DEUTSCHES ELEKTRONEN – SYNCHROTRON

DESY 91-067
June 1991

τ Decays: An Experimental Review

C. Kiesling

Max-Planck-Institut für Physik und Astrophysik, München

ISSN 0418-9833

NOTKESTRASSE 85 · D-2000 HAMBURG 52

DESY 91-067
June 1991

ISSN 0418-9833

τ Decays: An Experimental Review*

C. Kiesling

Max-Planck-Institut für Physik und Astrophysik

ABSTRACT

The experimental data on the topological and exclusive decays of the τ lepton are reviewed. Comparisons of these data reveal an inconsistency in the τ decay pattern: About 6 % of the τ decays are not accounted for when summing up all measured exclusive decay branching ratios. While the various measurements for a given decay channel are in mutual agreement, a combined analysis of all decay channels of the τ lepton, using the CELLO detector at PETRA, does not confirm such an inconsistency: The sum of the exclusive branching ratios saturates to 100 % within better than 2 %. Moreover, the topological branching ratios measured by the same experiment are consistent with the corresponding partial sums from the exclusive channels. While most of the exclusive branching ratios given by CELLO are in agreement with existing measurements, the decays $\tau^- \to e^- \bar{\nu} \nu_\tau$, $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$ and $\tau^- \to \pi^- \pi^0 \pi^0 \nu_\tau$ are larger than the present world averages. All the branching ratios measured by CELLO are in good agreement with the expectations from a standard τ lepton. Preliminary data from the ALEPH experiment at LEP confirm the CELLO findings.

---

*Invited talk at the Orsay Worshop on τ physics, September 24 - 27, 1990

1. Introduction

Among the known elementary building blocks of matter the τ lepton, discovered in 1975 by Perl and his collaborators [1], plays a particular role: It is the heaviest *free* fermion, with a rich and theoretically well-understood decay pattern. As a member of the third ("sequential") lepton family together with its associated neutrino ν_τ, the τ is believed to couple in the conventional way via the Z^0 (production) and the $W^\pm$ (decay) to the weak charged lepton and quark currents. Apart from the purely leptonic decays, kinematics allows coupling only to the first quark doublet, consisting of the u quark and the Cabibbo-rotated d_C quark fields. This standard picture of the τ lepton leads to precise predictions for its decay channels and branching ratios. These calculations are free of the uncertainties usually encountered when the decays of heavy quarks are studied which are only available in bound states with other (light) quarks. The decay properties of the τ lepton thus can serve for very detailed tests of the standard theory of electroweak interactions [2]. In addition, the hadronic decay modes of the τ lepton may provide insight into the strong interaction, opening up a new way to measure the strong coupling constant α_s (or $\Lambda_{\overline{MS}}$), potentially with high accuracy [3].

In this review we summarize the available experimental data on the τ decay branching ratios as well as the theoretical expectations and describe some inconsistencies among the various measurements. These results may be suited to indicate a possible deviation of the τ decay pattern from conventional expectation, thus pointing to "new" physics. Recent analyses of the τ decays are discussed which do not show such inconsistencies and which are in full accord with the standard theory. Although these new measurements are not precise enough to significantly change the world averages for the τ branching ratios, they still point towards a conventional interpretation of the τ within the framework of the standard theory.

2. The "τ problem"

Evidence is overwhelming that the τ is a standard sequential lepton: The interactions of the τ with the Z^0 boson have been tested well both below and at the Z^0 pole. The experimental results on the weak neutral couplings of the τ to the Z^0, leading to a charge asymmetry in the differential cross section for τ pair production are in excellent agreement with the standard expectation (see, e.g., [4] for a compilation). Also the new measurements from LEP on the Z^0 branching ratio into τ pairs and the τ polarization follow the expectations [5]. The decays of the τ itself, on the other hand, mediated by the charged $W^\pm$, have so far not been completely understood. A major part of the decays can be calculated from "first principles" [6–8] and these decays have indeed been observed with the expected branching ratios (see [9–14] for recent reviews). However, summing up the measurements of the exclusive channels leaves room for about 6 % of so far unobserved decay modes. Moreover, measurements of the topological branching ratios, i.e. the branching ratios into one, three or five charged particles ("prongs") plus neutrals, show that the "missing" decay channels should be found in the one-prong decays only. Unless questioning the measurements of the conventional decay channels, one is forced to conclude that new, exotic decays of the τ with branching ratios of order 6 % have not yet been discovered [15]. This fact has often been called the "τ problem". One has to realize, however, that the results for the various τ decay branching ratios are usually derived as the formal world averages, where many different experiments with different systematics contribute, starting with the early experiments at SPEAR and DORIS up to the high statistics experiments at PEP and PETRA. To calculate the uncertainties of the world averages for the branching ratios is not unproblematic [12].

2.1 Measurement of Branching Ratios

To evaluate the present experimental situation on the τ branching ratios let us recall the methods to isolate τ pair events from the competing background of other e^+e^- reactions. Traditionally, τ pair events have been selected in the so-called "1-3 topology" where one τ decays into one charged particle plus neutrals and the other into three charged particles plus neutrals. With this selection one excludes a large portion of the τ pair sample, but is protected against multihadronic background (high charged multiplicity) as well as against QED processes (low charged multiplicity, mostly two-prongs, i.e. 1-1 topologies).

The "simplest" observable in the decay of the τ lepton is the fraction of decays into a given charge multiplicity. Defining the topological branching ratios B_i as

$$B_i = \frac{\Gamma(\tau \rightarrow i \text{ charged particles} + \text{neutrals})}{\Gamma(\tau \rightarrow \text{all})}$$

one can determine these ratios from the number of observed τ pairs N_{ij}, where i and j are the charge multiplicities for the two τ's in the event, respectively. Having measured only the "1-3" class one obtains

$$\begin{aligned} N_{13} &= 2N\epsilon_{13}B_1B_3 \\ &= 2\epsilon_{13}L\sigma B_1(1-B_1) \quad , \end{aligned} \tag{2.1}$$

from which B_1 can be determined. In the above relation we use the fact that up to a very small fraction (< 0.2 %, see below) all τ's decay into 1 or 3 prongs. One realizes that for a precise measurement of the topological branching ratios one needs accurate knowledge of the luminosity L and of the *absolute* selection efficiency ϵ_{13}. Furthermore one has to assume a standard production cross section. This technique was applied by all experiments at SPEAR, DORIS and CESR.

