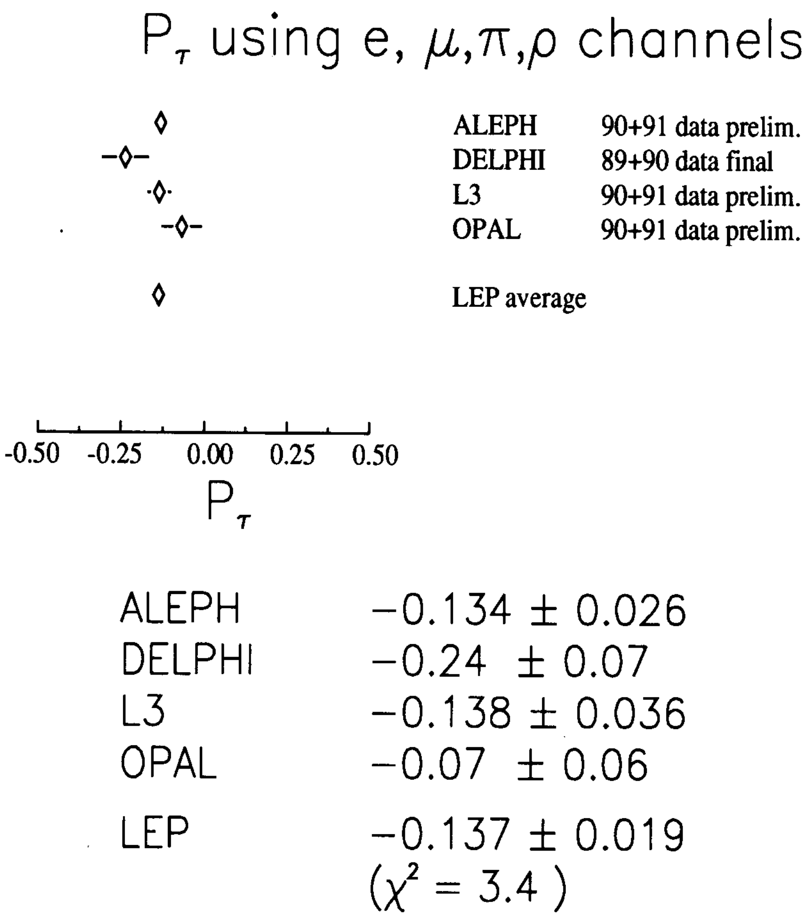


Figure 8: Overall tau polarization results from LEP.

5.1 Polar angle dependence of tau polarization

The tau polarization is a strong function of the polar angle, going from zero in the backward direction to about twice the average polarization in the far forward direction ("backward" and "forward" here have the same meaning as for A^{τ}_{FB}). An approximate analytic formula for the dependence of tau polarization on polar angle is given in [7]:

$$P_\tau(\cos\theta) = -(\mathcal{A}_\tau + \frac{2\cos\theta}{1+\cos^2\theta}\mathcal{A}_e)/(1 + \frac{2\cos\theta}{1+\cos^2\theta}\mathcal{A}_\tau\mathcal{A}_e) \qquad (19)$$

where $\mathcal{A}_\tau$ and $\mathcal{A}_e$ are as defined in section 4. It is clear that the difference in polarization between the forward and backward hemispheres (i.e., the forward-backward tau polarization asymmetry, or P_τ^{FB}) yields a measure of the electron couplings. From equation 19 we see that $P_\tau^{FB} = -\frac{3}{4}\mathcal{A}_e$ and the average polarization is $-\mathcal{A}_\tau$.

OPAL has measured the polarization in the forward and in the backward hemispheres using the four main channels. Their results gives $\mathcal{A}_e(\mathrm{OPAL}) = 0.23 \pm 0.09$. ALEPH has measured the tau polarization in nine bins in polar angle and fit to those data using equation 19. The data are shown in figure 9. The result for the electron couplings is $\mathcal{A}_e(\mathrm{ALEPH}) = 0.120 \pm 0.031$. Both results are preliminary and use the 1990 data and at least part of the 1991 data. The LEP result is the average of these two:

$$\mathcal{A}_e(LEP) = 0.132 \pm 0.029. \qquad (20)$$

The polar angle dependence of the tau polarization provides the most accurate single measurement from LEP of the electron vector coupling to the Z.

