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Abstract

The most recent experimental results on τ physics are reviewed. The covered topics include precision measurements of semihadronic τ decays and their impact on tau branching ratio budget, the current status of the tau consistency test, a determination of Michel parameters and τ neutrino helicity, and upper limits on lepton-number violating τ decays.

1 Introduction

During the last years two long-standing problems in τ physics were widely discussed, namely, an indication for the deficit in the τ branching ratio budget and an inconsistency between the measured τ lifetime and τ leptonic branching ratios. A possible source of the tau deficit problem could be the averaging between the experimental results which are internally inconsistent. In particular, there is a large spread in the measurements of the largest semihadronic tau decay channels: $\tau^- \to h^-\pi^0\nu_\tau$, $\tau^- \to h^-2\pi^0\nu_\tau$ and $\tau^- \to h^-h^-h^+\nu_\tau$. The newer precision measurements of their branching ratios are reviewed in the second section of this article. This section also includes recent results on Cabibbo suppressed τ decays. The third section contains a summary of the current status of the τ consistency problem. A great deal has been done in the study of the Lorentz structure of the weak charged current in τ decays. The beautiful experimental results on the measurement of the Michel parameters in leptonic τ decays and the helicity of the tau neutrino in semihadronic τ decays are presented in the fourth section. Finally, the results of the searches for lepton-number violating τ decays are summarized in the fifth section. The measurement of the τ polarization [1] is ***not*** covered in this article.

2 Semihadronic τ Decays

A deficit in the τ branching ratio budget was first noticed in 1984 [2]. This observation was based on the world average values of the measured τ branching ratios and theoretical constraints on the unmeasured modes; so the significance of the deficit depended strongly on the details of the averaging procedure as well as the theoretical assumptions. The first accurate measurement of all τ branching ratios in a single experiment was performed by the ALEPH collaboration [3]. The sum of the exclusive branching ratios measured by ALEPH was found to be in good agreement with unity. In their data ALEPH saturated the τ deficit by an excess over world average values measured, essentially, for the three largest semihadronic τ decay channels: $\tau^- \to h^-\pi^0\nu_\tau$, $\tau^- \to h^-2\pi^0\nu_\tau$ and $\tau^- \to h^-h^-h^+\nu_\tau$. Therefore, confirmation of the large ALEPH branching ratios for these τ decay modes would be highly desirable in view of solving the τ deficit "problem".

2.1 The Decay $\tau^- \to h^-\pi^0\nu_\tau$

Since the $\tau^- \to h^-\pi^0\nu_\tau$ decay represents the largest τ decay mode, the significance of the tau deficit depends in large part on the magnitude and precision of its value. There is a substantial spread in the magnitude of $BR(\tau^- \to h^-\pi^0\nu_\tau)$ with measured values ranging from 22% to 26 % [4, 5] with little errors.

The CLEO collaboration performed a high-precision measurement of the branching ratio $BR(\tau^- \to h^-\pi^0)\nu_\tau$ [6] using the largest data sample to date: 1.44 million produced $\tau^+\tau^-$ events. They selected $\tau^- \to h^-\pi^0\nu_\tau$ decays in events with the second τ lepton decaying into $e^+\nu\bar{\nu}$, $\mu^+\nu\bar{\nu}$, $h^+\pi^0\bar{\nu}$, and $h^+h^+h^-(n\pi^0)\bar{\nu}$, denoted as e, μ, ρ and 3 tag, respectively. Those combinations of event topologies which yield the branching ratio for $h^-\pi^0\nu_\tau$ final state with minimum systematic and uncorrelated statistical errors were chosen for the analysis. The branching ratio $BR(\tau^- \to h^-\pi^0\nu_\tau)$ was calculated via the following relations:

$$BR(\tau^- \to h^-\pi^0\nu_\tau) = \sqrt{\frac{N_{e\rho}N_{\mu\rho}}{2N_{e\mu}N_{\tau\tau}}}, \quad \sqrt{\frac{N_{\rho\rho}}{N_{\tau\tau}}}, \quad or \quad \frac{N_{3-\rho}}{N_{3-1}}B_1 .$$

The $l-\rho$ and $\rho-\rho$ methods require for normalization the number of produced tau pairs $N_{\tau\tau}$, while the $3-\rho$ method is independent of this quantity. Since the branching ratio for the first two methods is determined from the square root of the measured rates, errors associated with these rates and with $N_{\tau\tau}$ are halved. The $l-\rho$ method arranges the measured rates in a combination that is independent of both the τ leptonic decay branching ratios and the lepton identification efficiency. The $\rho-\rho$ method has no dependence on branching ratios other than the one that is being measured. There is a significant discrepancy between different measurements of the $3-prong$ inclusive τ branching ratio [5]. Therefore, the $3-\rho$ method is designed to avoid the uncertainty in the three-prong inclusive branching ratio of the tau by normalizing instead to the one-prong inclusive branching ratio which is known more precisely [5]. All these methods rely strongly on an understanding of the absolute efficiency for π^0 reconstruction as well as the level of background from other $\tau^-\tau^+$ topologies.

The distributions of many kinematical quantities in the signal events were compared between data and Monte Carlo. There is good agreement in all distributions indicating that the acceptance is well modelled and that no significant background (other than the $\tau^+\tau^-$ feed-across component included in the Monte Carlo simulation) remains in the data. An example of such comparison is shown in Fig. 1. The $h^-\pi^0$ mass distribution is well described by the ρ-contribution. The largest background comes from the $\tau^- \rightarrow h^-2\pi^0\nu_\tau$ decays in which an additional π^0 meson is not reconstructed. In order to minimize this background CLEO applied tight veto cuts on the presense of extra photons in the event. All other backgrounds were found to be small except contributions from the hadronic continuum $e^+e^- \rightarrow q\bar{q}$ in the $3-\rho$ and $3-l$ topologies; these were estimated from the data using events with the reconstructed mass of the observed particles in the $3-prong$ hemisphere above the tau mass.

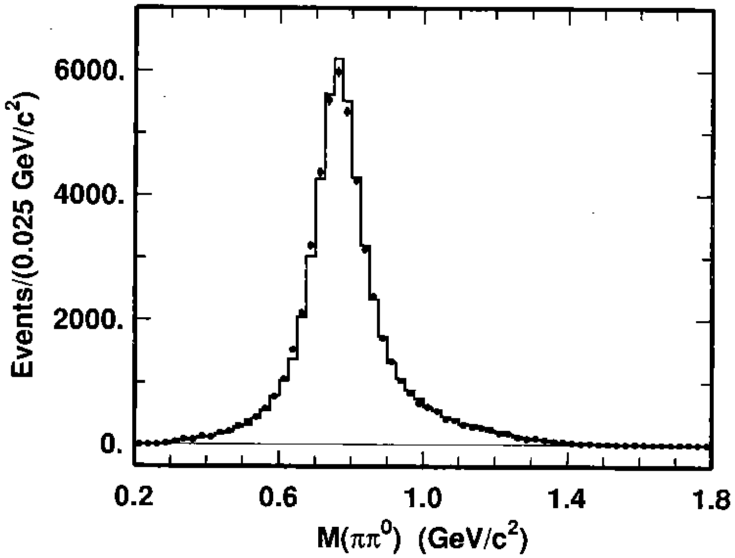

Figure 1: The $h^-\pi^0$ invariant mass.