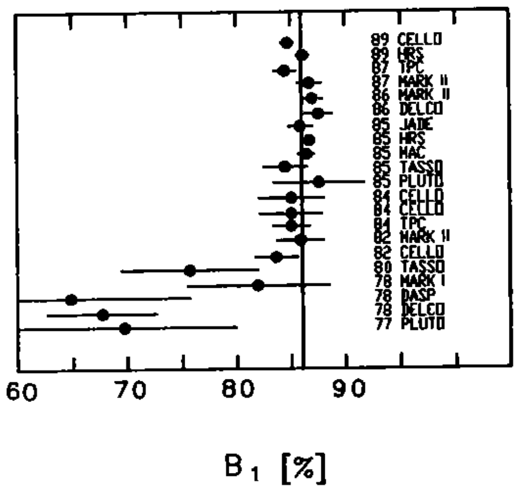


Fig. 1. Time evolution of measurements on the topological branching ratio B_1 of the τ lepton into one charged and an arbitrary number of neutral particles.

The τ event samples at PEP and PETRA were easier to separate from the background (see, e.g., [14] for details of the experimental strategies to isolate clean τ event samples), allowing, at least in principle, the efficient selection of "1-1" and "3-3" topologies in addtion. With these additional data samples one is in a position to extract the topological branching ratios free of normalization uncertainties from the following relations:

$$\begin{aligned} N_{11} &= \epsilon_{11}NB_1^2 \\ N_{13} &= 2\epsilon_{13}NB_1(1-B_1) \end{aligned}$$

leading to

$$B_1 = \frac{1}{1 + \left(\frac{\epsilon_{11}}{\epsilon_{13}}\right)\left(\frac{N_{13}}{2N_{11}}\right)} . \tag{2.2}$$

As an additional benefit of measuring the complete set of final topologies, the selection efficiencies for the various charge topologies only enter in ratios rather than absolutely, so that many systematics in the acceptance calculations will cancel. Furthermore this ratio is multiplied by a small coefficient ($N_{13}/N_{11} \approx 0.2$). Finally one gains an important cross-check from the number of observed "3-3" events.

The measurement of the 1-prong branching ratio has had quite some history, showing a definite "learning" process, as can be seen in Fig. 1. Starting from relatively low first measurements, B_1 was constantly climbing as a function of time and has finally settled around 87 %. The data are dominated by the recent high statistics measurements of HRS [16] at PEP and CELLO [17] at PETRA. Both experiments have employed (2.2) to determine the

Table 1. High statistics measurements by HRS [16] and CELLO [17] on the topological branching ratios (in percent) of the τ lepton into i charged and an arbitrary number of neutral particles. The errors given are statistical and systematic, respectively. Note that the 5-prong branching ratios determined by the same experiments are below 0.2 % and are omitted here.

topol. br.	CELLO	HRS
B_1	$84.9 \pm 0.4 \pm 0.3$	$86.4 \pm 0.3 \pm 0.3$
B_3	$15.0 \pm 0.4 \pm 0.3$	$13.5 \pm 0.3 \pm 0.3$

branching ratios B_i. However, their values only marginally agree. A closer inspection of these measurements, which are shown in Table 1, reveals a discrepancy of about 2.3 σ.

While the HRS measurement is in good agreement with the other high statistics measurements from PEP, notably MAC [18] and DELCO [19], of approximately 87 %, the measurements of CELLO clearly favour a lower value for the 1-prong branching ratio (correspondingly a higher value for the 3-prong branching ratio). Although the observed difference between CELLO and HRS might at first sight seem small in absolute units, it is still significant for the further discussion of the τ problem. It should be noted that the CELLO experiment has measured the topological branching ratios over a wide range of center-of-mass energies between 14 and 46 GeV, with varying background contaminations and systematics, but consistently find a value of about 85 %, quoted in Table 1. Since we attribute significance to the observed difference between the so-far dominating experiments CELLO and HRS, no attempt is made to calculate a world average for B_1 or B_3 including all data and rather refer to Table 1.

It is not easy to pin down the sources for the early underestimations of the one-prong branching ratio B_1 (or the overestimations of B_3) at SPEAR and DORIS (see Fig. 1). However, as can be seen from (2.1), one may suspect in such cases either a systematic underestimation of the efficiencies to detect τ events in the "1-3" class, i.e. a conservative, pessimistic (too low) estimate of the detector efficiencies (in particular the charged particle triggering and track reconstruction efficiencies) or a systematic underestimation of the luminosity measurement, or both. All these effects would lead to a low B_1 (high B_3). Conversely, measurements of B_1 higher than the "real" one (not known for the time being, taking a pessimistic view of the experimental situation) might indicate an over-optimistic estimate of the detector capabilities (i. e. too high efficiencies ϵ_{13}) or an overestimation of the luminosity actually taken by the experiment. Only further precise experiments will be able to decide on the question of what really B_1 is (new input is expected from the LEP experiments, see below), so the subject will be interesting for some more time to come.

From a detector point of view, the measurement of the exclusive branching ratios is much more demanding than that of the topological ones. Exclusive branching ratio measurements require particle identification, i.e. separation of electrons, muons and hadrons and, particularly important for reconstructing the various multihadronic final states, good photon detection capabilities. Thus, in addition to solid tracking, electromagnetic calorimetry with good energy resolution and high granularity over a large solid angle is essential to do a good job on the exclusive τ branching ratios. Even with a coarse-granularity calorimeter one is able to discriminate electrons from other charged particles. But with increasing granularity of the calorimeter the degree of differentiation between the various final states, in particular those with additional neutral pions, improves considerably. For a measurement of the purely leptonic decay $\tau \rightarrow \mu\nu\nu$† a muon filter is mandatory (see, e. g., [14] for further experimental details).