The LEP tau polarization measurements alone provide a test of of electron-tau universality:

$$\frac{\mathcal{A}_e(LEP)}{\mathcal{A}_\tau(LEP)} = 0.90 \pm 0.22. \qquad (21)$$

confirming electron-tau universality at about the 25% level.

Assuming electron-tau universality one can determine the effective weak mixing angle $sin^2\theta_W^{eff}$ from these tau polarization measurements. Averaging the LEP measurements of $\mathcal{A}_e$ and $\mathcal{A}_\tau$ one finds

$$\mathcal{A}_{e-\tau}(LEP) = 0.135 \pm 0.016. \qquad (22)$$

These couplings are related approximately to $sin^2\theta_W^{eff}$ [7] through the equation

$$\mathcal{A}_{e-\tau} \simeq 2(1 - 4sin^2\theta_W^{eff}). \qquad (23)$$

Thus the LEP tau polarization measurements alone give a 1% measurement of $sin^2\theta_W^{eff}$:

$$sin^2\theta_W^{eff}(LEP \text{ tau pol.}) = 0.2331 \pm 0.0020. \qquad (24)$$

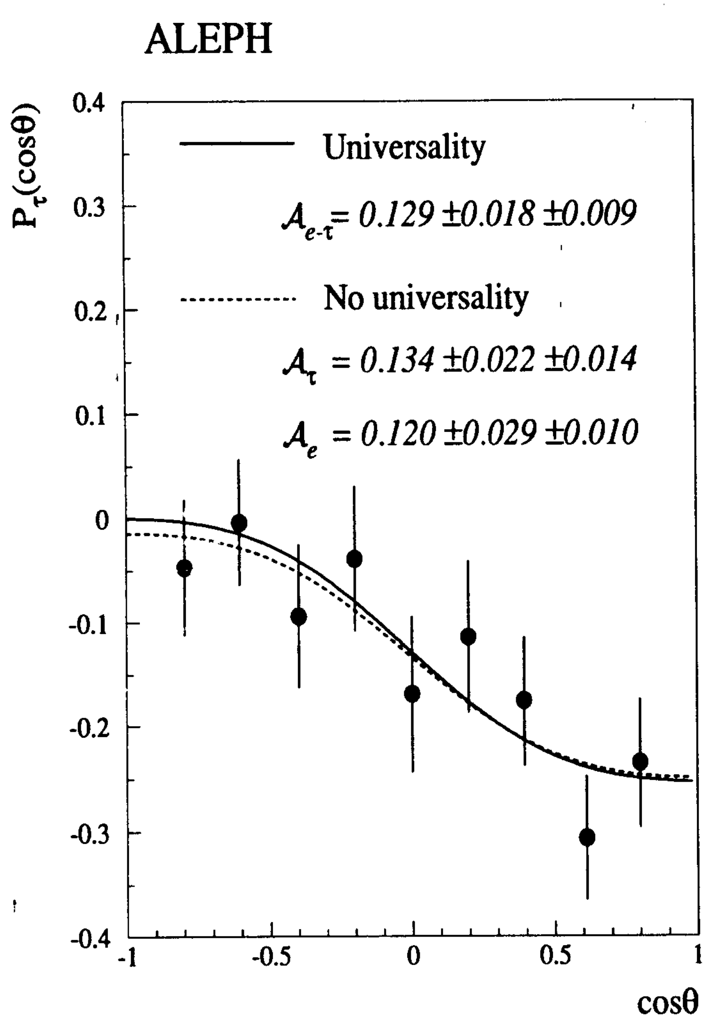


Figure 9: Tau polarization as a function of polar angle. Preliminary result from ALEPH 1990 and 1991 data.

5.2 Vector and axial-vector couplings

Combining the results on $\Gamma_{Z\to\tau^+\tau^-}$, the tau forward backward asymmetry and the tau polarization measurements, values for g_{V_τ} and g_{A_τ} can be extracted using the simple formulas in the text. The electron couplings appear in A^{τ}_{FB}. For the following results information on electron couplings comes only from the angular dependence of the tau polarization, and is used as a constraint in the fit for g_{V_τ} and g_{A_τ}. The only explicit use of information not from tau events is that for the Z mass [10], $M_Z = 91.187$ GeV. Implicitly, of course, the Z full width and partial width to electrons also enter because the tau lineshape was fit along with the hadrons and other leptons [10]. The results from the LEP averages are:

$$g_{V_\tau} = -0.0378 \pm 0.0044, \tag{25}$$

$$g_{A_\tau} = -0.501 \pm 0.0020. \tag{26}$$

6 Topological branching ratios

Charge conservation requires that the tau decay into an odd number of charged particles. The branching ratios Br_1, Br_3, and Br_5 into 1, 3, and 5, charged particles (along with any number of neutrals) are called the topological branching ratios. They are also called the "1-prong" (about 85%), "3-prong" (about 15%), and "5-prong" (about 0.1%) branching ratios. The "7-prong" branching ratio is suppressed [11] by an order of magnitude with respect to the "5-prong" and the LEP experiments should have only a few such decays each at this point. For these analyses the "7-prong" branching ratio is ignored.

If an experiment can determine the topological branching ratios in an unconstrained way then a check that their sum is consistent with one is a check that no decay mode has gone undetected.

Interest in the topological branching ratios may also arise when one compares the 1-prong result with the sum of the exclusive branching ratios to one charged track. While in principle these two measures should give the same result, historically there has been a discrepancy [11]. ALEPH has recently done a comprehensive study of branching ratios and their result is sensitive to new decays involving photons; such decays are a possible source of the 1-prong problem (see the following section).

Tracking efficiencies and systematics are the main area of work in this measurement. Particle identification is generally used only to reject $e^{\pm}$ pairs from photon conversions. The method most often used is to study the topology of whole events (rather than just one hemisphere). The detected event may have any topology $i-j$ where $i,j = 1,2,3,4,5$. Presumably the true event topology, $k-l$ was one allowed from two tau decays, i.e. $1-1, 1-3, 1-5, 3-3,$

etc. The detected topology can differ from the original topology for any number of reasons, including tracking inefficiencies, problems with the detector, neutral kaon decay, and charge exchange interactions in the detector. The experiments determine from Monte Carlo the migration matrix which gives the probability that a detected topology $i-j$ came from true topology $k-l$. This matrix is then used with the array of detected topologies from the data in a fit to determine the topological branching ratios. The details of how the fit is accomplished are important, particularly the normalization of the total number of tau events, when interpreting the results. ALEPH and DELPHI use an absolute normalization of the tau sample (based either on the number of hadronic events or on the integrated luminosity) and fit for Br_1, Br_3, and Br_5. With this method the resulting fitted branching ratios are moderately correlated and their sum may or may not be consistent with 100%. L3 and OPAL work under the assumption that $Br_1 + Br_3 + Br_5 = 1$. Sensitivity to undetected decay modes is lost with this method but it is independent of the overall tau sample normalization. In this way smaller systematic errors on the branching ratios are obtained. The method of L3 and OPAL also results in highly correlated values of Br_1 and Br_3; Br_5 is still only moderately correlated to the other branching ratios.

The LEP [12] results on Br_1 and Br_3 are shown in figures 10 and 11. The averages are

$$Br_1(LEP) = (84.69 \pm 0.28)\% \qquad (27)$$

$$Br_3(LEP) = (14.91 \pm 0.22)\% \qquad (28)$$

The unconstrained results on Br_5 reported by ALEPH and DELPHI are $Br_5 = (0.10 \pm 0.05)\%$ and $Br_5 = (0.31 \pm 0.13)\%$, respectively. ALEPH also puts a limit on undetected decay modes since the sum of the topological branching modes is consistent with 100% for their analysis. Such a decay could be $\tau \to eN$ where N is a very heavy neutrino-like object and the electron goes unseen because it is has very low energy. The limit is

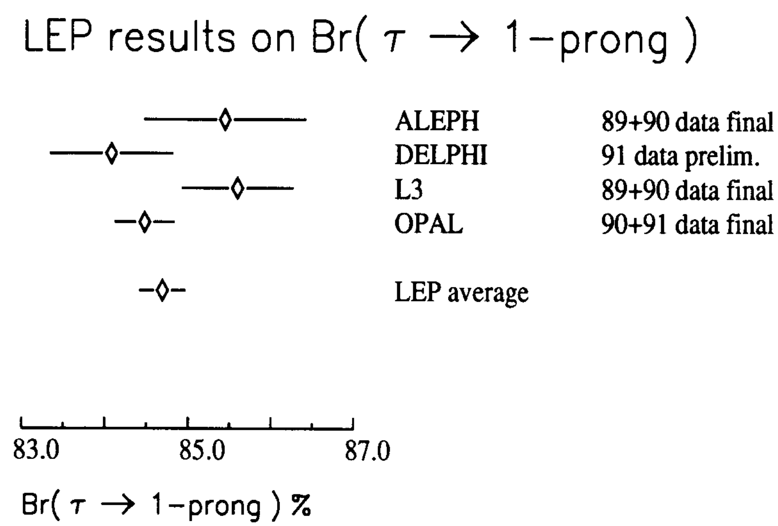
$$Br_{\text{UNDETECTED}} \leq 2.1\% \text{ at } 95\% \text{ C.L.} \qquad (29)$$

