PRAMANA
— journal of
physics

Supplement to Vol. 41
December 1993
pp. 45–53

Electroweak tests with τ leptons at LEP

KRISHNA S KUMAR

Department of Physics, Harvard University, Cambridge, MA 02138, USA.

Abstract. We report on two sensitive tests of lepton universality carried out by the 4 LEP experiments at the Z^0 pole. From measurements of the τ polarization in $e^+e^- \rightarrow \tau^+\tau^-$, the ratios of the vector and axial vector coupling constants of the electron and the tau lepton to the weak neutral current are obtained to be $g_{Ve}/g_{Ae} = 0.066 \pm 0.015$ and $g_{V\tau}/g_{A\tau} = 0.070 \pm 0.009$ respectively. From measurements of the τ lifetime and the τ leptonic branching ratios, the ratio of the coupling constants describing weak leptonic decays of the τ and the μ is measured to be $G_\tau/G_\mu = 0.996 \pm 0.008$.

1. Introduction

With the commissioning of LEP and its successful running with high luminosity, it has become possible to measure the couplings of fermions with high precision, allowing sensitive tests of flavor universality in weak and strong interactions. This has allowed a comprehensive program of precision tests of the Standard Model. LEP has also facilitated stringent tests of the gauge structure of the Standard Model. With the precision measurement of the mass of the Z^0 boson m_Z, we now have three parameters which have been measured experimentally to a precision of better than 10^{-4}: [1,2] the fine structure constant α, the Fermi coupling constant G_F, and m_Z. Using these as input, the model makes precise predictions for the couplings of the fermions to the vector bosons as functions of the masses of the top quark (m_t) and the Higgs boson (m_H) at a given Q^2. A comparison of theoretical estimates with precision measurements of these couplings helps constrain m_t and m_H and may provide clues towards new physics at higher energies.

In this paper, we report on two sensitive tests of lepton universality, one in weak neutral currents and one in weak charged currents. We first motivate the measurement of the τ polarization, describe the experimental technique and summarize the results. We also report on measurements of the τ lifetime and τ leptonic branching ratios.

These measurements have been made possible not only due to the high statistics at LEP, but also due to the good performance of the four LEP detectors: ALEPH, DELPHI, L3 and OPAL. Each detector is characterized by hermetic coverage for jets, precision microvertex detectors, momentum and specific ionization measurements of charged particles, good electromagnetic resolution for high energy electrons and photons, fine segmentation of the calorimeters and good muon detection.

2. τ Polarization

2.1. Motivation

For unpolarized e^+e^- beams, the polarization $\mathcal{P}_f$ of final state fermions in $e^+e^- \to Z^0 \to f^+f^-$ is sensitive to the parity-violating components of the weak neutral current interaction. $\mathcal{P}_f$ is the asymmetry in the total production cross section σ of positive ($h = +1$) and negative ($h = -1$) helicity fermions:

$$\mathcal{P}_f = \frac{\sigma(h=+1) - \sigma(h=-1)}{\sigma(h=+1) + \sigma(h=-1)} . \quad (1)$$

If the weak neutral current contains only vector and axial-vector couplings g_V and g_A, helicity conservation in the massless limit implies $\mathcal{P}_{f^-} = -\mathcal{P}_{f^+} \equiv \mathcal{P}_f$.

Further, due to the parity violation in Z^0 production, $\mathcal{P}_f$ varies with the polar angle θ of f^- with respect to the e^- direction:

$$\mathcal{P}_f(\theta) = -\frac{A_f + A_e\left(2\cos\theta/(1+\cos^2\theta)\right)}{1 + A_f A_e\left(2\cos\theta/(1+\cos^2\theta)\right)} . \quad (2)$$

A_e and A_f are functions of g_V and g_A:

$$A_e = \frac{2g_{Ve}/g_{Ae}}{1+(g_{Ve}/g_{Ae})^2}, A_f = \frac{2g_{Vf}/g_{Af}}{1+(g_{Vf}/g_{Af})^2}, \quad (3)$$

thus making it possible to measure them simultaneously and independently. This must be contrasted to the case of the forward backward charge asymmetry (A_{FB}), which is sensitive to the product $A_e A_f$. It is possible to analyze the final state polarization in the case of τ leptons since it decays close to the interaction region.