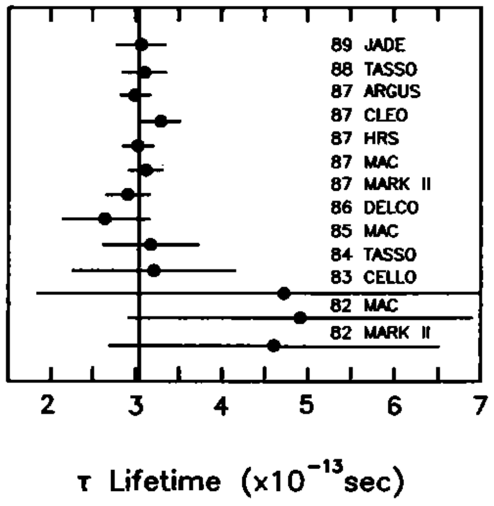
Table 2. World averages [20] for the various exclusive decay channels of the τ lepton, together with the expectations from the standard model (see text).

Decay channel	world av.	theor. expect.
$\tau \rightarrow e\nu\nu$	17.9 ± 0.4	18.3 ± 0.23
$\tau \rightarrow \mu\nu\nu$	17.8 ± 0.4	17.8
$\tau \rightarrow \pi\nu$	10.9 ± 0.6	11.0
$\tau \rightarrow K\nu$	0.67 ± 0.23	0.71
$\tau \rightarrow \rho\nu$	22.2 ± 1.0	24.1
$\tau \rightarrow K^*\nu$	1.39 ± 0.20	1.2
$\tau \rightarrow \pi 3\pi^0\nu$	3.2 ± 1.4	1.1
$\tau \rightarrow 3\pi\pi^0\nu$	4.6 ± 1.0	5.5
$\tau \rightarrow 6\pi\nu$	$> 0.05 \pm 0.02$	0.18
$\tau \rightarrow K\bar{K}\nu$		0.55
$\tau \rightarrow K\bar{K}\pi\nu$	0.22 ± 0.15	0.2
$\tau \rightarrow \pi 2\pi^0\nu$	7.5 ± 0.9	9.3
$\tau \rightarrow 3\pi\nu$	6.7 ± 0.6	9.3
$\tau \rightarrow K\pi\pi\nu$	0.22 ± 0.16	0.2
$\tau \rightarrow 5\pi\nu$	$> 0.11 \pm 0.03$	0.5
Sum	93.5 ± 2.4	100.0

---

†Here and for the rest of this review the τ stands for both charge signs. Unsigned leptons and mesons are understood to carry charge. We also do not distinguish in our notation between the various types of neutrinos.

Fig. 2. Recent measurements on the τ lifetime.



Although an impressive amount of information exists about the τ decay branching ratios (see Table 2) it is not surprising, considering the above detector requirements for a complete measurement of the τ final state, that most experiments so far could only measure a subset of these decay channels at a time. Therefore the rather complete picture of the τ decay pattern suggested in Table 2 derives from averaging over the measurements from many different experiments, taken from the 1990 edition of the Particle Data Group [20]. The procedure for constructing these "formal" averages is generally based on the assumption of uncorrelated systematic errors for the various experiments. A very detailed statistical analysis of the available branching ratio measurements and their averaging has been presented by Hayes and Perl [12].

2.2 Theoretical Expectations

In Table 2 the world averages for the measured exclusive branching ratios are compared with the expectations from standard $W^{\pm}$ exchange. Some comments concerning these predictions, however, are necessary. Most importantly, the theory can only predict partial widths, not branching ratios. Some of these widths are known, e.g. from weak interactions ($\tau \to e\nu\nu, \mu\nu\nu$), some are related to measured meson lifetimes via time reversal ($\tau \to \pi\nu, K\nu$) or to measured e^+e^- cross sections via the CVC theorem ($\tau \to \rho\nu, 4\pi\nu$). But the widths into odd numbers (≥ 3) of pions is not predicted, although several phenomenological models exist (see, e.g. [21]).

In absence of a complete theory of τ decay one has to know at least one branching ratio of the many calculated decay channels, either from direct measurement or from external sources. Once one such width is translated to a branching ratio, all others can be calculated from

the ratios of the respective partial widths. Using universality, the electronic branching ratio $B(\tau \to e\nu\nu)$ can be calculated from the measured τ lifetime:

$$B(\tau \to e\nu\nu) = \frac{T_\tau}{T_\mu}\left(\frac{m_\tau}{m_\mu}\right)^5$$

A compilation of the available measurements for the τ lifetime are shown in Fig. 2 (see also [22]), yielding an average of $(3.03 \pm 0.08) \times 10^{-13}$ s. This translates to an electronic branching ratio of $B(\tau \to e\nu\nu) = (18.9 \pm 0.5)\%$. This normalization point can be improved by also including the direct measurements of the electronic and muonic branching ratios, which are related through universality. Excluding the measurements from SPEAR and DORIS from the compilation (remember the walk in the topological branching ratio measurements shown above) we arrive at the weighted averages given in Table 3. Taking the average from all three sources we obtain as our best present estimate

$$B(\tau \to e\nu\nu) = (18.3 \pm 0.23)\% \quad .$$

This value is used in Table 2 to normalize all other branching ratios.

One noticible change in the theoretical estimates with respect to earlier analyses [6, 15] has occurred recently for the decay channel $\tau \to \rho\nu$: A redetermination [23] of the CVC prediction with new cross section data for the reaction $e^+e^- \to \pi^+\pi^-$ yielded a somewhat increased relative width of the ρ decay channel with respect to the old value by about 7.5 %:

$$\frac{B(\tau \to \rho\nu)}{B(\tau \to e\nu\nu)} = 1.32 \pm 0.05$$

What remains largely unknown theoretically are the branching ratios into an odd number of pions (mainly $\tau \to 3\pi\nu, \pi 2\pi^0\nu$). In absence of a reliable model for these two channels we have chosen to adjust the corresponding branching ratios so that the sum of the theoretical branching ratios is 100 %, and use further more the constraint from isospin conservation which demands $B(\tau \to 3\pi\nu) \geq B(\tau \to \pi 2\pi^0\nu)$, where the equal sign has been chosen. This treatment of the axial hadronic current is suggested by the fact that no exotic decay channels outside the standard model have been observed (see next chapter) and that the 3 pion decay channel seem to be dominated by the a_1 resonance (see, e. g., [14]), where the chosen isospin equality follows naturally. From the point of view of the standard model, Table 2 is essentially complete. What is missing are the expectations for decay channels containing η mesons. These, however, are expected at a very low level as will be discussed in the next chapter.