L3 reports the limit $Br_5 \leq 0.34\%$ at 95% C.L. The OPAL measurement is $Br_5 = (0.26 \pm 0.08)\%$. Averaging the ALEPH, DELPHI, and OPAL measurements on Br_5 gives

$$Br_5(LEP) = (0.16 \pm 0.04)\%. \qquad (30)$$

7 Exclusive branching ratios

The main exclusive branching ratios measured by the experiments at LEP are those used for tau polarization: $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$ (including Kν), and $\rho\nu$. These



ALEPH	85.45	±	0.97
DELPHI	84.08	±	0.74
L3	85.60	±	0.67
OPAL	84.48	±	0.36
LEP	84.69	±	0.28 %
	($\chi^2 = 3.5$)		

Figure 10: Topological tau branching ratio to one charged particle ("1-prong") from LEP.

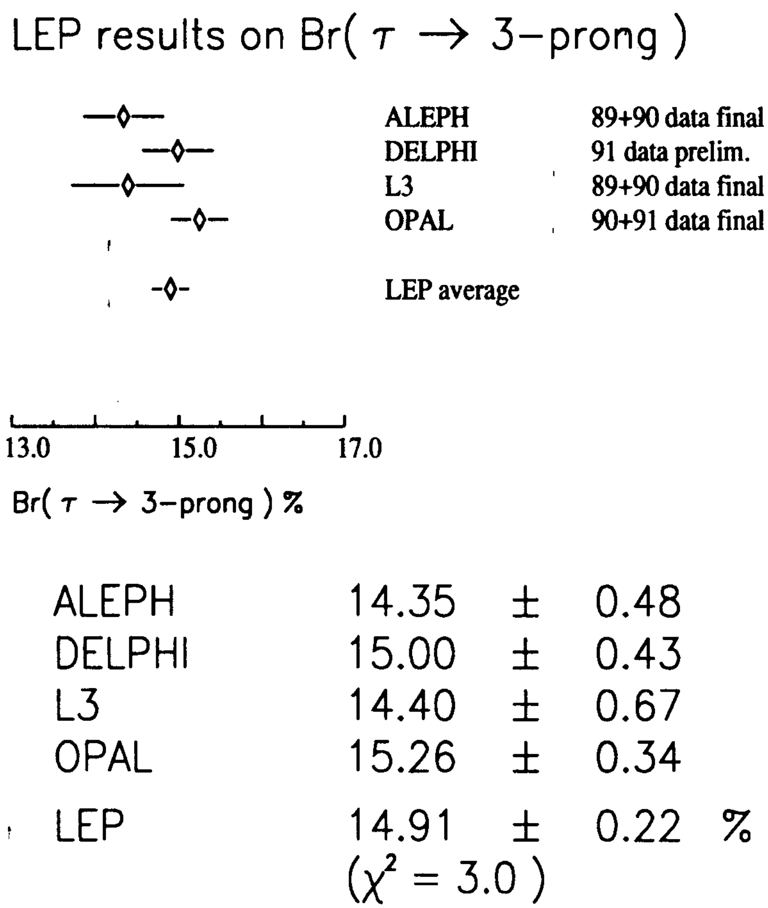


Figure 11: Topological tau branching ratio to three charged particles ("3-prong") from LEP.

decay modes represent almost three-fourths of all tau decays. The remaining decay modes have three or five charged particles (and possibly neutral hadrons) or have more than one neutral hadron accompanying a single charged hadron.

Particle identification is obviously very important for the exclusive branching ratio measurements. In order to reduce cross mode background tighter restrictions are made on the events than are necessary for the cross section measurement, for example.