The values of $BR(\tau^- \rightarrow h^-\pi^0\nu_\tau)$, determined in different event topologies, were found to be:

$$BR(\tau^- \rightarrow h^-\pi^0\nu_\tau) = 25.59 \pm 0.19 \pm 0.47\% \quad (l-\rho)$$

$$BR(\tau^- \rightarrow h^-\pi^0\nu_\tau) = 25.67 \pm 0.17 \pm 0.45\% \quad (\rho-\rho)$$

$$\text{and} \quad BR(\tau^- \rightarrow h^-\pi^0\nu_\tau) = 26.43 \pm 0.29 \pm 0.52\% \quad (3-\rho)\ .$$

The combined result,

$$BR(\tau^- \rightarrow h^-\pi^0\nu_\tau) = 25.87 \pm 0.12 \pm 0.42\%\ ,$$

was obtained by weighting each measurement by its statistical and uncorrelated systematic errors.

Another precision measurement of $BR(\tau^- \rightarrow h^-\pi^0\nu_\tau)$ was performed by the OPAL collaboration [7]. At LEP it is possible to obtain pure samples of $\tau^+\tau^-$ events with background contamination from other processes below the few percent level. The τ leptons from $Z \rightarrow \tau^+\tau^-$ decays are highly energetic and the subsequent τ decay products are collimated along the τ direction of motion. Therefore, special care has to be taken in order to separate the reconstructed τ decay products. OPAL applied two different event selections based on a shower shape technique, where the reconstructed energy depositions in the lead-glass blocks are compared with reference distributions, and a fine clustering algorithm requiring discrete clusters. Both $h^-\pi^0$ selections produce samples with the background dominated by $\tau^- \rightarrow h^- \geq 2\pi^0\nu_\tau$ decays. The numbers of $h^-\pi^0$ and $h^- \geq 2\pi^0$ candidates can be expressed in terms of the corresponding branching ratios. These branching ratios can be simultaneously derived assuming that the background from other tau decays is properly described in the Monte Carlo simulation. The

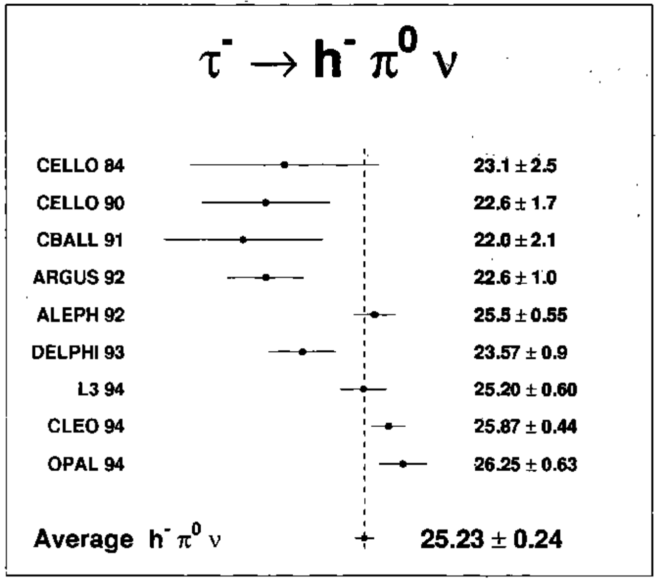

Figure 2: The present status of $BR(\tau^- \rightarrow h^-\pi^0\nu_\tau)$ measurements.

uncertainty in the branching ratios for the background channels produces only a small effect on the final result.

Both methods applied by OPAL give consistent results:

$$BR(\tau^- \to h^-\pi^0\nu_\tau) = 26.15 \pm 0.38^{+0.51}_{-0.80}\% \quad \text{(shower shape technique)}$$

$$\text{and} \quad BR(\tau^- \to h^-\pi^0\nu_\tau) = 26.25 \pm 0.36 \pm 0.52\% \quad \text{(fine clustering algorithm)}\ .$$

The samples obtained using the two methods are highly correlated having more than 50% of the selected events in common. Since the two results are not independent, they are not averaged. Instead, the OPAL collaboration quotes the $BR(\tau^- \to h^-\pi^0\nu_\tau)$ obtained from the fine clustering algorithm as the result to be considered.

The present status of $\tau^- \to h^-\pi^0\nu_\tau$ branching ratio measurements is shown in Fig. 2. One observes a definite trend towards a higher values of $BR(\tau^- \to h^-\pi^0\nu_\tau)$. Both the CLEO and OPAL measurements are in good agreement with the previous ALEPH measurement [3]. Taking into account these new results the new world average value of $BR(\tau^- \to h^-\pi^0\nu_\tau)$ is found to be as large as 25.23±0.24%, reducing substantially both the magnitude and significance of the τ deficit problem.

Subtracting the contribution from $\tau^- \to K^-\pi^0\nu_\tau$ decays (the measurement of $BR(\tau^- \to K^-\pi^0\nu_\tau) = 0.52 \pm 0.07$ is discussed in section 2.3) one arrives at $BR(\tau^- \to \pi^-\pi^0\nu_\tau) = 24.71 \pm 0.25\%$. This value is in perfect agreement with the CVC prediction [8] obtained using the data on the cross-section $\sigma(e^+e^- \to \pi^+\pi^-)$: $BR(\tau^- \to h^-\pi^0\nu_\tau) = 24.58 \pm 0.93 \pm 0.27 \pm 0.50\%$, where the errors come from the e^+e^- data, the tau lifetime, and radiative corrections, respectively.

2.2 The Decays $\tau^- \to h^-2\pi^0\nu_\tau$ and $\tau^- \to h^-h^-h^+\nu_\tau$

The τ decays into final states containing three hadrons have the second largest (after $BR(\tau^- \to h^-\pi^0\nu_\tau)$) branching ratio among semihadronic τ decay channels. In the absence of firm theoretical predictions for the $\tau^- \to (3h)^-\nu_\tau$ decay the precision measurement of its branching ratio is of large importance in view of understanding the τ deficit problem. There are two possible final states, $h^-2\pi^0\nu_\tau$ and $h^-h^-h^+\nu_\tau$, which are expected to occur at comparable rates by isospin conservation. The experimental situation is quite unsatisfactory. In particular, there is a troublesome discrepancy between ARGUS 92 [9] and ALEPH 92 [3] measurements of $BR(\tau^- \to h^-h^-h^+\nu_\tau)$, and between ALEPH 92 [3] and CBALL 91 [10] measurements of $BR(\tau^- \to h^-2\pi^0\nu_\tau)$.

The present status of $BR(\tau^- \to h^-2\pi^0\nu_\tau)$ measurements is shown in Fig. 3 The most precise measurement of the $\tau^- \to h^-2\pi^0\nu_\tau$ decay was made by the CLEO collaboration [11]. The reconstruction of multiple $\pi^0 \to \gamma\gamma$ decays is favourable at CLEO thanks to the relatively large opening angle between photons and the high efficiency, excellent energy resolution and fine segmentation calorimeter, made of 7800 CsI (Tl) crystals located inside the magnet. In order to cancel out common systematic errors CLEO has measured the ratio of the branching ratios $BR(\tau^- \to h^-2\pi^0\nu_\tau)/BR(\tau^- \to h^-\pi^0\nu_\tau)$. Taking the latest CLEO value of $BR(\tau^- \to h^-\pi^0\nu_\tau)$, the measured ratio is turned into $BR(\tau^- \to h^-2\pi^0\nu_\tau) = 8.93 \pm 0.44\%$, which is somewhat smaller than the ALEPH92 result. The present world average is $BR(\tau^- \to h^-2\pi^0\nu_\tau) = 9.21 \pm 0.32\%$.