The measurement of $\mathcal{P}_\tau$ has many advantages as a precision electroweak measurement. Being the measurement of an asymmetry, it is insensitive to the absolute luminosity. A_e and A_τ are approximately linear in the couplings; thus $\mathcal{P}_\tau(\theta)$ measures the relative sign of g_V and g_A as well as tests e-τ universality in weak neutral current interactions. Non-zero values for A_e and A_τ constitute observations of parity violation in Z^0 production and decay respectively. In the Standard Model, $A_e = A_\tau \simeq 2(1-4\sin^2\theta_W)$, demonstrating the large sensitivity of the measurement to the the weak mixing angle. $\mathcal{P}_\tau$ is relatively insensitive to radiative corrections, unlike A_{FB}.

2.2. Experimental technique

Due to the short decay length of τ leptons and the parity violating V − A structure of the weak charged current decay, $\mathcal{P}_\tau$ can be deduced from an analysis of the kinematics of τ decays [3]. τ leptons of opposite helicity have different decay angular distributions in the τ rest frame, and thus different energy distributions in the laboratory frame. However, deviations from the V−A structure of the weak charged current would modify these decay distributions. In the following, we assume that any such deviations are negligible. The kinematics of the two body decays $\tau^- \to \pi^-\nu_\tau$, $\rho^-\nu_\tau$ and $a_1^-\nu_\tau$ and the three body decays $\tau^- \to e^-\overline{\nu}_e\nu_\tau$ and $\mu^-\overline{\nu}_\mu\nu_\tau$[1] have been studied, which together comprise 77% of all τ decays.

[1] In all cases, charge conjugated decays are also used. In decays involving π^-s the corresponding decays involving K^-s are also used.

Table 1: Sensitivity to $\mathcal{P}_\tau$ for relevant decay modes.

Channel	J	Branch. Ratio	Anal. Power	Stat. Weight
$e^-\overline{\nu}_e\nu_\tau$	1/2	0.178	0.37	0.07
$\mu^-\overline{\nu}_\mu\nu_\tau$	1/2	0.175	0.37	0.07
$\pi^-\nu_\tau$	0	0.125	1.00	0.32
$\rho^-\nu_\tau$	1	0.230	0.87	0.50
$a_1{}^-\nu_\tau$	1	0.070	0.40	0.03

For all the decay modes, the differential cross section with respect to the energy of the decay particle can be calculated as a function of the $\mathcal{P}_\tau$. [4] Table 1 summarizes the sensitivity of each decay mode to $\mathcal{P}_\tau$. [5] The analyzing power is maximal for $\tau^- \rightarrow \pi^-\nu_\tau$ since π^- is spinless, the decay is two-body and the neutrino is purely left-handed. For the two-body decays into vector particles, the analyzing power is smaller since there are two allowed spins states. The sensitivity is enhanced by analyzing their subsequent decays, [5,6] gaining information about the spin state from the decay angular distribution. After accounting for the various branching fractions, the largest statistical significance comes from $\tau^- \rightarrow \rho^-\nu_\tau$. For the three-body decay modes, the analyzing power is significantly smaller.

In each case, $\mathcal{P}_\tau$ is measured by obtaining the linear combination of the $h = +1$ and $h = -1$ monte carlo distributions (*i.e.* reweighting), of the relevant kinematic variables which best fits the data. The Monte Carlo distributions are obtained after event generation [7] and full detector simulation and after applying the same selection as that for the data. In the fits, $\mathcal{P}_\tau$ and the overall normalization are left as free parameters. The dominant systematic errors arise from distortions of the energy distributions from efficiency corrections, calibration and final state radiation, and from uncertainties in the background subtraction mainly from other τ decays.

2.3. Data analysis

The significantly higher multiplicity of multihadronic events and the relatively small cross section of the two photon background due to the Z^0 resonance allows the isolation of a pure sample of leptonic Z^0 decays. To remove decays to dielectrons and dimuons, additional cuts are applied to reject events with two identified electrons and muons. An important consideration in the preselection is to minimize the variation in the selection efficiency as a function of the visible energy, which is sensitive to $\mathcal{P}_\tau$ since the τ^+ and τ^- helicities are fully correlated. The results for each channel from the four experiments are summarized in Fig. 1.[2] In what follows, we indicate very briefly the important considerations for the measurement of $\mathcal{P}_\tau$ in each decay mode.

τ decays to electrons are characterized by an isolated track pointing to the center of gravity of a narrow and symmetric shower in the electromagnetic calorimeter, with little activity in the hadron calorimeter. The main backgrounds come from $Z^0 \rightarrow e^+e^-(\gamma)$ where one of the electrons has been misidentified, and from $\tau^- \rightarrow \rho^-\nu_\tau$ decays with an energetic π^0.

