OPAL-CR124

TAU LEPTON LIFETIME AND DECAY BRANCHING RATIO MEASUREMENTS AT LEP

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Abstract

The τ lifetime has been measured at LEP to be $\tau_\tau = 294.6 \pm 3.7$ fs. This result, together with precise measurements of the leptonic decay branching ratios of the τ from LEP, and the new τ mass measurement from BES, provides a better than 1% test of τ-μ universality in the weak charged current interaction. Accurate measurements of the topological and some of the hadronic decay branching fractions of the τ are also reported.

(Invited talk, XXVIII Rencontres de Moriond, 13–20 March 1993)

Introduction

The copious production of τ leptons at LEP from Z^0 decays provides an excellent opportunity for measuring τ decay properties. The decay products of the τ's are quite collimated, allowing clean separation of $Z^0 \to \tau^+\tau^-$ decays from other processes. This feature, and the excellent performance of the LEP detectors, allow very precise determinations of the τ lifetime, leptonic and topological branching ratios to be made. The collimation of the τ decay products complicates the measurement of the hadronic branching ratios of the τ since it is difficult unambiguously to identify neutral decay products. In spite of this, the dominant hadronic decay mode branching ratios have been measured accurately.

Measurements of the lifetime of the τ lepton together with its leptonic branching ratios can be used to probe whether the weak charged-current interaction is independent of the lepton flavour. In particular:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \left(\frac{\tau_\mu}{\tau_\tau}\right)\left(\frac{m_\mu}{m_\tau}\right)^5 B(\tau^- \to \mathrm{e}^-\overline{\nu}_\mathrm{e}\nu_\tau), \tag{1}$$

where g_ℓ represents the charged current coupling to lepton flavour ℓ, τ_ℓ the lifetime of that lepton, and m_ℓ its mass. The μ lifetime and mass have been very precisely measured, so that in the standard model (where $g_\tau = g_\mu$) it predicts the relationship between τ_τ, $B(\tau^- \to \mathrm{e}^-\overline{\nu}_\mathrm{e}\nu_\tau)$ and m_τ. This provides a particularly interesting test, since the different physical quantities are measured in very different ways. The ratio of the muonic and electronic branching ratios of the τ can be written:

$$\frac{B(\tau^- \to \mu\overline{\nu}_\mu\nu_\tau)}{B(\tau^- \to \mathrm{e}^-\overline{\nu}_\mathrm{e}\nu_\tau)} = \left(\frac{g_\mu}{g_e}\right)^2 f({m_\mu}^2/{m_\tau}^2), \tag{2}$$

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2\ln x$ is a phase-space factor. This relationship can be used to probe e–μ universality. The recent world averages derived by the Particle Data Group ("PDG 92") [1] give $g_\mu/g_\mathrm{e} = 1.004 \pm 0.011$ and $g_\tau/g_\mu = 0.972 \pm 0.012$. This latter result might indicate a discrepancy from the standard model couplings.

Measurements of the inclusive branching ratios of the τ lepton into 1, 3 or 5 charged particles have also been made at LEP with excellent precision. These topological branching ratio results help in understanding the so-called "τ decay problem" [2], as can improved measurements of the different hadronic decay branching fractions.

Most of the measurements reported here use data collected in 1990 and 1991. Some preliminary results include 1992 data. Up to the end of 1991, each LEP experiment had collected around 20 000 $Z^0 \to \tau^+\tau^-$ decays – the 1992 data provide an additional 35 000 τ-pair events, promising further increases in the precision of many measurements in the τ sector.

Lifetime

The τ lifetime is measured from the distributions of track impact parameters, and by reconstructing displaced τ decay vertices for those τ's which decay to three charged particles. At LEP, such measurements benefit from the clean τ sample, from the excellent vertex detectors installed in the experiments, and from the large boost of the decaying τ. All four LEP experiments have recently published, or submitted for publication, updated τ lifetime results including 1991 data [3,4].

At the start-up of LEP in 1989 the four experiments all relied on gas chambers for tracking. In 1990 and 1991 three experiments (ALEPH, DELPHI and OPAL) added silicon microvertex detectors inside the original chambers to improve the resolution, while L3 is adding such a detector for data-taking in 1993. Typical impact parameter resolutions transverse to the beam axis of between 40 and 130 μm were obtained with the original components, improving to 20–30 μm after addition of the silicon detectors. This can be compared to the typical (3-d) impact parameter for a τ decay, of $c\tau_\tau \simeq 90$ μm. At this level of precision the finite size of the LEP beam spot has a significant impact on the lifetime analysis. In 1990 and 1991 the beam spot size was roughly 150 μm by 10 μm in the plane transverse to the beam direction, and about 1 cm along it. For this reason τ lifetime analyses are performed using only two-dimensional impact parameter information.