With respect to the theoretical expectations the world averages determined from the individual measurements show a lack of about 6 %. The error on the experimental sum has been calculated by summing all the individual errors given in Table 2 in quadrature. The significance of the mismatch (2.6 standard deviations from the purely experimental numbers) can be raised by including isospin invariance which demands $B(\tau \to \pi 2\pi^0\nu) \leq B(\tau \to 3\pi\nu)$ (see e.g.

Source	$B(\tau \to e\nu\nu)$
direct measurement	18.00 ± 0.33
from $\tau \to \mu\nu\nu$	18.29 ± 0.41
lifetime	18.93 ± 0.51
average	18.28 ± 0.23

Table 3. Compilation of the branching ratio $B(\tau \to e\nu\nu)$ in percent from the various sources related by universality. The early data from SPEAR and DORIS are omitted in these compilations.

[24]): One may substitute the poorly determined number for $B(\tau \to \pi 2\pi^0\nu)$ by its theoretical prediction derived from $B(\tau \to 3\pi\nu)$, which yields an almost five standard deviation effect.

From the exclusive measurements one can derive the topological branching ratios and compare them to the direct measurements. While there seems to be consistency for B_3, one observes a 1-prong branching ratio of about 6 % larger than from the direct measurement. Taking all the measured branching ratios at face-value, the τ-problem can be stated as follows (see also [25]): In order to saturate the τ branching ratio one has to find final states other than those in Table 2 with the condition that they only feed into the 1-prong decay channels. Within the standard model, such channels can only be semihadronic final states (with several hadrons), the single-hadronic systems being already exhausted in the list of Table 2. Multiparticle hadronic systems, however, preferentially feed into the 3-prong class, thus getting into conflict with the topological measurements.

While at this point it is rather speculative to derive any strong conclusions from the theoretical expectations given in Table 2 (remember the somewhat ad hoc saturation condition), it is worth noting that the predicted branching ratios for the 3-prong final states are indeed in conflict with the measurements: The naive model demands more 3-prong final states than given by the world averages. Based on isospin invariance one expects a branching ratio for the decay $\tau \to \pi 2\pi^0\nu$ similar to $\tau \to 3\pi\nu$, again in contrast to the experimental world average. These facts allow reformulating the τ problem (see also [13]): Given the overall agreement in many exclusive decay channels between theory and experiment, the major discrepancies arise in the decays containing three pions. It thus seems likely that the "τ problem" is in fact a "3 pion" problem.

3. Searches for "new" decays

An exciting possibility is to interpret the apparent experimental inconsistency between the exclusive and inclusive measurements as evidence for the non-standard nature of the τ particle. Searches for unexpected decays of the τ lepton have a long tradition (see, e. g. [9]). However, no "exotic" decay has been observed so far: Decay channels violating lepton number conservation, such as $\tau \to eee$ to give just one example, have all been constrained below 10^{-4} or better in their branching ratios (see the compilations of the Particle Data Group [20]).

Quite some excitement was generated, when the decay $\tau \to \eta\pi\nu$ had apparently been observed [26] with a branching ratio of order 5 %, just enough to explain the deficit in the one-prong decays. However, these findings were quickly disproved by many other experiments, limiting the branching ratio below 1 % (see, e.g., [14] for a review on the experimental details). Furthermore, being generated by a second class current, the decay $\tau \to \eta\pi\nu$ is strictly forbidden within the standard model in the limit of vanishing mass differences for the light quarks. In summary, no decay of the τ has been observed so far which is forbidden within the standard model, assuming the τ to be an ordinary sequential lepton with its own neutrino.

On the other hand, decays containing an η meson plus two or more pions, such as $\tau \to \eta\pi\pi\nu$, are allowed. Several experiments have searched for decays containing η's (see, e. g., [27] for a recent compilation) and have not found any signal. Using CVC, the branching ratio for $\tau \to \eta\pi\pi\nu$ is expected to be smaller than 0.3 %, so these channels do not seem to offer a solution to the τ problem.

At present one has to conclude that decays other than those listed in Table 2 are either not existing ("exotic" decays outside the standard model) or are too small (but allowed by the standard model) to be able to explain the τ problem. The key to the inconsistencies in the τ decay pattern thus seems to reside in the experiments themselves. To test this hypothesis we will discuss some recent high statistics experiments remeasuring the standard decays.

Decay channel	$B(\tau \to X)$
$\tau \to e\nu\nu$	$18.23 \pm 0.39 \pm 0.68$
$\tau \to K^*\nu X^0$	$1.43 \pm 0.11 \pm 0.13$
$\tau \to K^{*0}\pi\nu X^0$	$0.38 \pm 0.11 \pm 0.13$
$\tau \to K^{*0}K\nu X^0$	$0.32 \pm 0.08 \pm 0.12$

Table 4. Recent measurements of various τ decay channels by the CLEO collaboration [28,30]. For the strange particle channels the state X^0 denotes possible additional neutral mesons.

4. Recent data on "old" decays

New data on $\tau \to e\nu\nu$ ([28], see also [29] for a review presented at this workshop) and $\tau \to$ strange particles $+X^0$ [30] have been presented by the CLEO collaboration running at the resonances $\Upsilon(3S, 4S, 5S)$. Their data sample consists of 24000 τ pairs in the 1-3 topology, with a background of about 17 %. Electrons and kaons are identified by dE/dx measurements from 64 drift chamber layers. For the electrons in addition the calorimetric energy deposition is cross-checked with the track momentum and is used in a likelihood ratio together with the dE/dx and TOF information. Since only the relative rate of identified electrons to 1-prongs can be measured in the experiment at present, the electronic branching ratio is normalized to the one-prong ratio, taken as 86 ± 0.3 %. The result is given in Table 4. It agrees with previous measurements and the world average shown in Table 2.

Also the new branching ratio measurements by CLEO for final states containing strange particles show no anomaly (see Table 4), being consistent with the theoretical expectations in Table 2. CLEO is the first experiment to observe K^* mesons in τ decay in their neutral charge mode. These neutral K^*'s were found in three-prong final states by combining a charged K meson, identified by dE/dx, with an oppositely charged pion.