[2] ALEPH and OPAL results are preliminary. The DELPHI results use 1990 data only

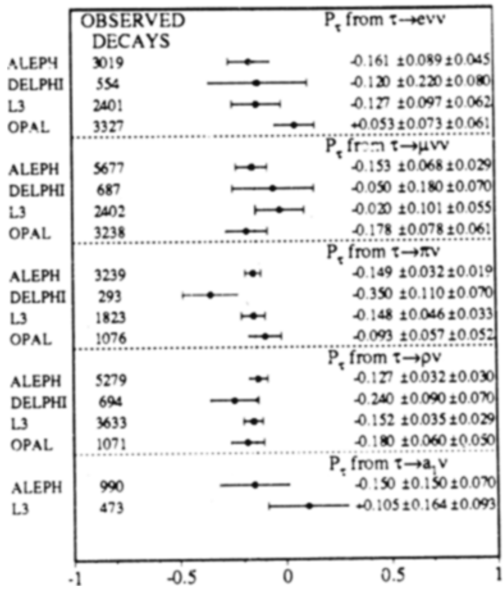

Figure 1. Compilation of all $\mathcal{P}_\tau$ measurements.

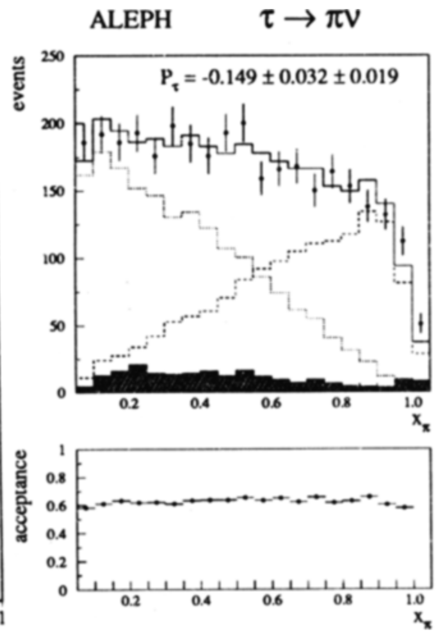

Figure 2. The pion energy distribution and the selection efficiency as a function of $x_\pi = E_\pi/E_{\text{beam}}$.

τ decays to muons are characterized by an isolated track pointing to a minimum ionizing shower in the calorimeters in addition to hits in the muon chambers behind the calorimeters. The main backgrounds come from $Z^0 \to \mu^+\mu^-(\gamma)$ where one of the muons interacts in the calorimeters, and from $\tau^- \to \pi^-\nu_\tau$ where the π^- does not interact in the calorimeters.

τ decays to pions are characterized by an isolated track pointing to an energetic shower in the calorimeters. The main backgrounds come from τ decays to π^-s with associated π^0s which are misidentified due to their proximity to the π^- shower. Figure 2 shows the pion momentum spectrum from the ALEPH data, clearly indicating a negative polarization.

τ decays to rhos are characterized by an isolated track pointing to an energetic shower, accompanied by one or two electromagnetic showers close to the π^- shower. The main background comes from τ decays involving more than one π^0 of which one or more are not reconstructed. To facilitate discrimination between these decays, it is important to have a high efficiency to find π^0s merged with a π^- shower.

2.4. Summary of results

To calculate the average value of $\mathcal{P}_\tau$, 0.003 has been subtracted from those measurements which were obtained with the reweighting procedure to account for the effects of initial and final state radiation as well as $\gamma - Z^0$ interference. Given the current statistical errors, no significant common systematic errors are foreseen among the results from the different experiments. The LEP average is

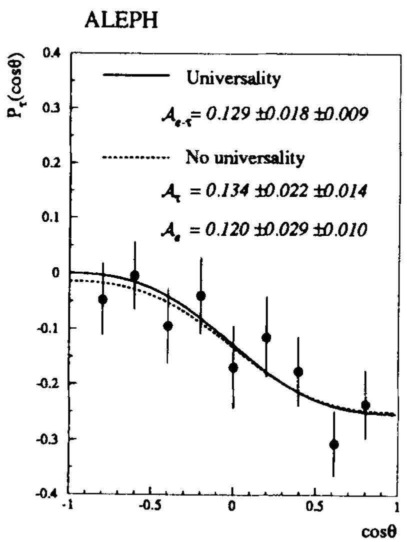

Figure 3. $\mathcal{P}_\tau(\theta)$ vs $\cos\theta$ from ALEPH.