The main systematic uncertainty in the $e\nu\bar{\nu}$ decay mode comes from e^+e^- background from Bhabha scattering and Z decays. Particle identification is the main source of systematic uncertainty in the $\mu\nu\bar{\nu}$ mode. Photon and π^0 reconstruction are the main problems in the modes with charged hadrons. Figures 12 and 13 show the results from the LEP experiments for the four main modes. The measurements from the different experiments are consistent with each other. The LEP [13] averages are:

$$Br_{e\nu\bar{\nu}}(LEP) = (17.89 \pm 0.29)\% \tag{31}$$

$$Br_{\mu\nu\bar{\nu}}(LEP) = (17.46 \pm 0.26)\% \tag{32}$$

$$Br_{\pi\nu}(LEP) = (12.18 \pm 0.40)\% \tag{33}$$

$$Br_{\rho\nu}(LEP) = (23.70 \pm 0.74)\%. \tag{34}$$

The average leptonic branching ratios is interesting because it can be used with the tau lifetime and parameters from the muon in a test of tau-muon universality (see below). The average leptonic branching ratio from LEP, correcting the muon channel (by 1/0.973) for mass effects [17], is

$$Br_{\mathrm{LEPTONIC}}(LEP) = (17.92 \pm 0.20)\%. \tag{35}$$

ALEPH has also measured the quasi-exclusive branching modes wherein all tau decays are classified into one of eight categories depending on charged particle type and number of π^0's and photons. The ALEPH analysis then goes one step further by classifying the events into exclusive modes based on the charged particle type and a specific number of π^0's only (not photons). By comparing the quasi-exclusive and exclusive results ALEPH sets a limit on new decay modes with neutral electromagnetic energy from other than π^0's (for example from η's) of $\leq 3.4\%$ at 95% C.L.

8 Tau lifetime

At LEP energies tau leptons have an average flight path of about 2 mm before they decay. This fact and the precision of the silicon strip micro-vertex

LEP exclusive branching ratios

$Br(\tau \rightarrow e\nu\nu)$

ALEPH	17.85	±	0.39	89+90+91 data prelim.
DELPHI	18.60	±	1.00	90 data final
L3	17.70	±	0.92	90 data final
OPAL	17.80	±	0.57	90+91 (partial) prelim.
LEP	17.89	±	0.29	%
	(χ^2 = 0.6)			

$Br(\tau \rightarrow \mu\nu\nu)$

ALEPH	17.54	±	0.32	89+90+91 data prelim.
DELPHI	17.40	±	0.92	90 data final
L3	17.50	±	0.94	90 data final
OPAL	17.20	±	0.57	90+91 (partial) prelim.
LEP	17.46	±	0.26	%
	(χ^2 = 0.28)			

Figure 12: Exclusive branching results from LEP on $\tau \rightarrow e\nu\bar{\nu}$ and $\mu\nu\bar{\nu}$.

LEP exclusive branching ratios

$Br(\tau \rightarrow \pi\nu)$

ALEPH	12.55	±	0.55	89+90 data final
DELPHI	11.90	±	0.99	90 data final
OPAL	11.70	±	0.71	90+91 (partial) prelim.
LEP	12.18	±	0.40	%
	(χ^2 = 1.0)			

$Br(\tau \rightarrow \rho\nu)$

ALEPH	24.56	±	1.09	89+90 data final
DELPHI	22.40	±	1.53	90 data final
OPAL	23.40	±	1.35	90 data prelim.
LEP	23.70	±	0.74	%
	(χ^2 = 1.4)			

Figure 13: Exclusive branching results from LEP on $\tau \rightarrow \pi\nu$ and $\rho\nu$.

detectors employed by some of the experiments allows very precise tau lifetime measurements at LEP.

Two measurables are used in the lifetime analysis. The first, the impact parameter is used with 1-prong tau decays. The impact parameter is the distance of closest approach of a track to the beam axis measured in the plane perpendicular to the beam axis. The impact parameter is given a sign according to the track's angular momentum about the beam axis. The second measurable is the decay distance measured from the Z production point to the tau decay vertex as reconstructed from 3-prong tau decays.