Four techniques have been used to measure the τ lifetime at LEP. Each of these methods has different strengths and weaknesses, particularly with regard to the influence of the beam spot size. Three of these approaches measure the lifetime with 1-prong τ decays. The first uses the impact parameter distribution of 1-prong decays, signed according to whether the τ apparently decayed in front of, or behind, the vertex – the latter case arising from resolution effects, or from incorrect estimation of the τ flight direction. The mean impact parameter is either obtained from a fit to this distribution, or as a simple truncated mean, and is converted to a lifetime using Monte Carlo simulation. The method has the advantage that it uses the full 1-prong τ decay statistics, and, if the truncated mean is used, is insensitive to errors in parameterizing the detector resolution. It has the disadvantage that its performance is degraded by the finite beam spot size. The other two 1-prong methods use τ-pair events in which both τ leptons decay to 1 charged track. These "impact parameter difference" and "miss-distance" methods have complementary advantages – the former requires no estimate of the τ flight direction but suffers doubly from degradation due to the finite beam size, the latter is insensitive to the beam spot size but requires a good understanding of τ decay dynamics and detector resolution. The different 1-prong methods are statistically correlated, with correlation coefficients between 20 and 50%. The fourth approach, used by all four experiments, employs 3-prong τ decays to reconstruct the τ decay vertex, and derives the lifetime from the decay length distribution. This is an intrinsically powerful method, but suffers due to lack of statistics in the 3-prong decay mode. Fuller discussions of the techniques can be found with the published results [3,4].

The results of the different techniques, as obtained by the four experiments, are shown in figure 1. Each experiment's combined result is shown in figure 2, together with the LEP average, obtained taking into account correlated statistical and systematic errors. The LEP average τ lifetime, based on results of completed analyses, is:

$$\tau_\tau = 294.6 \pm 3.7 \text{ fs}, \tag{3}$$

where the error includes both statistical and systematic effects. As can be seen from figure 2, this result is significantly more precise than the PDG 92 average value. A preliminary DELPHI result using 1992 data was also presented at this conference [5], of $\tau_\tau = 297.6 \pm 4.0 \pm 7.0$ fs. If this result were also included, the LEP average would change to 295.0 ± 3.4 fs.

Leptonic Branching Ratios and Lepton Universality

Identification of τ decays to an electron or muon plus neutrinos is experimentally rather straightforward, due to the simple topology. The details of experimental lepton identification cuts of course differ between experiments, but similar basic observed quantities are used by all. Electrons are identified using a combination of the ionization loss, $\mathrm{d}E/\mathrm{d}x$, in the tracking chambers, the electron shower shape in the calorimeters, and good matching of the position and momentum of the charged track to the shower.

Muons are identified by associating a track seen in the central detectors with hits in the outer layers of the calorimeter, or in external muon chambers surrounding the experiment. The muons may also be required to have left no more than a minimum ionizing deposit in the electromagnetic calorimeter. Vetoing events with two high-energy leptons of the same flavour removes backgrounds from $Z^0 \to e^+e^-$ and $Z^0 \to \mu^+\mu^-$ decays. Isolation cuts remove other τ decays. Overall, the selection efficiency is typically 75–80% within the clean acceptance, with around 4% background. The results obtained by the four experiments are shown in figure 3, together with the LEP average and the PDG 92 average. The recent $B(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ result from the CLEO-II Collaboration [6] is also shown.

Comparing the LEP average $B(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ and $B(\tau^- \to \mu\overline{\nu}_\mu\nu_\tau)$ results gives, from equation 2:

$$\left(\frac{g_\mu}{g_e}\right) = 0.998 \pm 0.010, \tag{4}$$

in excellent agreement with lepton universality. This ratio has also been measured in $\pi^\pm$ decays at TRIUMF [7] to be 1.0030 ± 0.0023. Using this precise constraint, the $B(\tau^- \to e^-\overline{\nu}_e\nu_\tau)$ and $B(\tau^- \to \mu\overline{\nu}_\mu\nu_\tau)$ results from LEP may be combined, after correcting for the phase-space factor f, to give $\overline{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau) = 17.88 \pm 0.17\%$, and from equation 1:

$$\left(\frac{g_\tau}{g_\mu}\right) = 0.996 \pm 0.008. \tag{5}$$

This result takes the new precise τ lifetime measurement from the BES Collaboration [8], of $m_\tau = 1776.9 \pm 0.5$ GeV$/c^2$. The measurements are shown in figure 4.