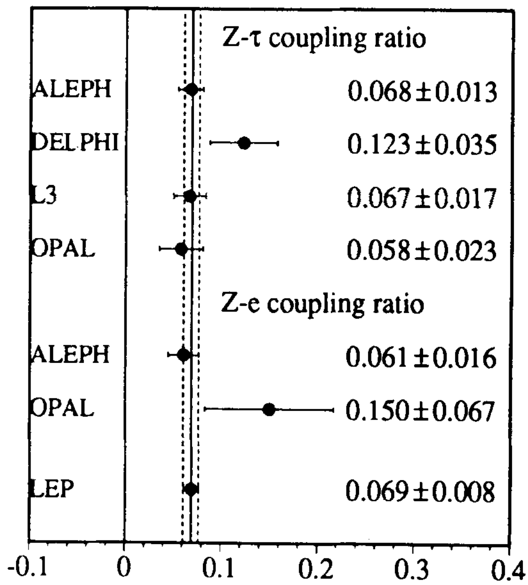

Figure 4. LEP measurements for $g_{V\tau}/g_{A\tau}$ and g_{Ve}/g_{Ae}.

$$\mathcal{P}_\tau(Q^2 = m_Z^2) = -0.140 \pm 0.018 \ .$$

ALEPH has determined A_e and A_τ simultaneously by dividing the data sample in bins of $\cos\theta$, where θ is the polar angle between the τ^- with respect to the e^-, and fitting all the channels in a given bin simultaneously. Figure 3 shows these measurements as well as result of fits using Eqn. 2 with and without the assumption of lepton universality.

The averages from the four experiments for g_V/g_A, obtained using eqn. 3, are summarized in Fig. 4. They constitute a summary of recently published measurements [8], as well as improvements due to increase in statistics. From these, we obtain the LEP averages for the ratio of the vector and axial vector coupling constants effective at $Q^2 = m_Z^2$:

$$\frac{g_{Ve}}{g_{Ae}} = 0.066 \pm 0.015; \ \frac{g_{V\tau}}{g_{A\tau}} = 0.070 \pm 0.009$$

consistent with lepton universality. From this, a value for the effective weak mixing angle is obtained:

$$\sin^2\theta_{\rm eff} = 0.2326 \pm 0.0020 \ ,$$

consistent with other measurements on the Z^0 peak [9]. It should be emphasized that these measurements are dominated by statistical errors and that there are no significant correlations in the systematic errors among the four experiments.

3. $\mu - \tau$ universality in weak decays

3.1. Motivation

For a sequential, heavy, charged lepton l, the electronic branching ratio B_l^e, the lifetime τ_l and the weak coupling constant G_l are related, up to small radiative and electroweak corrections by

$$\frac{B_l^e}{\tau_l} = \frac{G_l^2 m_l^5}{192\pi^3}. \tag{4}$$

It is thus possible to perform a stringent and unambiguous experimental test of lepton universality in charged weak interactions by comparing the decay widths of the muon and the tau into an electron and two neutrinos:

$$\left(\frac{G_\tau}{G_\mu}\right)^2 = \left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B_\tau^e}{B_\mu^e}\frac{\tau_\mu}{\tau_\tau}. \tag{5}$$

Radiative corrections to this formula can be neglected at the current level of precision [10].

Recently, the τ mass has been measured to be $1776.9^{+0.4}_{-0.5} \pm 0.2$ MeV at the Beijing Electron Positron Collider in a scan near the $\tau^+\tau^-$ threshold [11], constituting a significant improvement over the previous world average. Consequently, the dominant errors contributing to the ratio in Eqn. 5 are the τ leptonic branching ratio and the τ lifetime, two measurements where LEP, owing to the clean environment, high boost and large statistics, can be contribute significantly.

3.2. The leptonic branching ratios

New measurements of the τ electronic and muonic branching ratios have also been performed. These can be measured with rather low systematic errors owing to the high efficiency of electron and muon identification and the easy rejection of potential physics backgrounds. Assuming $e - \mu$ universality, which has been tested to high precision [12], the measurement of the leptonic branching ratio can be improved by taking the weighted average of the electronic branching ratio and the the muonic branching ratio, using a factor of 1/0.9728 to account for the non-negligible muon mass. Figs. 5 and 6 summarize the electronic and muonic ratios from the 4 LEP experiments.