Recently the CLEO collaboration reported on a new measurement of the $\tau \to h^-h^-h^+\nu_\tau$ decay [12]. Their large data sample of produced $\tau^+\tau^-$ events allows to apply the double-tag method which provides the absolute measurement of the branching ratio. Using this method the knowledge of any other τ decay branching ratio is required only to estimate the level of the τ feed-across background. The disadvantage of the double-tag method for the measurement of the $h^-h^-h^+\nu_\tau$ decay mode is a rather large contribution from hadronic events containing 6 charged tracks. At the expense of some decrease in efficiency ($\epsilon = 12.4\%$) the fraction of hadronic background (the background from two-photon events is negligible) was suppressed to the level of $\sim 4.5\%$ by cutting out events having an $h^-h^-h^+$ invariant mass smaller than 1.5 GeV/c^2 and events containing extra "photon-like" calorimeter showers. The latter cut reduces as well the feed-across f_{xf} from $\tau^- \to h^-h^-h^+ \geq 1\pi^0\nu_\tau$ decays (mostly from $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ decay) to the level of $\sim 12\%$.

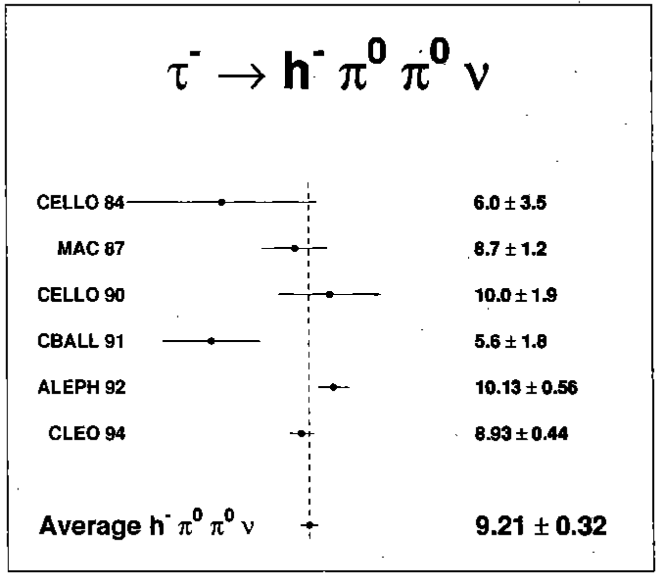

Figure 3: The present status of $BR(\tau^- \to h^-\pi^0\pi^0\nu_\tau)$ measurements.

There were 2030 events (N_{obs}) observed after event selection with $non-\tau$ background contamination of $N_{bg} = 95$ events. The branching ratio of the $\tau \to h^-h^-h^+\nu_\tau$ decay was calculated using the following relation:

$$BR(\tau^- \to h^-h^-h^+\nu_\tau) = \sqrt{\frac{(N_{obs} - N_{bg})(1 - f_{xf})}{N_{\tau\tau} \times \epsilon}}\ .$$

This leads to the most precise measurement to date of the branching ratio $BR(\tau^- \to h^-h^-h^+\nu_\tau) = 9.79 \pm 0.14 \pm 0.34\%$. The accuracy is limited by systematic uncertainties in the track reconstruction efficiency (2.0%) and variation of the event selection cuts (2.2%). The CLEO measurement is in good agreement with the ALEPH 92 result.

Fig. 4 summarizes the measurements of the $\tau^- \to h^-h^-h^+\nu_\tau$ decay resulting in the world average value with a rather little error:

$$BR(\tau^- \to h^-h^-h^+\nu_\tau) = 8.80 \pm 0.18\%\ .$$

However, the standard averaging procedure is obviously not a good one for this case. Given the sizable inconsistency between the results of different experiments, improved measurements of the $\tau \to h^-h^-h^+\nu_\tau$ decay are called for.

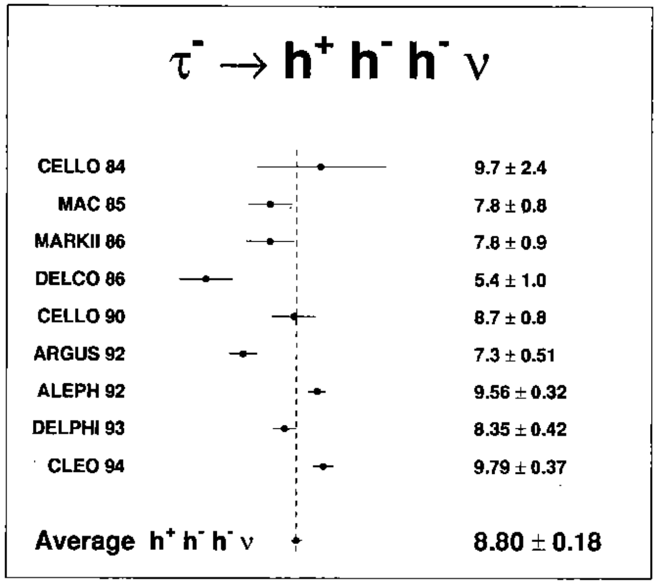

Figure 4: The present status of $BR(\tau^- \to h^-h^-h^+\nu_\tau)$ measurements.

2.3 Cabibbo Suppressed Decays of the τ Lepton

Until very recently Cabibbo suppression of τ decays involving the strange quark had been tested with only limited precision. The DELPHI measurement of the $\tau^- \to K^-\nu_\tau, K^{*-}\nu_\tau$ decay branching ratios [13] allowed a more stringent test of this important aspect of the Standard Model. The precision has been further improved by the newer measurements of the ALEPH [14, 15] and CLEO [16] collaborations described in more detail here. ARGUS also updated their previous measurement of the $\tau^- \to K^{*-}\nu_\tau$ decay [17]. The most precise measurements of the $\tau^- \to K^-\nu_\tau$ and $\tau^- \to K^{*-}\nu_\tau$ decays are presented in Fig. 5 and Fig. 6.

The CLEO collaboration reported on a new measurement of the branching ratio for $\tau^- \to K^-\nu_\tau$ and a measurement of the decay $\tau^- \to K^-\pi^0\nu_\tau$, which is expected to proceed through the $K^{*-}(892)$ resonance. The CLEO detector provides reliable K/π separation for particle momenta below ~0.7 GeV/c using the combined measurements of the characteristic energy loss (dE/dx) in the tracking chamber and the particle's time-of-flight. The decrease of the acceptance due to the rather limited momentum range of kaon identification is compensated by the large data sample of produced $\tau^+\tau^-$ events available at CLEO. The kaon identification efficiency and pion misidentification probability have been calibrated as a function of momentum and polar angle using kaons from $D^{*+} \to D^0\pi^+ \to K^-\pi^+\pi^+$ decays and isolated pions from K^0_S decays in hadronic events as reference data samples. The $1-$***prong*** tau decays into kaons were selected in $1-1$ and $1-3$ *prong* topologies resulting in a sample of 230 events. The dominant background of 12% arises from semihadronic τ decays due to pions misidentified as kaons; the background contamination from non-τ events is below 2%. Using this data sample the inclusive branching ratio into one charged kaon was determined to be $1.60 \pm 0.12 \pm 0.19\%$. To discriminate between the exclusive decay modes containing zero or one π^0, the calorimeter information in the kaon

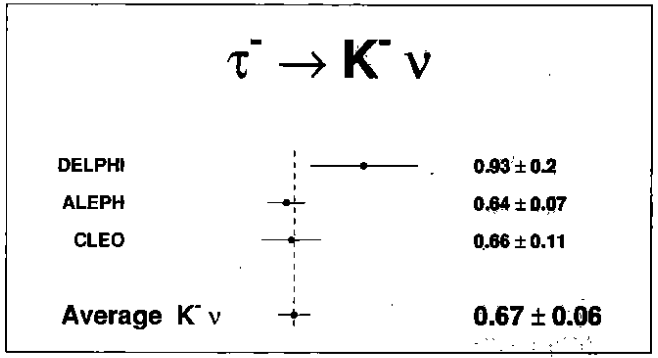

Figure 5: The present status of $BR(\tau^- \to K^-\nu_\tau)$ measurements.