For the standard impact parameter analysis a linear relationship between mean impact parameter and tau lifetime is developed using full simulation Monte Carlo. The analysis is carried out on individual 1-prong tau decays not on whole events. Typically the same Monte Carlo events are used several times with different weights to simulate different lifetimes and average impact parameters. The mean impact parameter in data is then measured; the assumption being that the same relationship between mean impact parameter and lifetime exists in data and Monte Carlo. There are several ways to define the mean impact parameter. The LEP experiments use a trimmed mean wherein the high and low tails of the distribution have been excluded from the calculation. The trimmed mean eliminates systematic effects from events with very large impact parameters which are difficult to model well in the Monte Carlo. All the collaborations have reported measurements using the standard impact parameter analysis.

The decay distance method is also used by all experiments. The tau decay point is reconstructed from 3-prong decays assuming the production point to be the center of the beam crossing region. The average decay length (or average decay time) is computed using a maximum likelihood fit to the distribution of decay lengths in the data. The probability for a certain decay length, given a tau lifetime, is taken to be a decreasing exponential convoluted with a Gaussian resolution function. The main sources of systematic uncertainty are the alignment of tracking detectors and pattern recognition problems.

ALEPH has developed two other techniques which use events in which both taus decay to one charged particle. The first method uses the difference in the two impact parameters along with the difference in azimuthal angle of the two tracks. This method has the advantages over the standard impact parameter method that it is not dependent on Monte Carlo and there is no need to estimate the tau direction. The disadvantage is that the smearing on the event origin from the size of the beam spot enters the statistical error twice. The method uses the fact that the average difference in impact parameters, divided by the average difference in azimuthal angles, is proportional to the tau lifetime. The second method uses the sum of the two impact parameters; the advantage being that the uncertainty introduced by the beam spot size is essentially removed. The disadvantage of the impact parameter sum method is that the tau directions enter the calculation and these are always approximate due to the neutrinos in tau decay.

	1990	1991
ALEPH	±14 fs	±6 fs
DELPHI	±25	±9
L3	±38	±15
OPAL	±13	±6

Table 3: Errors reported from data taken in 1990 and 1991 on the tau lifetime. Improvements in 1991 are due to use of silicon vertex detectors for ALEPH, DELPHI, and OPAL. L3 has a new calibration of the tracking system for 1991.

The average tau lifetimes using all techniques and the errors reported by the experiments are summarized in figure 14. The LEP [14] average is

$$\tau_\tau(LEP) = 294.5 \pm 3.8 \text{ fs} \tag{36}$$

where we have added a conservative common systematic of 1 fs in quadrature with the error from the experiments to account for the possible large change in the measured tau mass [15]. All methods except the standard impact parameter method are sensitive to the tau mass.

There has been a suggestion [16] that the tau lifetime from 3-prong decays is systematically high due to pattern recognition problems. For the 1991 data ALEPH, DELPHI, L3 and OPAL report tau lifetimes from 3-prong decays of 295 ± 11, 303 ± 15, 315 ± 25 fs, and 284 ± 9 respectively. The average is

$$\tau_\tau(LEP \text{ 3-prong}) = 292 \pm 6 \text{ fs}. \tag{37}$$

So no such problem seems to exist in the LEP experiments.

The use of silicon vertex detectors for ALEPH, DELPHI, and OPAL and a new calibration of the tracking system for L3 result in greatly improved measurements. In fact the overall measurements are completely dominated by the new results. Table 3 shows the errors quoted by the experiments for 1990 and for the new results. These reductions are far more than one would expect from the greater number of events in 1991, which is roughly a factor of two over 1990.