Topological Branching Ratios

Measurements of the inclusive decay modes of the τ to 1, 3 and 5 charged particles have been made by all four LEP experiments [4, 9, 10]. Events are categorised according to their observed charged multiplicity in the two sides of the event, corresponding to the two τ decays. The experimental technique consists of constructing a mixing matrix describing how real event topologies feed through to observed topologies, and using this to fit for the 1, 3 and 5-prong branching ratios. Off-diagonal elements of the matrix arise due to effects such as the inability to resolve close-by tracks decreasing the observed multiplicity, and track splitting, hadronic interactions in the tracking chambers, K^* decays and photon conversions increasing the multiplicity. The sum of the three branching fractions is constrained to unity, so that the 1 and 3-prong measurements are strongly anticorrelated (since the 5-prong branching ratio is very small). The results obtained are shown in figure 5, and compared to the PDG 92 average. The LEP average 1-prong branching ratio is $(0.9\pm0.3)\%$ lower than the PDG average, the 3-prong result correspondingly higher.

Hadronic Branching Ratios

Several exclusive hadronic decay modes of the τ have been measured at LEP – the results for $B(\tau^- \to \pi^\pm(K^\pm)\nu_\tau)$, $B(\tau^- \to \rho^\pm\nu_\tau)$ and $B(\tau^- \to 3h^\pm\nu_\tau)$ are shown in figure 6. The combined LEP measurements have greater precision than the 1992 PDG averages for these three modes.

A new preliminary result has also been made by the DELPHI Collaboration of the inclusive branching ratio of the τ to $K^\pm$ in 1-prong decays. This measurement uses the particle identification capabilities of the DELPHI RICH imaging Čerenkov detector. Combining data from

1991 and 1992, a result of $B(\tau^- \to \mathrm{K}^\pm \nu_\tau \geq 0\mathrm{neutrals}) = 1.67 \pm 0.24\%$ is obtained, compared to the PDG 92 average value 1.68 ± 0.24 %. By looking for additional π^0 candidates in decays separated as $\mathrm{K}^\pm$ candidates by the RICH, a preliminary result for the branching ratio product $B(\tau^- \to \mathrm{K}^{*-}\nu_\tau)B(\mathrm{K}^{*-} \to \mathrm{K}^-\pi^0)$ of 0.57 ± 0.21 % is obtained. Using $B(\mathrm{K}^{*-} \to \mathrm{K}^-\pi^0) = 0.333$ gives $B(\tau^- \to \mathrm{K}^{*-}\nu_\tau) = 1.7 \pm 0.6$ %, consistent with the PDG 92 average of 1.42 ± 0.18 %.

The ALEPH Collaboration has also published a global analysis of all τ decays, categorised into leptonic and different hadronic decay modes [10]. These results have been updated to include 1991 data [11].

Acknowledgements

I would like to thank my colleagues in the LEP collaborations for their invaluable assistance in preparing this review, particularly M. Davier, E. Gross, R. Mount, M. Pohl, D. Reid, K. Riles, M. Roney and P. Weber. I also thank the organisers of the Rencontre for arranging a stimulating conference in a friendly atmosphere.

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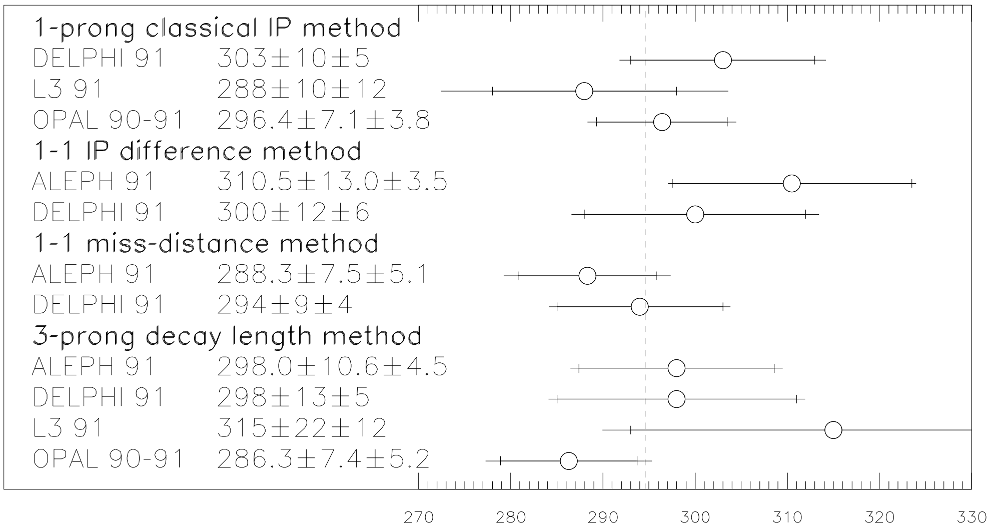