A new type of analysis of the τ exclusive branching ratios was presented recently by the CELLO collaboration [31], concluding the continuous τ physics programme of the experiment [17,32–35]. The data come from a high statistics run at 35 GeV, where about 87 pb^{-1} have been collected. Details about the detector can be found elsewhere [36]. One of the important properties of CELLO is its ability to identify electrons, muons, hadrons and photons, therefore being able to detect all τ decay channels. In addition, τ pair events can be selected in all charge topologies, allowing exploitation of the relations (2.2). The analysis is based on 3032 τ pair events with non-τ background of 5 % (mainly multipe-radiative Bhabha events). For details on the τ event sample, the selection procedures and the various background contributions we refer to [37,31]. The total background and the Bhabha contributions are very well checked by the τ pair production cross sections and the charge asymmetries [17].

To demonstrate the overall small background, distributions of the invariant masses from all observed particles in one-prong decays (with at least one additional photon) are shown in

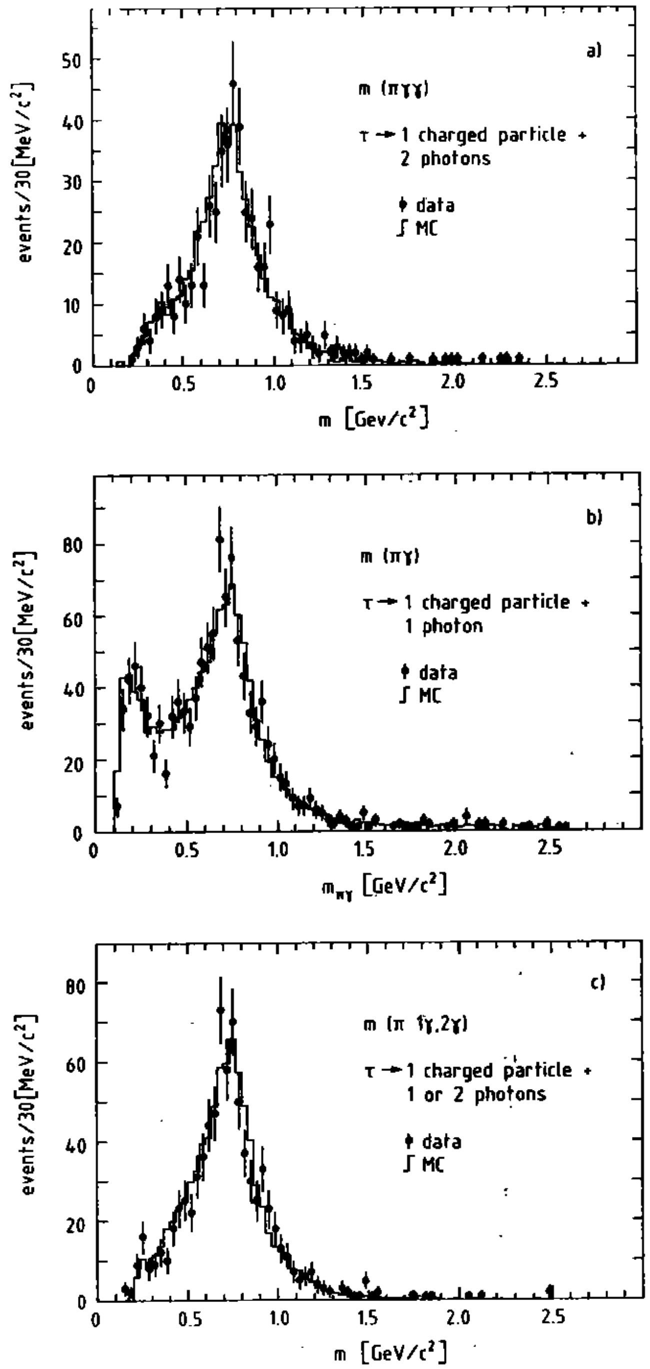


Fig. 3. Distributions of the invariant mass of one charged particle, assumed to be a pion, and additional photons in τ decays with one charged particle and one or two neutral showers in the calorimeter from the CELLO experiment.
a) exactly two photons in the final state,
b) exactly one neutral shower in the final state and no particle identification performed for the charged particle,
c) sum of a) and b) but decays are removed where the charged particle is identified as an electron.
The histograms show the expectations from a detailed Monte Carlo simulation of production and decay of τ leptons in the detector.

Fig. 3 for the data and for a detailed τ Monte Carlo simulation of the experiment. The invariant masses are calculated from the charged particles, assuming pion masses, and the photons in each hemisphere separately. No excess of events above the expectation is observed at masses larger than the τ. The degree of understanding of the detector performance is indicated in Fig. 3b), where, e. g., a spurious "mass peak" is observed around 200 MeV, in addition to the expected ρ peak. This peak comes from unidentified electrons combined with additional showers in the same hemisphere (radiative photons or fragmented electromagnetic showers). Switching on the particle identification (Fig. 3c)), the peak disappears. This kind of detail in the detector Monte-Carlo demonstrates the precision of the shower simulation in the calorimeter and thus indicates the good control of systematics for multi-photon final states.

Class	obs. part.	decay
1	e	$\tau \to e\nu\nu$
2	μ	$\tau \to \mu\nu\nu$
3	m	$\tau \to \pi(K)\nu$
4	$m + 1, 2\gamma$	$\tau \to \rho(K^*)\nu$
5	$m+ \geq 3\gamma$	$\tau \to \rho\pi\nu$
6	$3m$	$\tau \to \rho^0\pi\nu$
7	$\geq 3m+ \geq 1\gamma$	$\tau \to 3\pi\pi^0$

Table 5. Division of τ final states into decay classes in the CELLO analysis of exclusive branching ratios [31]. The second column indicates the requirement from particle identification (m stands for charged meson), the third column gives examples for the major decay modes. Class 7 also includes five-prong decays.

For the identification of individual decay channels the sample of τ leptons (two from each event) was divided into seven classes, depending on the number and types of the charged particles and the number of photons. A one-prong, e.g., with no additional photons was classified according to its particle identification as electron, muon or meson (discrimination of charged pions from kaons is not possible with CELLO). The classes largely correspond to exclusive decay channels and are shown in Table 5. These classes are complete in the sense that all τ decays expected from the standard model can be associated with one of the classes. The full details of the analysis are described elsewhere [38].