3.3. The τ lifetime

The lifetime of the τ has been measured with improved precision at LEP using microvertex detectors installed recently in 3 of the 4 experiments. Typical resolutions on the impact parameter are better than 20 μm. The lifetime is measured using both, the impact parameter technique with 1-prong decays and by direct reconstruction of the decay length with 3-prong decays [13]. A new method exploiting correlations among impact parameters and azimuthal angles in events of the 1 vs 1 topology has also been employed to increase sensitivity. Figure 7 shows the new results of the four LEP experiments. The LEP average improves the precision of the previous world average by better than a factor of 2.

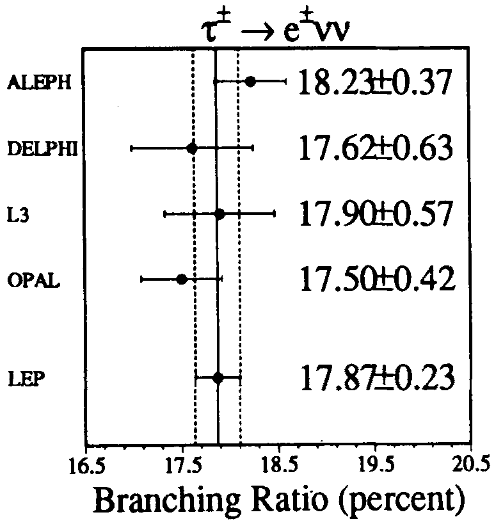

Figure 5. LEP measurements of the $\tau^- \to e^-$ branching ratio.

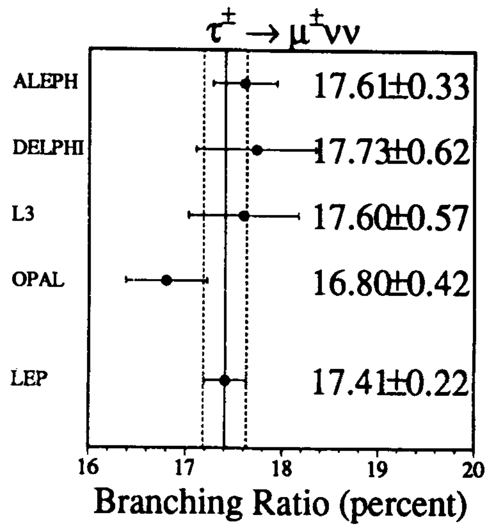

Figure 6. LEP measurements of the $\tau^- \to \mu^-$ branching ratio.

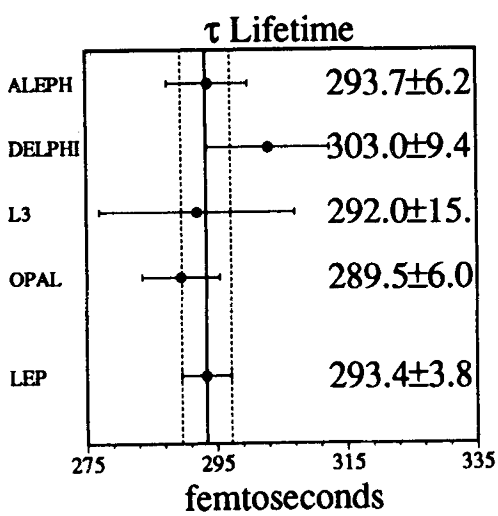

Figure 7. LEP measurements of the τ lifetime.

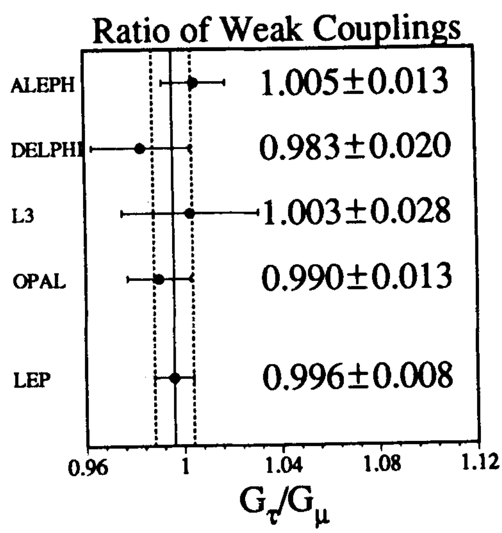

Figure 8. LEP measurements of the G_τ/G_μ.