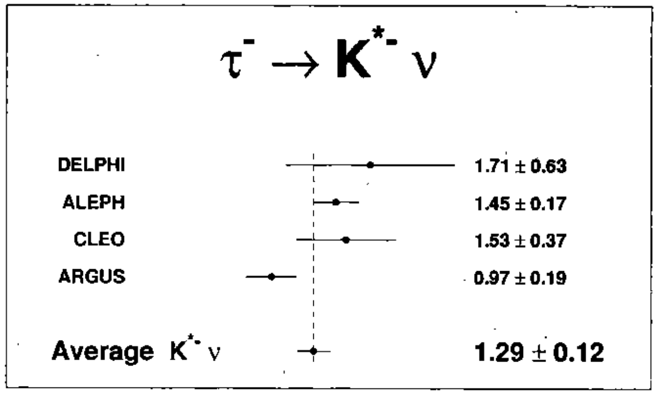

Figure 6: The present status of $BR(\tau^- \to K^{*-}(892)\nu_\tau)$ measurements.

hemisphere was analyzed. The $K^-\gamma\gamma$ invariant mass spectrum, shown in Fig. 7(b), exibits the resonant shape of $K^{*-}(892)$ with no indication of non-resonant production. The distribution of the photon-pair invariant mass, $M_{\gamma\gamma}$, is shown in Fig. 7(a) for the $\tau^- \to K^-\pi^0\nu_\tau$ candidates. The π^0 peak position, width, low mass tail, and background level are well reproduced by the Monte Carlo simulation. So, the number of $K^-\pi^0$ events was determined from the fit of $M_{\gamma\gamma}$ spectrum.

For the exclusive decay modes the following values of the branching ratios were found:

$$BR(\tau^- \to K^-\nu_\tau) = 0.66 \pm 0.07 \pm 0.09\%$$

$$\text{and} \quad BR(\tau^- \to K^-\pi^0\nu_\tau) = 0.51 \pm 0.10 \pm 0.07\%$$

The ALEPH experiment selected a high purity sample of inclusive 1-prong semihadronic τ decays with a non-τ background of 0.1 %. In order to distinguish charged kaons from pions, ALEPH used the dE/dx information from their tracking chambers. The K/π separation at more than two standard deviations is possible on a statistical basis over almost the full momentum range. To improve the calibration of the measurements of dE/dx its shape was taken from data using muons produced in Z and τ decays. This procedure has the advantage that the same angular distribution observed for the muons and hadrons under study is used.

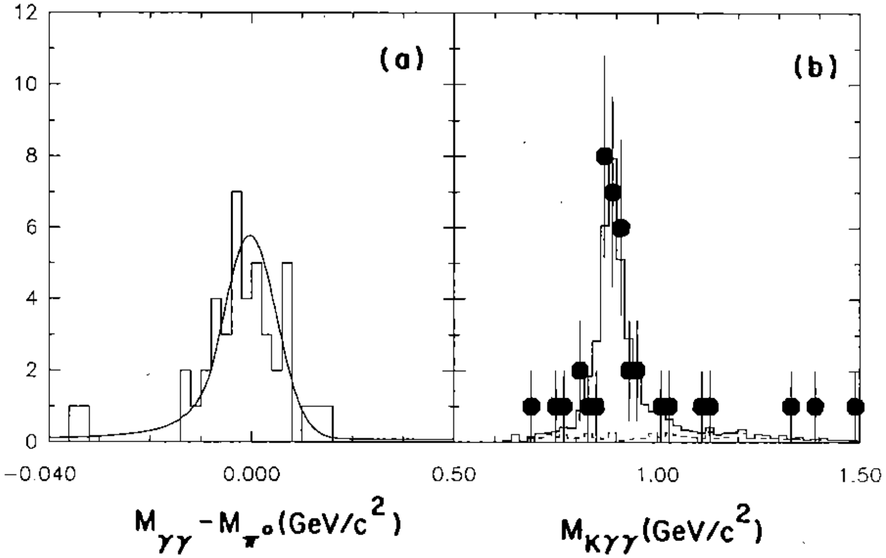

Figure 7: (a) The invariant mass of the photon pair in $\tau^- \to K^-\pi^0\nu_\tau$ events. (b) The invariant mass of $K^0\gamma\gamma$ combinations.

The fraction of kaons was derived from a fit to the linear combination of expected pion and kaon contributions (the small components for electrons and muons from leptonic τ decays were also included). Beyond statistical limitations the main source of uncertainty is the description

of the pion dE/dx distribution as a function of momentum. The resulting statistical power of the ALEPH method is only 25 % below that of an ideal analysis identifying kaons perfectly on an event-by-event basis. After classifying the selected events with respect to the π^0 multiplicity the following branching ratios were extracted:

$$BR(\tau^- \to K^- \geq \pi^0\nu_\tau) = 1.60 \pm 0.07 \pm 0.12\% \,,$$

$$BR(\tau^- \to K^-\nu_\tau) = 0.64 \pm 0.05 \pm 0.05\% \,,$$

$$\text{and} \quad BR(\tau^- \to K^-\pi^0\nu_\tau) = 0.53 \pm 0.05 \pm 0.07\% \,.$$

The invariant mass distribution of the $K^-\pi^0$ final state, as obtained from separate dE/dx fits in each mass bin, is shown in Fig. 8(a) together with the Monte Carlo prediction (solid line). The observed shape is well described by the $K^{*-}(892)$ resonance contribution.

ALEPH also performed a complimentary measurement of the $\tau^- \to K^{*-}(892)\nu_\tau$ decay using the π^-K^0 decay mode of the $K^{*-}(892)$ resonance. The K^0 production in 1-prong semihadronic τ decays was studied by tagging the K^0_L component using only the information from a fine-grain hadronic calorimeter. The detection of K^0_L meson was based on a large energy deposition in $HCAL$, exceeding the expected amount for the charged hadron alone, and on a displacement of the shower energy barycentre from the extrapolation point of the track into $HCAL$.

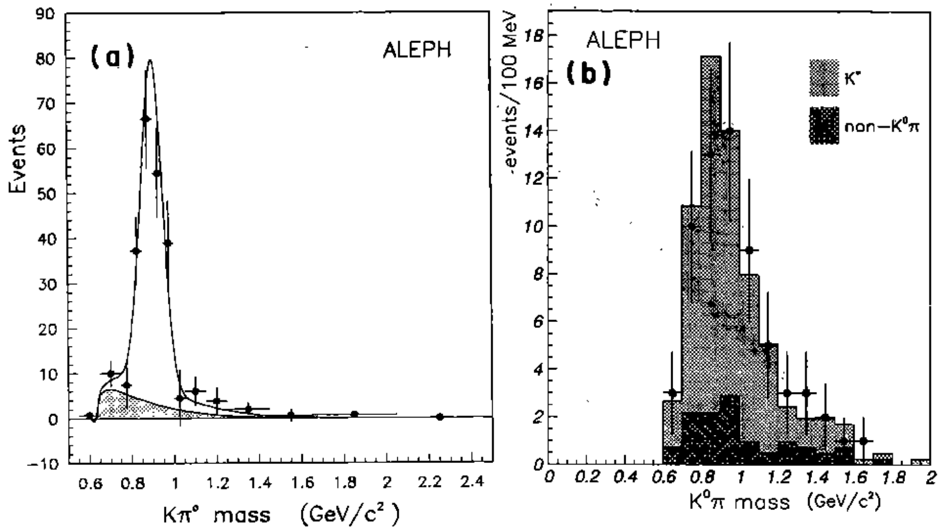

Figure 8: The invariant mass of $K^-\pi^0$ (a) and $K^0\pi^-$ (b) combinations. The Monte Carlo distributions are shown for the $K^{*-}(892)$ contribution (solid line) and feed-across background (shaded).