Figure 1: Recent τ lifetime results, in fs, from the LEP experiments. In this and other figures statistical error bars are shown by tick marks, full (statistical $\oplus$ systematic) errors by the total error bar drawn.

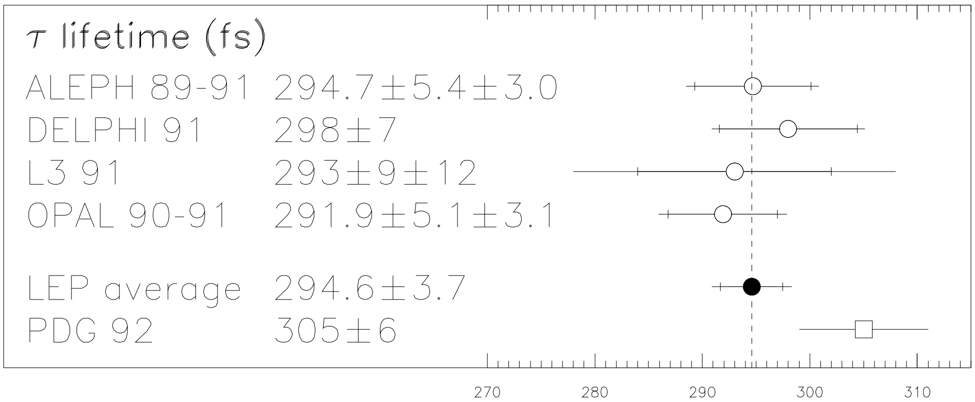

Figure 2: LEP combined τ lifetime results.

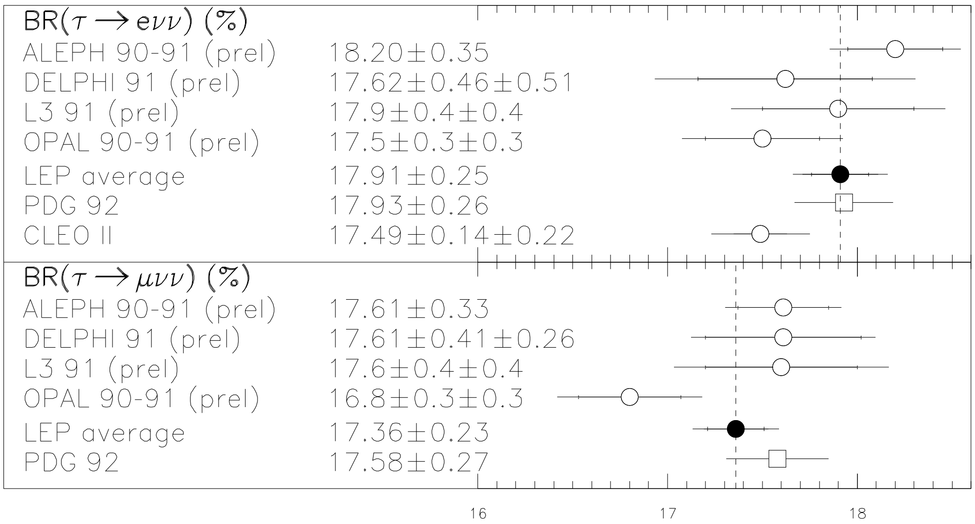

Figure 3: Recent measurements of the leptonic decay branching ratios of the τ.