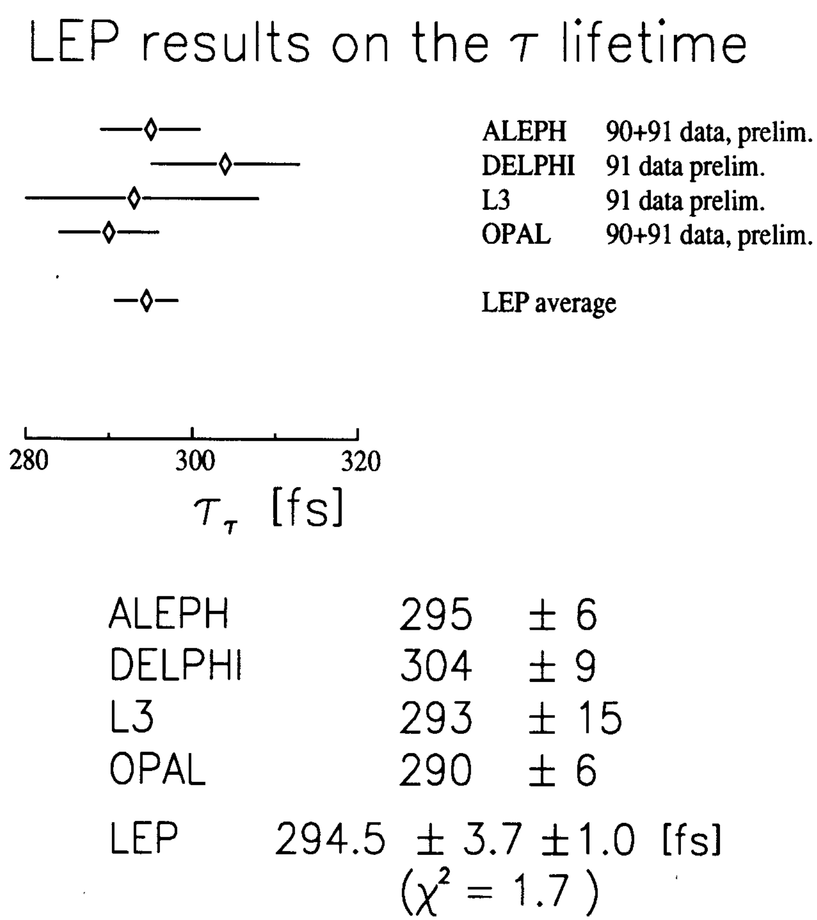


Figure 14: Tau lifetime measurements at LEP. Each experiment reports an average of at least two measurements using the impact parameter and decay length. The second error on the average is a conservative common systematic added here to account for a possible large change in the tau mass. χ^2 is calculated without the common systematic.

8.1 Universality in charged currents

The Standard Model and tau-muon universality require that the ratio g_τ/g_μ be unity. This ratio may be written

$$(g_\tau/g_\mu)^2 = \frac{\tau_\tau}{\tau_\mu} \cdot (\frac{M_\mu}{M_\tau})^5 \cdot Br_{\tau \to e\nu\bar{\nu}}. \tag{38}$$

Using the average tau lifetime from LEP of 294.5 ± 3.8 fs, the average LEP leptonic branching ratio of (17.92 ± 0.20)%, and the PDG tau mass of 1784.1 ± 3.2 MeV the ratio is

$$(g_\tau/g_\mu) = 0.987 \pm 0.006(\tau_\tau) \pm 0.004(M_\tau) \pm 0.006(Br_{\tau \to e\nu\bar{\nu}}) \tag{39}$$

where the contributions to the total error of 0.009 from tau lifetime, tau mass, and leptonic branching ratio are indicated. If instead, the BES [15] mass of 1776.6 ± 0.5 MeV is used[3], the ratio is

$$(g_\tau/g_\mu) = 0.997 \pm 0.006(\tau_\tau) \pm 0.001(M_\tau) \pm 0.006(Br_{\tau \to e\nu\bar{\nu}}) \tag{40}$$

for a total error of ±0.009.

9 Summary and conclusions

The LEP experiments are providing a wealth of results on the tau lepton. Both the production and decay of the tau are studied at LEP. Recent results include the Z partial decay width to taus, the vector and axial vector couplings of the tau to the Z, the tau lifetime, and the leptonic branching ratio of the tau:

$$\Gamma_{Z \to \tau^+\tau^-} = 83.88 \pm 0.67 \text{ MeV} \tag{41}$$

$$g_{V\tau} = -0.0378 \pm 0.0044 \tag{42}$$

$$g_{A\tau} = -0.501 \pm 0.0020 \tag{43}$$

$$\tau_\tau = 294.5 \pm 3.8 \text{ fs} \tag{44}$$

$$Br_{\text{LEPTONIC}}(LEP) = (17.92 \pm 0.20)\%. \tag{45}$$

Electron-tau universality is confirmed at the 25% level in the weak neutral current couplings. Muon-tau universality in the weak charged current interaction

[3]The tau lifetime extracted from the LEP measurements is dependent on the tau mass. A conservative common systematic of 1 fs has been added here to take this into account and the LEP tau lifetime has not been adjusted to take the change in mass into account. The effect on g_τ/g_μ coming directly from a change in tau mass is five times larger than the change in the ratio due to the shift in lifetime resulting from the new tau mass.

is tested at the 1% level; no evidence of universality violation is seen in the LEP data.