Using particle identification, the number of charged and neutral particles and kinematical quantities such as particle momenta and invariant masses, a probability vector $\vec{P}$ has been determined for each τ decay, with elements P_i giving the probability that the decay originates from class i. For the first three classes one evidently requires the proper particle identification with no photon in the same hemisphere. Classes 4 and 5 are discriminated by the number of observed photons. Given a certain observed τ final state, the elements P_i are calculated based on Monte-Carlo distributions characteristic for each of the seven classes. Many checks have been carried out to verify that the Monte Carlo reference distributions used to estimate the elements P_i are correct [37, 31].

The probabilities P_i have been used in two ways to identify the τ decay channels, i.e. to attribute a given τ decay to a specific class i: First, the largest element P_i was used to tag the class i, thus forcing each τ decay into one of the seven classes. Secondly, a cut was introduced for each element P_i and the largest element had to satisfy the condition $P_i > P_i^{\mathrm{cut}}$ in order to tag class i. With this latter method a certain number of τ decays were discarded, the number depending on the value for the cuts P_i^{cut}. The assignment in either case leads to the numbers n_i of τ decays attributed to class i. The true numbers N_i are related to the observed numbers n_i by a transition matrix ϵ_{ij}

$$n_i - n_i^B = \sum \epsilon_{ij} N_j \,, \tag{4.1}$$

where n_i^B is the number of non-τ background events in class i remaining in our sample. Assuming Poisson statistics for the observed number of events n_i the following expression was minimised:

$$\mathcal{L} = \sum_i \Big\{ \sum_j \epsilon_{ij} N_{\mathrm{tot}} B_i - (n_i - n_i^B) \ln(\sum_j \epsilon_{ij} B_j) \Big\} \tag{4.2}$$

The branching ratios B_i are defined as the ratios N_i/N_{tot}, where the N_i are the corrected numbers of τ decays in class i (see (4.1)), the total number N_{tot} of τ decays was taken from the analysis of the topological branching ratios [17]. For $i \neq j$ the matrix elements ϵ_{ij} give the probability that a certain τ final state i will be misidentified as final state j ("migration matrix"). CELLO have determined the matrix elements ϵ_{ij} and the numbers n_i^B of background events using a full detector simulation with input branching ratios for the τ taken from the measurements after iteration.

Table 6 shows the resulting branching ratios for the seven classes together with their statistical and systematic errors using the second (P_i^{cut}) method. The systematic errors have been determined by varying the particle identification criteria, the values for the probability cuts P_i^{cut}, the photon selection criteria, the transition matrix elements and the expected backgrounds within their estimated uncertainties. Using the varied input parameters the branching ratios have been refitted and the final systematic errors have been determined from the spread of the results. In all fits the sum of the branching ratios stayed within the interval from 98 to 102 %. Within the errors, the results for the individual classes for both methods are in very good agreement. Furthermore, the sum of the branching ratios saturate, suggesting that the τ decay classes considered in this analysis are complete. In both methods exotic decay hypotheses are not explicitely tested. Note, however, that if exotic channels exist, the resulting exclusive branching ratios will *not* sum up to 100 % using the second method. Other choices for the cut variables P_i^{cut} lead to the same conclusion [38].

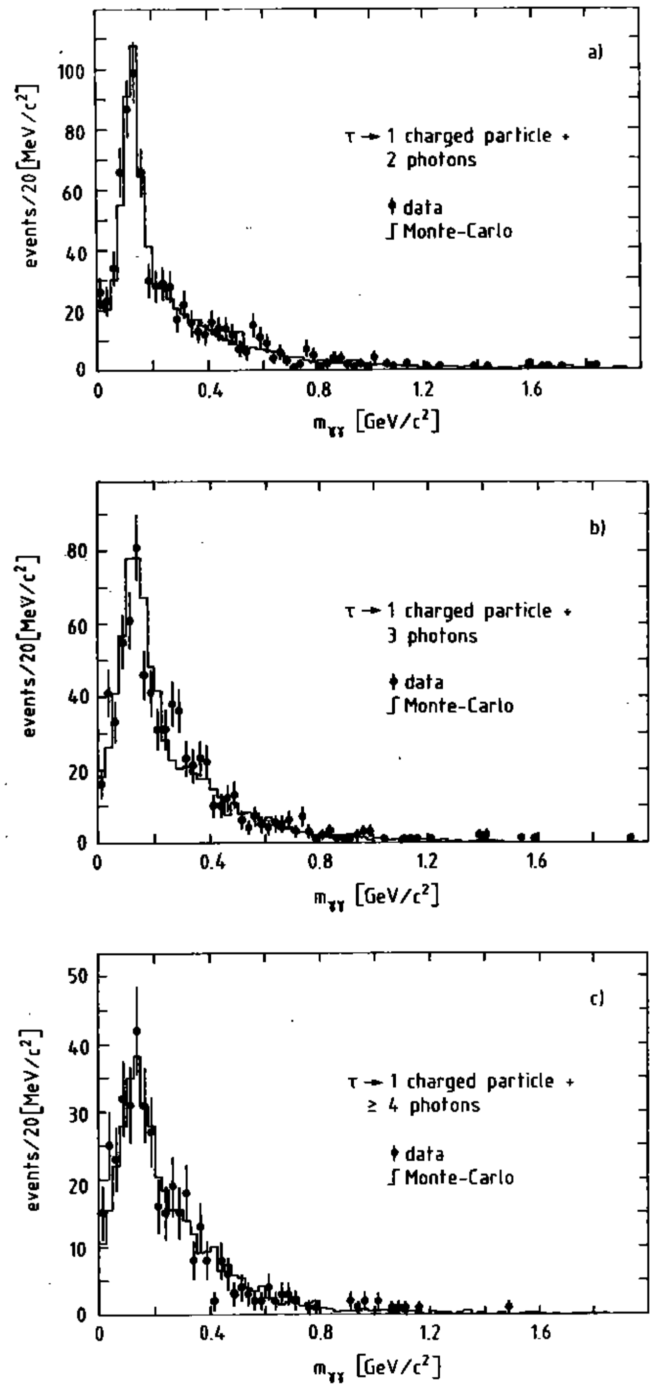


Fig. 4. Distributions of the invariant $\gamma\gamma$ masses in τ decays with one charged particle and an arbitrary number of neutral showers (+ neutrino) from the CELLO experiment.
a) two reconstructed photons
b) three reconstructed photons,
c) four or more reconstructed photons.
The histograms show the expectations from a detailed Monte Carlo simulation of production and decay of τ leptons in the detector.