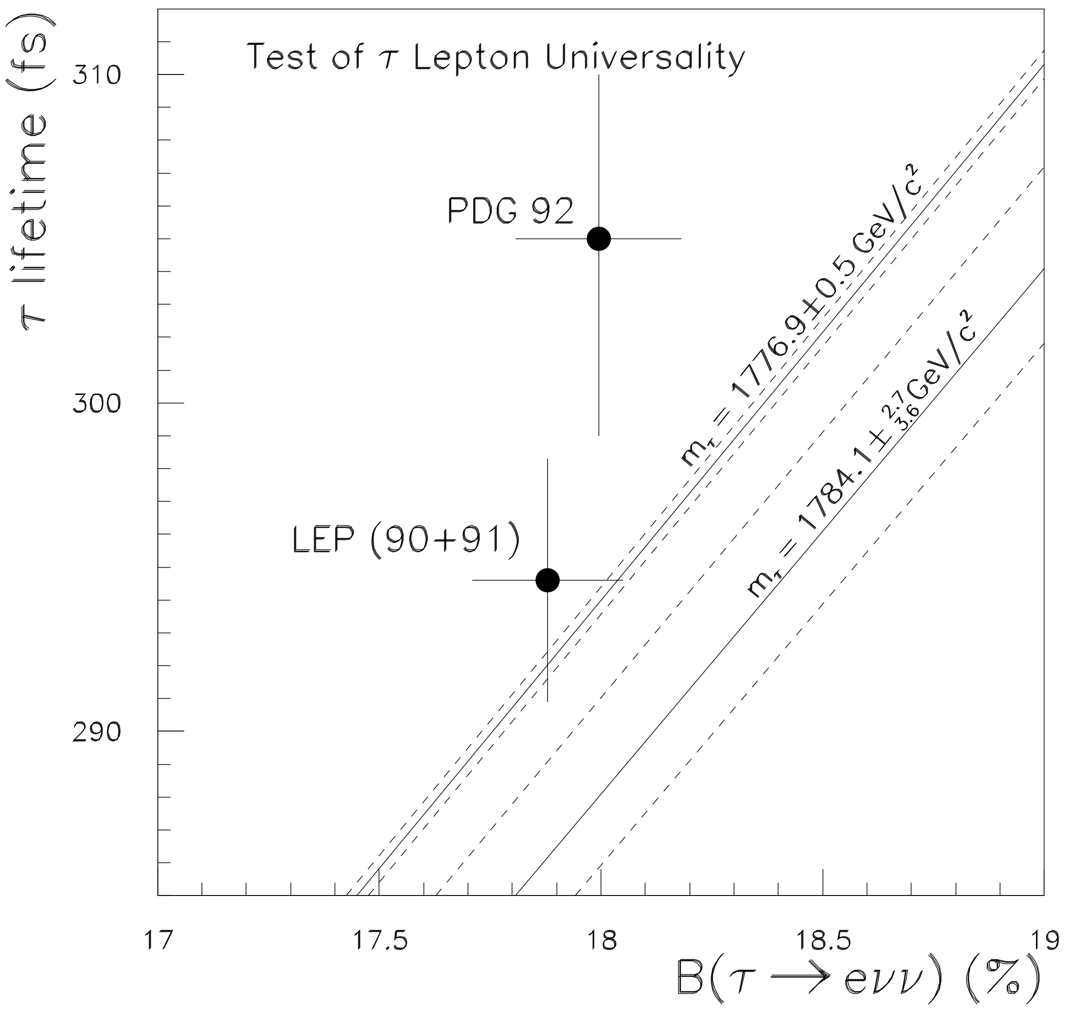

Figure 4: Lepton universality test from τ lifetime, leptonic branching ratio and mass measurements, with PDG 92 average values, with the new LEP measurements, and with the new BES τ mass measurement.