The charged hadron in each τ decay was statistically identified as a pion or kaon using the dE/dx measurement in the TPC, as described above. From a sample of 74 selected $h^-K^0_L$

events, the dE/dx fit yields the pion and kaon fractions of 89% and 11% respectively. This allows one to determine the branching ratios, scaled to the full K^0 rate:

$$BR(\tau^- \rightarrow \pi^- K^0 \nu_\tau) = 0.88 \pm 0.14 \pm 0.09\%$$

$$\text{and} \quad BR(\tau^- \rightarrow K^- K^0 \nu_\tau) = 0.29 \pm 0.12 \pm 0.03\% \,.$$

Similarly to the $K^-\pi^0$ final state, the invariant mass distribution of the $\pi^- K_L^0$ system, shown in Fig. 8(b), agrees well with the Monte Carlo prediction assuming a dominant $K^{*-}(892)$ contribution.

The two independent measurements of $BR(\tau^- \rightarrow K^-\pi^0\nu_\tau)$ and $BR(\tau^- \rightarrow \pi^- K^0 \nu_\tau)$ can be converted into the $\tau^- \rightarrow K^{*-}(892)\nu_\tau$ decay branching ratio. Scaled up to the full $K^{*-}(892)$ decay modes using isospin invariance,

$$BR(\tau^- \rightarrow K^{*-}(892)\nu_\tau) = 1.32 \pm 0.21 \pm 0.13\% \quad (K^0\pi^- \text{ decay mode})$$

$$\text{and} \quad BR(\tau^- \rightarrow K^{*-}(892)\nu_\tau) = 1.58 \pm 0.16 \pm 0.20\% \quad (K^-\pi^0 \text{ decay mode}) \,.$$

The combined ALEPH result $BR(\tau^- \rightarrow K^{*-}(892)\nu_\tau) = 1.45 \pm 0.13 \pm 0.11\%$ is listed in Fig. 6.

The averaging of the measurements of the Cabibbo-suppressed $\tau^- \rightarrow K^-\nu_\tau$ and $\tau^- \rightarrow K^{*-}(892)\nu_\tau$ decays made over the last two years yields:

$$BR(\tau^- \rightarrow K^-\nu_\tau) = 0.67 \pm 0.06\%$$

$$\text{and} \quad BR(\tau^- \rightarrow K^{*-}\nu_\tau) = 1.29 \pm 0.12\% \,.$$

Using the value of $BR(\tau^- \rightarrow K^-\nu_\tau)$ permits a precise test of the $\tau - \mu$ universality by comparing to the value of $BR(K^- \rightarrow \mu^-\bar{\nu}_\mu)$. It is convenient to perform such a test by normalizing the value of $BR(\tau^- \rightarrow K^-\nu_\tau)$ to the electronic τ branching ratio. Using the average value $BR(\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau) = 17.84 \pm 0.12\%$, obtained from [18, 19] assuming $e - \mu$ universality, one derives:

$$\frac{BR(\tau^- \rightarrow K^-\nu_\tau)}{BR(\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau)} = 0.037 \pm 0.003 \,,$$

which is in good agreement with the value of the corresponding ratio 0.0399 ± 0.0002 expected from $\tau - \mu$ universality, the measured $BR(K^- \rightarrow \mu^-\bar{\nu}_\mu)$ [4] and radiative corrections [20].

In the Standard Model the rate for the $\tau^- \rightarrow K^{*-}(892)\nu_\tau$ decay is related to that of its Cabibbo-favoured analog $\tau^- \rightarrow \rho^-\nu_\tau$ [21, 22]. Using the DMO sum rule prediction [23] ($\frac{f^2_{K^*}}{f^2_\rho} = \frac{M^2_{K^*}}{M^2_\rho}$ neglecting the width of the resonances), one expects $BR(\tau^- \rightarrow K^{*-}(892)\nu_\tau) = 1.19 \pm 0.01$. This prediction agrees well with the new world average for the $\tau^- \rightarrow K^{*-}(892)\nu_\tau$ decay branching ratio.

3 Consistency of the τ Lifetime and τ Leptonic Branching Ratio

It has recently been the focus of much attention that the world average values of the tau lifetime and leptonic branching ratio are at the limit of being consistent with lepton universality implied by the $SU(2) \times U(1)$ gauge symmetry of the Standard Model. Within this model, and ignoring small radiative corrections, τ_τ and $BR(\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau)$ are related through the following equation:

$$BR(\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau) = (\frac{G_F^\tau}{G_F^\mu})^2 \times \frac{\tau_\tau}{\tau_\mu} \times (\frac{m_\tau}{m_\mu})^5 \,.$$

Fig. 9 shows the so called consistency test in graphical form. The most precise measurements of the τ lifetime [18, 24] are plotted versus the electronic τ branching ratio [19]. The diagonal band represents the prediction of the Standard Model for the new world average value of the τ mass [25]

$$m_\tau = 1777.0 \pm 0.3 \; MeV/c^2 \,.$$

The present values of τ_τ and $BR(\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau)$ are entirely consistent indicating that the consistency problem does not stand any more. The major change in the consistency test with respect to the previous measurements is due to a sizeable reduction in the τ lifetime and τ mass.

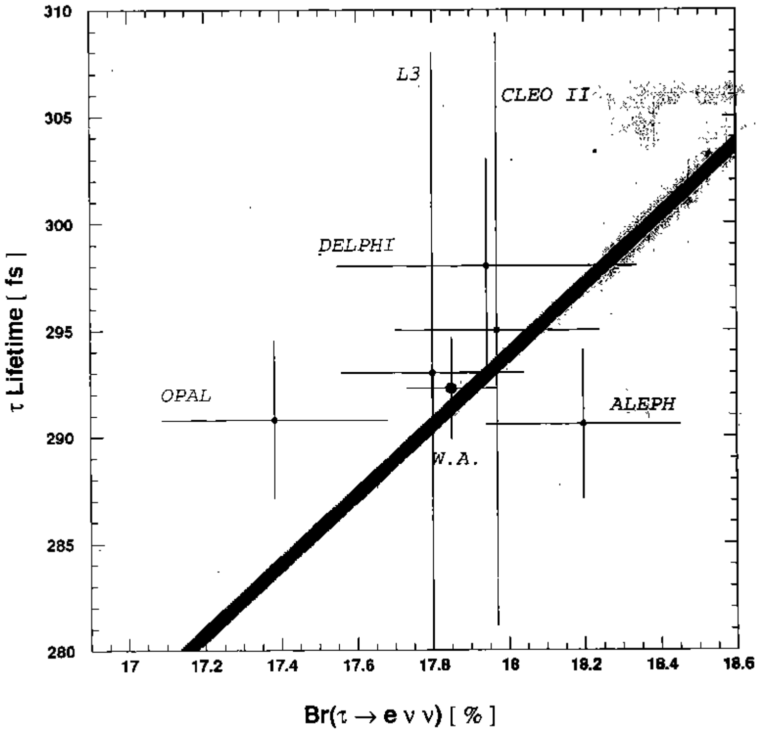

Figure 9: The consistency test in graphical form. The diagonal band represents the prediction of the Standard Model for the new world average value of the τ mass.