3.4. Update on G_τ/G_μ

Using the results of the lifetime and branching ratios presented above as well as the new, precise measurement of the τ mass [11], it is straightforward to calculate the ratio of the τ and μ weak couplings using Eqn 5. The results from the four LEP experiments are shown in Fig. 8. The LEP average is:

$$\frac{G_\tau}{G_\mu} = 0.996 \pm 0.008$$

which is a significant improvement over the previous world average.

4. Outlook

In the near future, we expect measurements of $\mathcal{P}_\tau$ with higher statistics and new measurements of $\mathcal{P}_\tau(\theta)$ from all four experiments. The statistical precision will also be improved by better exploitation of the energy correlation between the τ leptons in the same event and by using the acollinearity angle between them [14]. In the interpretation of these measurements, we have assumed the V − A structure of the weak charged current in τ decays. The current experimental data [15], though supporting this hypothesis, are not very precise. The $\mu - \tau$ universality test presented here is also statistics limited and it is hoped to improve the sensitivity by a further factor of 2. Thus, with improved statistics, LEP can begin to probe the structure of the weak charged current in τ decays by assuming the neutral current couplings as determined from other processes on the Z^0 peak [16].

References

[1] K. Hikasa *et al.*, Review of Particle Properties, Phys. Rev. **D45**, No. 11, (1992).

[2] G. Quast, "LEP Energy Calibration, Measurement of m_Z", in the proceedings of XXVI ICHEP, Dallas, USA, August 1992, and references therein.

[3] Y. S. Tsai, Phys. Rev. **D4** (1971) 2821.

[4] S. Jadach *et al.* in *Z Physics at LEP1*, CERN Report CERN-89-08, eds G. Altarelli, R. Kleiss and C. Verzegnassi, Vol. 1, p. 235.

[5] A. Rougé, Z. Phys. **C48** (1990) 75.

[6] K. Hagiwara, A. D. Martin, D. Zeppenfeld, Phys. Lett. **B235** (1990) 198.

[7] S. Jadach and Z. Was, Comput. Phys. Commun. **66** (1991) 276.

[8] K. S. Kumar, "Measurement of τ Polarization in Z^0 Decays", in the proceedings of XXVI ICHEP, Dallas, USA, August 1992, and references therein.

[9] L. Rolandi, "Precision Tests of the Electroweak Interaction", in the proceedings of XXVI ICHEP, Dallas, USA, August 1992, and references therein.

[10] W. Marciano and A. Sirlin, Phys. Rev. Lett. **61** (1988) 1815.

[11] J. Z. Bai *et. al.*, Phys. Rev. Lett. **69** (1992) 3021.

[12] D. I. Britton *et. al.*, Phys. Rev. Lett. **68** (1992), 3000;
G. Czapek *et. al.*, LHEP Preprint, BUHE-92-1 (1992).

[13] M. McCubbin, "Lifetime and Branching Ratios of the τ", in the proceedings of XXVI ICHEP, Dallas, USA, August 1992, and references therein.

[14] R. Alemany *et. al.*, CERN Preprint, CERN-TH/6191/91, (1991).

[15] Argus Collab., H. Albrecht *et al.*, Phys. Lett. **B246** (1990) 278;
Argus Collab., H. Albrecht *et al.*, Phys. Lett. **B250** (1990) 164.

[16] P. Privitera, CERN Preprint, CERN-PPE/92-88, (1992).

Discussion

R. Raja : How well does the ALEPH neural network τ-finding algorithm work compared to conventional techniques?

K. Kumar: For the τ polorization measurement, the two methods are equivalent.

Probir Roy : Your comments please on tau identification through narrow low-multiplicity jets in inelastic events where new physics is sought instead of precision measurements?

K. Kumar : It is possible to construct calorimeter shape variables and particle identification to identify tau leptons. For selecting $\tau^+\tau^-$ pairs at LEP, this procedure is not required.

A. Gurtu : What are the prospects of the other 3 LEP experiments getting P_τ as a function of $\cos\theta$?

K. Kumar : The other LEP experiments should have new results in the next 3 months.

S.D. Rindani : Can you elaborate on a test of CP violation through τ decays?

K. Kumar : We hope to construct CP-odd observables from the energy and directions of the charged tracks in each event. This work is just beginning.

J. Pati : My impression is that if you take both LEP and Non-LEP data, the tau lifetime anomaly still exists at the two standard deviation level. Can you comment on this?

K. Kumar : If you use the full 1991 data sample, the anamoly is about 1 standard deviation.