Table 6. Recent measurements of the various τ decay channels by the CELLO collaboration [31] and the ALEPH collaboration [39]. The theoretical expectations based on the standard model (see Table 2) are also given, where the strange particle decays have been distributed to the measured final states not including particle identification.

Decay channel	CELLO	ALEPH (prel.)	theory
$\tau \to e\nu\nu$	$18.4 \pm 0.8 \pm 0.4$	$18.4 \pm 0.6 \pm 0.4$	18.3 ± 0.23
$\tau \to \mu\nu\nu$	$17.7 \pm 0.8 \pm 0.4$	$17.6 \pm 0.6 \pm 0.3$	17.8
$\tau \to$ meson ν	$12.3 \pm 0.9 \pm 0.5$	$12.7 \pm 0.5 \pm 0.4$	11.8
$\tau \to \pi\nu$	11.2 ± 1.0		
$\tau \to$ meson $+ \pi^0 \nu$	$22.6 \pm 1.5 \pm 0.7$	$24.8 \pm 0.7 \pm 0.2$	24.5
$\tau \to \rho\nu$	22.1 ± 1.7		
$\tau \to$ meson $+ \geq 2\pi^0 \nu$	$14.0 \pm 1.2 \pm 0.6$		
$\tau \to$ meson $+ 2\pi^0 \nu$	$10.0 \pm 1.5 \pm 1.1$	$10.0 \pm 0.5 \pm 0.5$	10.4
$\tau \to$ meson $+ \geq 3\pi^0\nu$	$3.2 \pm 1.0 \pm 1.0$	$1.9 \pm 0.2 \pm 0.2$	1.2
$\tau \to$ 3 mesons ν	$9.0 \pm 0.7 \pm 0.3$	$10.5 \pm 0.3 \pm 0.5$	10.0
$\tau \to 3\pi\nu$	8.8 ± 0.8		
$\tau \to \geq$ 3 mesons $+ \geq 1\pi^0 \nu$	$5.8 \pm 0.7 \pm 0.2$	$4.1 \pm 0.3 \pm 0.5$	5.8
$\tau \to 3\pi\pi^0\nu$	5.6 ± 0.8		
Sum	$99.8 \pm 2.6 \pm 1.2$	100.0	99.9

With the knowledge of the strange particle branching ratios the Cabibbo-allowed decays of the τ can be extracted from the classes 3 and 4 (see Table 6). Using the present world averages [14] $B(\tau \to K\nu) = (0.67 \pm 0.17)$ % and $B(\tau \to K^*\nu) = 1.56 \pm 0.20$ % their contributions can be subtracted yielding the exclusive branching ratios $\tau \to \pi\nu$ and $\tau \to \rho\nu$. Similarly, the K^* contribution was subtracted in classes 6 and 7 to obtain the branching ratios for $\tau \to 3\pi\nu$ and $\tau \to 3\pi\pi^0\nu$ given in Table 6 (a small contribution from 5 pion final states has also been subtracted from class 7 to obtain the latter channel).

In a further step the separation of class 5 ($\tau \to$ hadron $+ \geq 4\gamma\nu$) into the physical decay channels $\tau \to \pi 2\pi^0\nu$ and $\tau \to \pi 3\pi^0\nu$ was attempted. To show that multi-π^0 final states can indeed be detected with CELLO, the invariant $\gamma\gamma$ masses from final states with two photons (mostly $\tau \to \rho\nu$), three photons (dominated by $\tau \to \pi 2\pi^0\nu$) and four photons (populated by both $\tau \to \pi 2\pi^0\nu$ and $\tau \to \pi 3\pi^0\nu$) are shown in Fig. 4. Clear π^0 signals are seen with the expected widths and combinatorial structure of the background. For each decay candidate in class 5 the π^0's were found either by reconstruction from two photons or from a single broad shower compatible with overlapping photons. Depending on the numbers of reconstructed π^0's and γ's ("photon-counting technique") a decay of class 5 was attributed either to the $2\pi^0$ or $3\pi^0$ state, with efficiencies and misidentification probabilities determined by Monte Carlo. Branching ratios were determined in a likelihood fit according to (4.1, 4.2). The values for the two branching ratios are also shown in Table 6. The sum of the branching ratios for the two multi-neutral decay channels is in good agreement with the branching ratio for class 5 , a non-trivial result checking the correctness of the efficiency calculations based on the Monte Carlo model.

All exclusive branching ratios determined in this analysis are compared in Table 6 with the theoretical expectations, based on the standard model and the normalisation chosen as in Table 2. The agreement between the CELLO data and the predictions is very good. It is stressed again that the predictions for $B(\tau \to 3\pi\nu)$ are quite uncertain. The values assumed here have been chosen to saturate the theoretical branching ratios. As is turns out, the CELLO measurements favour this assumption. The exclusive branching ratios are also fully consistent with the topological branching ratios, so that the "τ problem" is not seen in the CELLO data.

CELLO have also explicitly checked that no unexpected τ decays have escaped detection in their analysis: First, the total production cross section is in agreement with the expectation. Second, the number of unobservable τ decays can be limited by the number of "mono-jet" events seen in the experiment. From this one obtains an upper limit for the branching ratio into unobserved decays less than one percent. Third, explicit searches for "exotic" one-prong decays were conducted, such as $\tau \to \pi X^0$ with X^0 being a heavy unobserved particle. For $M_X \geq 0.5(1.0)$ GeV CELLO obtain the 95 % C. L. upper limits $B(\tau \to \pi X^0) < 1.2(0.9)$ %.