4 Lorentz Structure of the Weak Charged Current in τ Decays

In the Standard Model the charged weak current has $V - A$ structure predicting 3/4, 0, 1, and 3/4 for the ρ, η, ξ, and δ Michel parameters respectively [26]. The actual structure of the weak coupling can be more complicated resulting in departures of the Michel parameter values from their $V-A$ predictions. For example, a non-zero value for η could only result from some scalar or tensor coupling. Even in the muon case, where very detailed studies have been done [27], an overall analysis with all possible weak couplings leaves enough room for decay contributions apart from that from the standard W-boson. In the τ sector, the experimental precision is far from allowing a comparable analysis. However, the more massive tau could provide a more sensitive test for the presence of some couplings different from the $V-A$ one. In addition semihadronic τ decays allow also a direct determination of the ν_τ helicity and, consequently, a test of its $V-A$ value h_{ν_τ}=-1.

The experimental results of the last few years on $\rho = 0.727 \pm 0.033$ [4, 28], on $|\xi| = 0.90 \pm 0.15 \pm 0.10$ [29], and on the τ neutrino helicity [30, 31] agree well with the Standard Model predictions. The most recent results include the first measurement of the Michel parameter η [32] in $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ and new measurements of the ν_τ helicity [34, 35] in semihadronic τ decays with much improved precision.

4.1 The First Measurement of the Michel Parameter η

The momentum spectrum of the final state charged lepton (electron or muon) in leptonic τ decays provides the most information on the Michel parameters. Neglecting radiative corrections and finite mass effects the lepton momentum spectrum in the decay of unpolarized τ is expressed by:

$$\frac{d\Gamma}{dx} \propto x^2\{12(1-x) + \rho \times (\frac{32x}{3} - 8) + \eta \times \frac{m_l}{m_\tau} \times \frac{24(1-x)}{x}\} ,$$

where $x = \frac{2E_l}{m_\tau}$ is the scaled lepton energy. While the shapes of both electron and muon spectra are sensitive to the Michel parameter ρ, the η parameter affects only the shape of the muon spectrum. Due to the very small factor $\frac{m_e}{m_\tau}$ in the expression above the value of η has no effect upon the electron momentum spectrum.

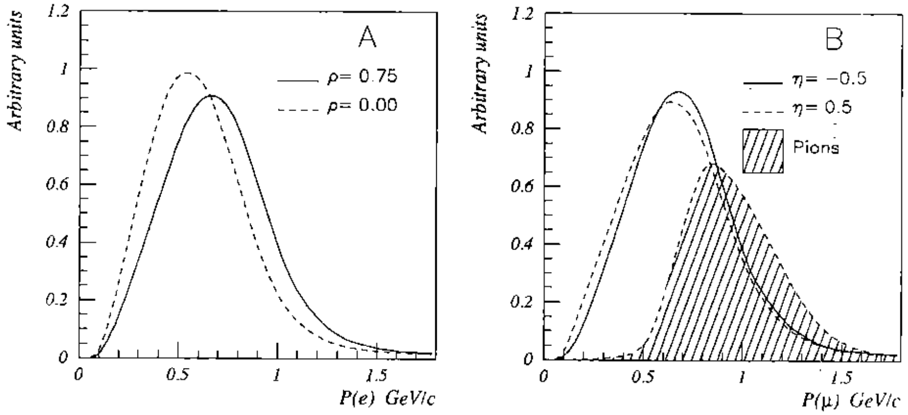

Figure 10: Prediction for the spectrum of electrons with $\rho = 0.75$ and $\rho = 0$ (A) and for muons with $\eta = -0.5$ and $\eta = 0.5$ together with the pion spectrum from the decay $\tau^- \to \pi^- \nu_\tau$ (B).

The best sensitivity to the Michel parameters can be achieved in the τ rest frame because the shape of the lepton spectrum is not diluted by the Lorentz transformation. In order to perform the Lorentz boost into the τ rest frame, the τ four-momentum has to be known. The τ energy is determined by the beam energy up to initial state radiative corrections. The direction of τ cannot be exactly reconstructed since the neutrinos escape detection. It can, however, be inferred from the direction of the system of charged hadrons originating from the decay of the second τ lepton in the event. Due to its relatively high mass this system gives a good approximation to the flight direction of τ leptons. The rest system determined using this approximation is called the τ "pseudo rest frame". The expected momentum spectra of leptons originating from $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ and $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ decays in the τ pseudo rest frame are shown in Fig. 10. The increased sensitivity to the Michel parameters in the τ pseudo rest frame is complemented by the advantage of analyzing the muon spectrum over almost the entire momentum range. In contrast to previous measurements in the laboratory frame the dominant background contribution from $\tau^- \to \pi^- \nu_\tau$ decays at low muon momenta (below the region of muon identification) can be separated kinematically in the τ pseudo rest frame, as shown in Fig. 10.

The efficiency corrected and background subtracted spectra of electrons and muons in the τ pseudo rest frame are shown in Fig. 11(a) and 11(b) correspondingly. The analysis of these spectra allows one to deduce the Michel parameters. In the most general case the muonic decay of the τ lepton can differ in its space time structure from the electronic one; the Michel parameters must be determined separately for these two decays. The fit of the muon spectrum itself does not allow one to make any restrictive constraints on the values of $\eta_\mu = 0.01 \pm 0.34$ and $\rho_\mu = 0.712 \pm 0.103$ due to limited statistics and high correlation between the fit parameters. Assuming the equality of ρ in $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ and $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ decays ARGUS performed a combined three parameter fit of electron and muon spectra with ρ, η and a normalization

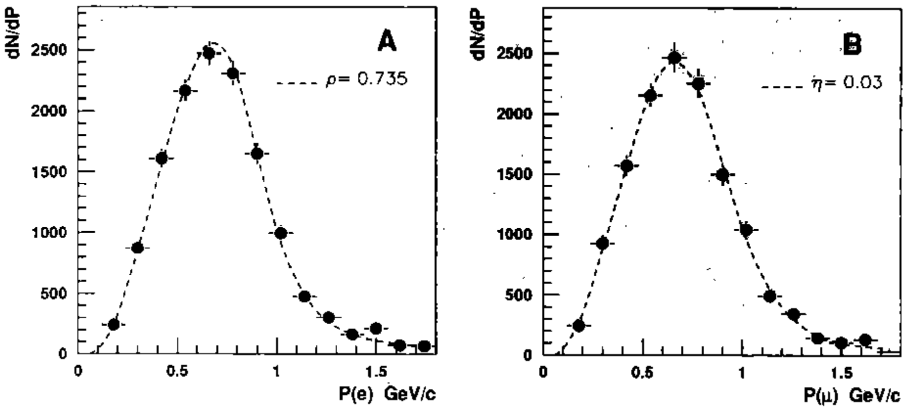

Figure 11: Efficiency corrected electron (A) and muon (B) spectra in the tau pseudo rest frame. The fit results are shown with the dashed lines.

parameter. The fit gives $\eta = 0.03 \pm 0.18$ and $\rho = 0.732 \pm 0.034$. The fit results are shown in Fig. 11 with dashed lines. Taking into account the systematic uncertainties (the largest uncertainty of $\sim 1\%$ comes from the lepton identification efficiency) the ARGUS result is:

$$\eta = 0.03 \pm 0.18 \pm 0.12$$

$$\text{and} \quad \rho = 0.732 \pm 0.034 \pm 0.20 \ .$$

The above values are in good agreement with the Standard Model predictions.