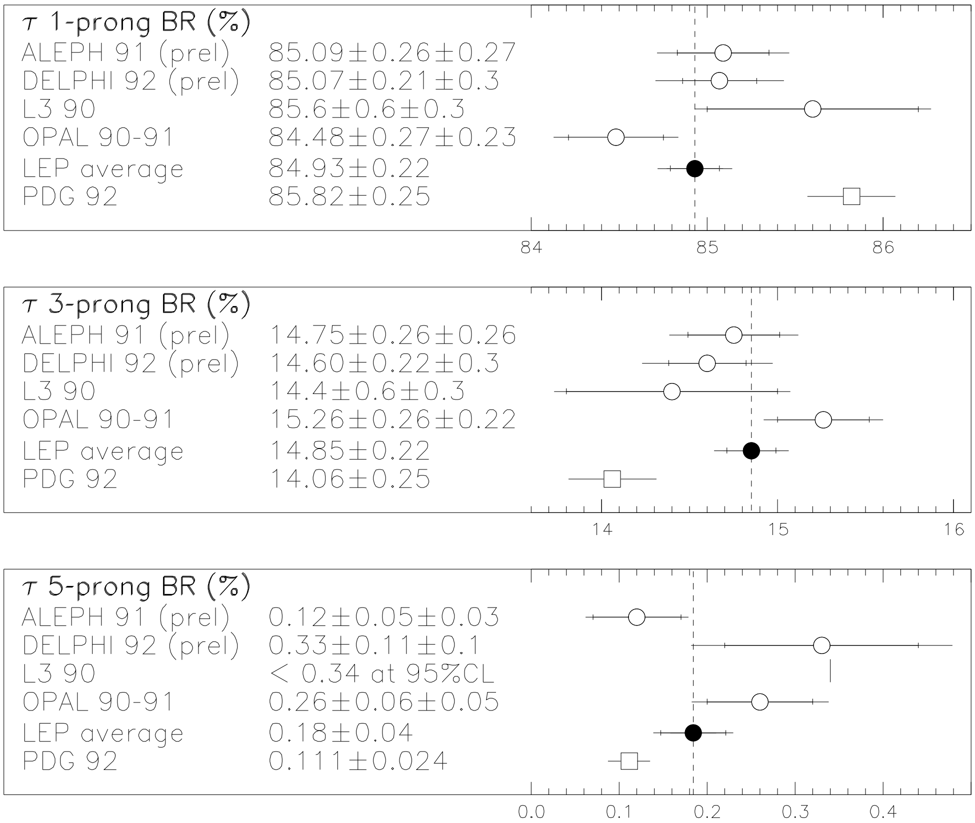

Figure 5: Topological branching ratio measurements at LEP.

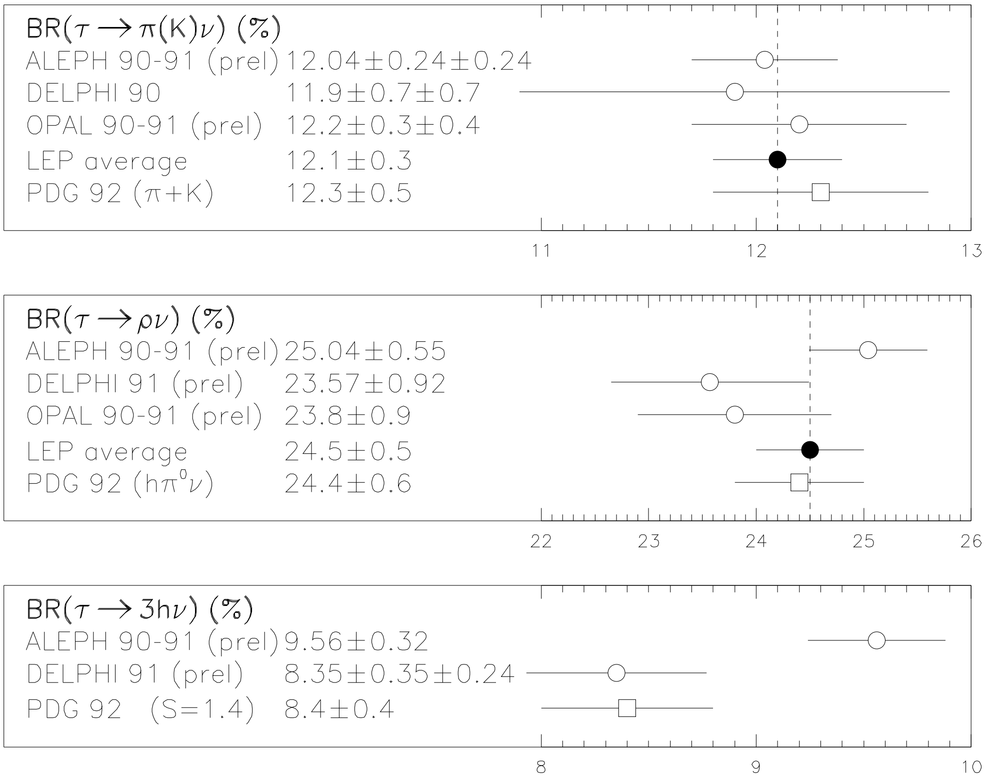

Figure 6: Some hadronic branching ratio measurements from LEP.