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References

[1] S. Jadach, Z. Wąs Comput. Phys. Comm. 36 (1985) 191;
S. Jadach, B.F.L. Ward, and Z. Wąs CERN TH-961-90.
See also CERN 89-08 Z physics at LEP I volume 3, KORALZ program.

[2] D. Decamp *et al.*, (Aleph Collaboration), *Phys. Lett.* B234 (1990) 209-218.

[3] F.A. Berends *et al.*, in "Z Physics at LEP I" CERN 89-08, 1989.
M. Martinez *et al.*, Z. Phys. C 49 (1991) 645-655;
S. Jadach, M. Skrzypek, M. Martinez, CERN-PPE 92-04 (1992).
D. Bardin *et al.*, COMP. PHYS. COMM 59,(1990)303;
D. Bardin *et al.*, Z. Phys. C44 (1989) 493;
D. Bardin *et al.*, Nucl. Phys. B351 (1991) 1;
D. Bardin *et al.*, Phys. Lett. B299 (1989) 405.

[4] Tau lineshape and forward backward asymmetry data from LEP:
Aleph: Priv. comm. preliminary update of Z. Phys. C53 (1992) 20.
Delphi: Priv. comm. preliminary update of Nucl. Phys. B367 (1991) 511.
L3: Priv. comm. preliminary update of Z. Phys. C51 (1991) 179.
OPAL: Priv. comm. preliminary update of Z. Phys. C52 (1991) 175.

[5] D.C. Kennedy, B.W. Lynn, Nucl. Phys. B322 (1989) 1.
M. Consoli, W. Hollik in CERN Report 89-08 Vol I,7.
W.J. Marciano, A. Sirlin Phys. Rev. Lett. 62 (1989) 163.

[6] S. Jadach, Z. Wąs Phys. Rev. D41 (1990) 1425.

[7] S. Jadach and Z Wąs *et al.*, in "Z Physics at LEP I" CERN 89-08, 1989.

[8] A. Rouge' Z. Phys. C48 (1009) 75.
K. Hagiwara *et al.*, Phys. Lett. B235 (1990) 198.

[9] Tau polarization data from LEP:
Aleph: Priv. comm. preliminary results. Previous publication is Phys. Lett. B265 (1991) 430.
Delphi: CERN-PPE/92-60.
L3: Preliminary results from R. Mount CERN Seminar 7 July, 1992.
OPAL: Priv. comm. preliminary results. Previous publication is Phys. Lett. B266 (1991) 201.

[10] R. Tanaka, "Electroweak Results from LEP," to appear in the Proceedings of ICHEP92.

[11] Particle Data Group, "Review of particle Properties," Phys. Rev. D45, Part 2 (June 1992).

[12] Tau topological branching ratio data from LEP:
Aleph: Z. Phys. C53 (1992) 211.
Delphi: Priv. comm. preliminary results for 1991 data.
L3: Phys. Lett.B265 (1991) 451.
OPAL: CERN-PPE/92-66.

[13] Tau exclusive branching ratio data from LEP:
Aleph: See ref. [12]. Additionally the $e\nu\bar{\nu}$ and $\mu\nu\bar{\nu}$ contain preliminary results for the 1991 data.
Delphi: See ref. [9]
L3: See ref. [12].
OPAL: Priv. comm. preliminary results. Previous publication is Phys. Lett. B266 (1991) 201.

[14] Tau lifetime data from LEP:
Aleph: Priv. comm. preliminary results on 1991 data; combined with published 1990 result from CERN-PPE/92-003.
Delphi: Priv. comm. preliminary results on 1991 data. The previous measurement is Phys. Lett. B267 (1991) 422.
L3: Priv. comm. preliminary results on 1991 data. Previous result is [12].
OPAL: Priv. comm. preliminary 1991 analysis and re-analysis of 1990 data. Previous result is Phys. Lett. B273 (1991) 355.

[15] The Particle Data Group 1992 tau mass is 1784.1 with an error of about 3.2 MeV. The recent measurement from the BES is 1776.9 ± 0.5 MeV. See the lecture by E. Soderstrom in the proceedings of this Summer School and SLAC-PUB-5870 and BEPC-EP-92-01.

[16] C. Jung SBHEP-92-1, May 1992.

[17] H.B. Thacker and J.J. Sakurai, Phys. Lett. B36 (1971) 103.