4.2 The Measurement of the ν_τ Helicity in Semihadronic τ Decays

The structure of the weak charged current can also be probed in semihadronic decays of polarized τ leptons. A particularly informative distribution is that of the polarization sensitive variable z. In general, this distribution in semihadronic τ decay, with the $\tau^{\pm}$ in a pure helicity state $h(\tau^{\pm})$, is given by [21, 33]:

$$\frac{d\Gamma}{dz} \propto F(z) \mp h(\tau^{\pm}) \times \xi_h \times G(z) \ ,$$

where the specific form of kinematic functions $F(z)$ and $G(z)$, as well as the z variable, depends on the semihadronic decay channel under consideration. These functions have a particularly simple form for the $\tau^- \to \pi^- \nu_\tau$ decay: $F_\pi = 1$ and $G_\pi = z$ with z defined as the cosine of the decay angle of the pion with respect to the τ spin in the tau rest frame $z = (2E_\pi/E_\tau - 1)$. The parameter ξ_h is sensitive to the Lorentz structure of the interaction. Restricting the general case of interaction to the mixture of only V and A couplings, ξ_h is equal to the negative τ neutrino helicity

$$\xi_h = \gamma_{AV} = -h_{\nu_\tau}$$

where $\gamma_{AV} = \frac{-2g_V^* g_A}{g_V^2 + g_A^2}$. In the Standard Model the neutrinos are left-handed corresponding to $h_{\nu_\tau} = -1$ and, consequently, to $\xi_h = +1$.

The first direct measurement of h_{ν_τ} was performed by ARGUS [30], demonstrating explicit parity violation in τ decays. Exploiting the interference between the two amplitudes of ρ^0 production in the decay $\tau^- \to a_1^- \nu_\tau$, $a_1^- \to \rho^0 \pi^-$, they obtained $h_{\nu_\tau} = -1.25 \pm 0.23^{+0.15}_{-0.08}$, which is in good agreement with the Standard Model prediction.

This year the precision of the τ neutrino helicity was much improved by the measurements of the ALEPH [34] and ARGUS [35] collaborations. At LEP the τ leptons produced in Z^0 decays are polarized due to their different left- and right-handed couplings to the neutral current. This feature has been utilized to measure, in fact, the product $< h(\tau) > \xi_h$ [36] in different semihadronic τ decays. The analysis of correlated decay spectra in $\tau^+\tau^- \to h_i^+ \bar{\nu}_\tau h_j^- \nu_\tau$ events allows one to determine ξ_{h_i}, ξ_{h_j} and $< h(\tau) >$ separately, if the sign of ξ_{h_i} or $< h(\tau) >$ is known.

ALEPH selected $\tau^+\tau^-$ events in which at least one of the τ decays is classified as $\pi\nu_\tau$ or $\rho\nu_\tau$. Thus each candidate event falls into five exclusive groups: $\pi\pi$, $\pi\rho$, $\rho\rho$, πX or ρX, where X stands for any other τ decay channel. The πX and ρX modes were retained to constrain the products $< h(\tau) > \xi_h$ in the fit. For every π and ρ candidate the polarization sensitive variable z_i (i=π or ρ) was computed assuming $E_\tau = E_{beam}$. The difference between E_τ and E_{beam} arising due to initial state radiation has been explicitly taken into account in the fitting procedure.

The parameters ξ_π, ξ_ρ and the τ polarization $< h(\tau) >$ were extracted from the simultaneous fit to the 1-dimensional distributions on z_i for πX and ρX groups, and to the 2-dimensional $z_i z_j$ distributions for $\pi\pi$, $\pi\rho$ and $\rho\rho$ groups. The fit gives $< h(\tau) > = -0.139 \pm 0.027$, $\xi_\pi = 0.95 \pm 0.11$ and $\xi_\rho = 1.03 \pm 0.11$. Accounting for the various systematic uncertainties in the acceptance, resolution and background rates (the largest uncertainty $\delta\xi_\pi = \pm 0.04$ and $\delta\xi_\rho = \pm 0.04$ is due to the finite Monte Carlo set used for the determination of the acceptance and resolution matrices), the ALEPH result is:

$$\xi_\pi = 0.95 \pm 0.11 \pm 0.05$$

$$\xi_\rho = 1.03 \pm 0.11 \pm 0.05 \ .$$

In models which contain only mixtures of V and A couplings in the weak charged current the measured values of ξ_π and ξ_ρ can be averaged leading to

$$\gamma_{AV} = 0.99 \pm 0.07 \pm 0.04 \ .$$

Tau pairs produced via the $e^+e^- \to \tau^+\tau^-$ reaction well below the Z^0 resonance have no net τ polarization. However, the electromagnetic production of the τ leptons results in their fully correlated spins. At $\sqrt{s}$ around 10 GeV the production of lepton pairs with opposite spin orientation is suppressed by a factor $\frac{2m_\tau^2 c^4}{s} \simeq \frac{1}{16}$. Thus using the final state hadrons as spin analyzers makes the structure of the coupling in τ decays observable.

ARGUS exploited spin correlations in the process $e^+e^- \to \tau^+\tau^- \to \rho^+ \bar{\nu}_\tau \rho^- \nu_\tau$. Assuming a $V - A$ structure these correlations are sensitive to the parameter γ_{AV}^2 which can be interpreted as the negative product of τ neutrino helicities, $\gamma_{AV}^2 = -h_{\nu_\tau} h_{\bar{\nu}_\tau}$.

In total 1707 $\rho^+\rho^-$ candidates were selected containing a relatively small non-τ background of 32 events. The main background contribution comes from other τ decays, mostly from the decay $\tau^- \to a_1^- \nu_\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$ (362 events) with one π^0 meson escaping detection.

The likelihood method described in reference [37] was applied to determine the parameter γ_{AV}^2. This method exploits the analysis of all kinematical information including 11 measurable quantities: 9 angles and 2 invariant masses. Some of these quantities are known up to a twofold ambiguity because the τ direction of flight cannot be measured directly. The kinematical information given by the observed hadronic decay products of the τ pairs constrains the τ axes yielding 0, 1 or 2 possible solutions. The case of no reconstructed τ axes can only occur due to initial state radiation effects and the finite detector resolution. The ambiguity has been explicitly taken into account in the likelihood analysis.

In order to extract a value for γ_{AV}^2 ARGUS carried out a detailed investigation of the likelihood functions for simulated event samples containing mixtures of signal and background events comparable to the data. Particular attention was paid to the study of the likelihood function for the primary background contribution from $\tau^- \to a_1^- \nu_\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$. This background results in a likelihood function with a maximum value, relative to other backgrounds, around 0.6. This is a consequence of the fact that the ρ^- meson produced in the a_1^- decay can carry all the spin information of the a_1^- meson for dominant S wave decay if the π^0 from the direct a_1^- decay escapes detection; this is not the case if the π^0 produced by the ρ^- is lost. A comparison of the likelihood function for the selected data sample (solid line) with the one for a simulated data sample with proper mixture of signal and background events (dashed line) shows a good agreement, as seen from Fig. 12. The dotted line in Fig. 12 corresponds to the likelihood function for the background from $\tau^- \to a_1^- \nu_\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$ decays. Since this function is particularly important for the determination of γ_{AV}^2, the simulated background was compared with the measured background by requiring an additional π^0 in one hemisphere of the selected events. The two corresponding likelihood functions were then calculated without using the additional π^0s of these events. Data and Monte Carlo were found to be in good agreement.

The likelihood function for the selected events (solid line in Fig. 12) yielded $\gamma_{AV}^2 = 0.856 \pm 0.056$. After introducing initial state radiation and detector acceptance effects the corrected value was found to be:

$$\gamma_{AV}^2 = 1.044 \pm 0.057 \pm 0.060 \; .$$

Combining this result with the previous measurement of the sign of γ_{AV}, ARGUS obtained a

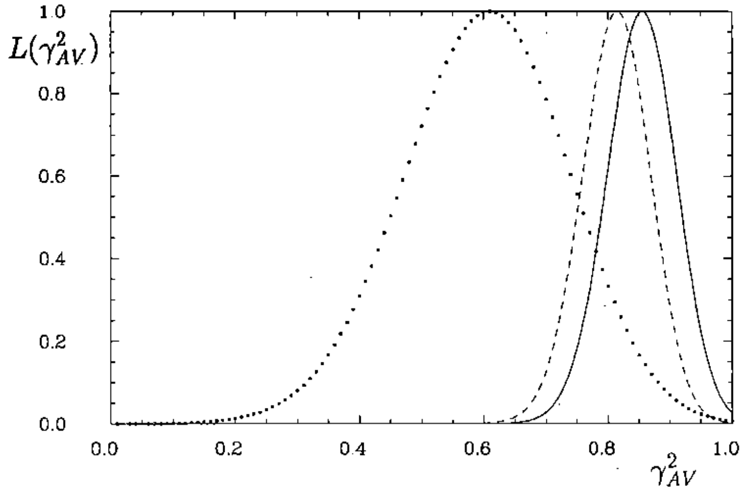

Figure 12: Comparison of the likelihood function for the selected data sample (solid line) with the one for a simulated data sample containing a comparable mixture of signal and background events (dashed line). The dotted line corresponds to background from $\tau^- \to a_1^- \nu_\tau \to \pi^- \pi^0 \pi^0 \nu_\tau$.

very precise value of the parameter γ_{AV}:

$$\gamma_{AV} = 1.022 \pm 0.028 \pm 0.030$$

Averaging the ARGUS and ALEPH results one arrives at

$$\gamma_{AV} = 1.014 \pm 0.036 \; ,$$

which is in excellent agreement with the Standard Model prediction.

5 Search for Lepton-Number Violating Decays of the τ Lepton

The Standard Model assigns each lepton a lepton quantum number which is postulated to be conserved in all reactions. However there is no underlying theoretical reason for such conservation. In fact, many extensions of the Standard Model exist which predict lepton number

violation in different processes. No experimental evidence of lepton number violation has been found so far.

Decay channel	$\epsilon(\%)$	B (in units of 10^{-6})	
		Previous	CLEO limits
$\tau^- \to e^- e^+ e^-$	20.4	13	3.3
$\tau^- \to \mu^- e^+ e^-$	19.6	14	3.4
$\tau^- \to \mu^+ e^- e^-$	19.9	14	3.4
$\tau^- \to e^- \mu^+ \mu^-$	18.8	19	3.6
$\tau^- \to e^+ \mu^- \mu^-$	19.4	16	3.5
$\tau^- \to \mu^- \mu^+ \mu^-$	15.9	17	4.3
$\tau^- \to e^- \pi^+ \pi^-$	15.5	27	4.4
$\tau^- \to e^- \pi^- K^+$	14.6	58	4.6
$\tau^- \to e^- \pi^+ K^-$	14.9	29	7.7
$\tau^- \to e^+ \pi^- \pi^-$	15.5	17	4.4
$\tau^- \to e^+ \pi^- K^-$	15.1	20	4.5
$\tau^- \to \mu^- \pi^+ \pi^-$	9.1	36	7.4
$\tau^- \to \mu^- \pi^- K^+$	7.4	77	15
$\tau^- \to \mu^- \pi^+ K^-$	7.8	77	8.7
$\tau^- \to \mu^+ \pi^- \pi^-$	9.8	39	6.9
$\tau^- \to \mu^+ \pi^- K^-$	7.7	40	20
$\tau^- \to e^- \rho^0$	16.2	19	4.2
$\tau^- \to e^- K^{*0}$	10.7	38	6.3
$\tau^- \to e^- \bar{K}^{*0}$	10.5	—	11
$\tau^- \to \mu^- \rho^0$	11.9	29	5.7
$\tau^- \to \mu^- K^{*0}$	7.2	45	9.4
$\tau^- \to \mu^- \bar{K}^{*0}$	7.8	—	8.7

TABLE 1. The detection efficiency, ϵ, and upper limit for the branching fraction at 90% CL, B, together with the most restrictive limits from previous exeperiments.

An interesting class of reactions forbidden in the Standard Model is represented by neutrinoless tau decays. A possible enhancement of their rate due to mass-dependent couplings has been emphasized in recent studies of left-right symmetric models [38] and superstring models [39]. Neutrinoless τ decays are relatively easy to search for experimentally. Since there are no neutrinos in the final state, all decay products are observable; so, these can be reconstructed to the τ mass. The most stringent upper limits come from the CLEO collaboration. Using a data sample of 1.87×10^6 $\tau^+\tau^-$ events they have reached a level of a $few \times 10^{-6}$ in radiative $\tau^- \to \mu^- \gamma$ decay [40] and in 22 three-prong τ decay channels [41]. The newest CLEO upper limits at 90% confidence level are summarized in Table 1. In order to estimate the efficiencies the three-prong neutrinoless τ decays were assumed to obey a phase space distribution. The results would change somewhat if a specific model were applied. The upper limits include a 10% increase to account for systematic uncertainties due to the luminosity calculation, tracking efficiency and detector resolution.

Another class of lepton number violating decays $\tau^- \to e^- \alpha$, $\tau^- \to \mu^- \alpha$ could occur if there is a weakly interacting Goldstone boson α. Such decays are predicted in some models to have a sizable rate [42]. However it is very difficult to find them because the τ mass can not be reconstructed in this case. The most severe background results from usual leptonic decays $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ ($\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$) with $\bar{\nu}_e(\bar{\nu}_\mu)\nu_\tau$ taken as a single particle α. In order to increase the sensitivity ARGUS performed the search for the $\tau^- \to e^- \alpha$ and $\tau^- \to \mu^- \alpha$ decays using the τ pseudo rest frame technique described in section 4.1. In the τ pseudo rest frame the $\tau^- \to e^-(\mu^-)\alpha$ decay would manifest itself as a peak in the lepton momentum spectrum.

In contrast, the charged lepton produced in the $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ ($\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$) decays has a smooth momentum distribution. No evidence was found for τ decays into Goldstone bosons in the entire kinematically allowed mass range of α. The corresponding upper limits at 95% confidence level are shown in Fig. 13 as a function of the Goldstone boson mass.

New limits on lepton flavour violation were also placed in the decays of the Z^0. The processes $Z^0 \to e\tau$ and $Z^0 \to \mu\tau$ were searched for at LEP. The best limits were set by the L3 collaboration [43],

$$BR(Z^0 \to e\tau) < 1.3 \times 10^{-5}$$

$$BR(Z^0 \to \mu\tau) < 1.9 \times 10^{-5}$$

at 95% confidence level.

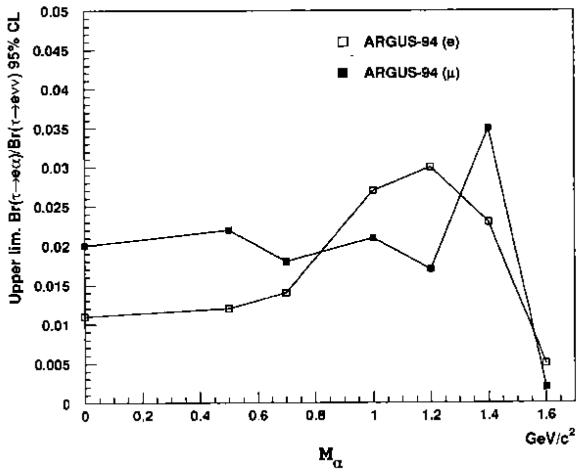

Figure 13: ARGUS upper limits at 95% confidence level on τ decays into Goldstone boson α as a function of its mass.

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