As a particular highlight of this workshop first preliminary results on the exclusive τ branching ratios by the ALEPH collaboration at LEP have been presented [39]. At LEP, the τ samples appear even cleaner than at PEP/PETRA energies and the ALEPH detector has demonstrated excellent capabilities in measuring all τ decay topologies and in distinguishing the various τ final states. In an analysis very similar to the one described above, ALEPH have extracted the exclusive branching ratios and find very good agreement with CELLO. The ALEPH results are also shown in Table 6. ALEPH and CELLO have about the same number of τ pairs, but due to the better granularity of the ALEPH detector, the contamination of a given decay channel by the other decays and thus the the statistical errors of the ALEPH measurements are smaller. In more technical terms, the migration probabilities or the off-diagonal elements of the matrix ϵ_{ij} are smaller compared to CELLO. The ALEPH results are so far the only ones to support the CELLO findings. However, as the data analyses of the LEP experiments are rapidly progressing, one can hope for further clarification in the near future.

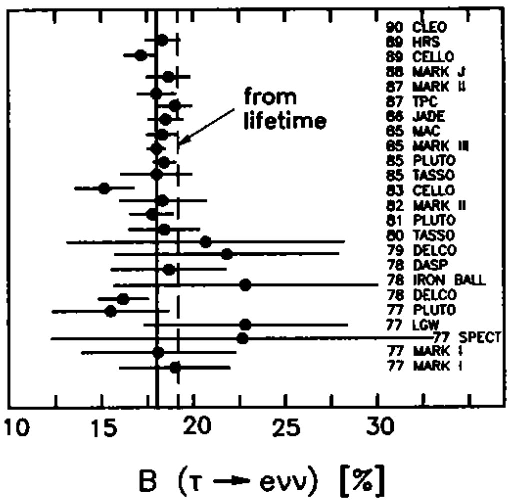


Fig. 5. World data on the leptonic branching ratios. The muonic branching ratios are translated into the corresponding electronic branching ratio using the universality constraint (see text). Statistical and systematic errors have been added in quadrature. The solid line is the PDG [20] value for $B_e = 17.7$ %.

5. Analysis of exclusive decay channels

With the exception of the recent experiments presented in the preceeding chapter we have discussed the status of the τ branching ratios mostly in terns of world averages. In fact, only when taking the formal world averages with their reduced errors are we justified to talk about a possible problem in the τ decay pattern. Let us now shortly discuss the individual measurements of the major branching ratios leading to the world averages (see also [12] for an exhaustive statistical analysis).

Figure 5 shows all available data on the leptonic branching ratios (see also [29]), where the measurements of the muonic channel have been translated into an electronic branching ratio using universality ($B_e = B_\mu/0.973$). The PDG [20] average of $B_e = 17.7$ % is shown as well as the expectation from the τ lifetime. Overall good agreement among the experiments is observed, although one point is worth noting: The more recent measurements of B_e tend towards larger values than the world average, but are still consistent with it. The recent data from CLEO, CELLO and ALEPH (not shown) are all above 18 % and are in very good mutual agreement.

The data on the semihadronic decays $\tau \to \rho\nu, \pi\nu$, shown in Figs. 6-7, are in very good mutual agreement, even "over-consistent" [12]. While the pionic decay channel is in excellent agreement with theory, there seems to be a slight deficit of order 1 σ (thus not significant) in the ρ channel with respect to the new CVC analysis of Kühn and Santamaria [23] (see also [40]). The CELLO and ALEPH data (not shown) agree with the world averages as well as with [23].

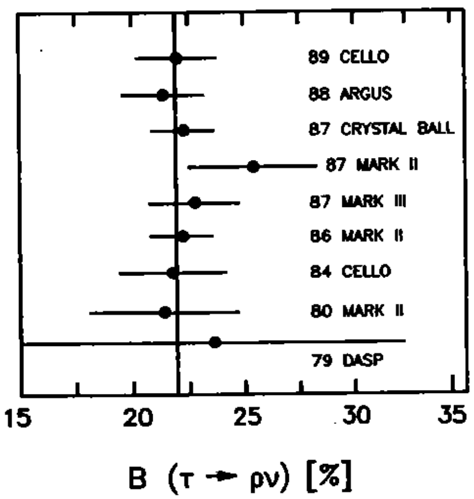


Fig. 6. World data on the branching ratio $\tau \to \rho\nu$. In the figure, statistical and systematic errors have been added in quadrature. The solid line corresponds to the PDG [20] value of $B_\rho = 22.3$ %.

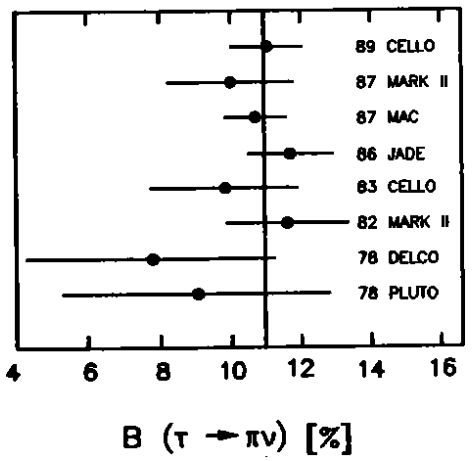


Fig. 7. World data on the branching ratio $\tau \to \pi\nu$. In the figure, statistical and systematic errors are added in quadrature. The solid line corresponds to the PDG [20] value of $B_\pi = 11.0$ %.

There are, however, some major discrepancies in the three-pion decay mode: CELLO (and ALEPH) measure a substantially higher branching ratio for the decay $\tau \to 3\pi\nu$, a 3 σ effect, and a higher branching ratio for the decay $\tau \to \pi + \geq 2\pi^0\nu$, for which only few measurements exist. These findings would profit from further confirmation. Evidently, the measurements of the multi-π^0 decay channels are quite demanding from a detector point of view. The experimental results published so far all use the photon counting technique. However, explicit reconstruction of multi-π^0 final states will be possible in the future with devices such as the new CLEO CsI calorimeter (see also [40]). In the case of $\tau \to 3\pi\nu$ the measurements are scattered over a substantial range, but the world average for this channel is dominated by the ARGUS measurement [41] which has by far the smallest error. It should be noted that the ARGUS measurement for $B(\tau \to 3\pi\nu)$ is barely consistent with the measurements for $B(\tau \to \pi 2\pi^0\nu)$, which isospin constrains to be smaller or equal to $B(\tau \to 3\pi\nu)$ (a new analysis† by the Crystal Ball Collaboration [42] at DORIS, published after the workshop, yields

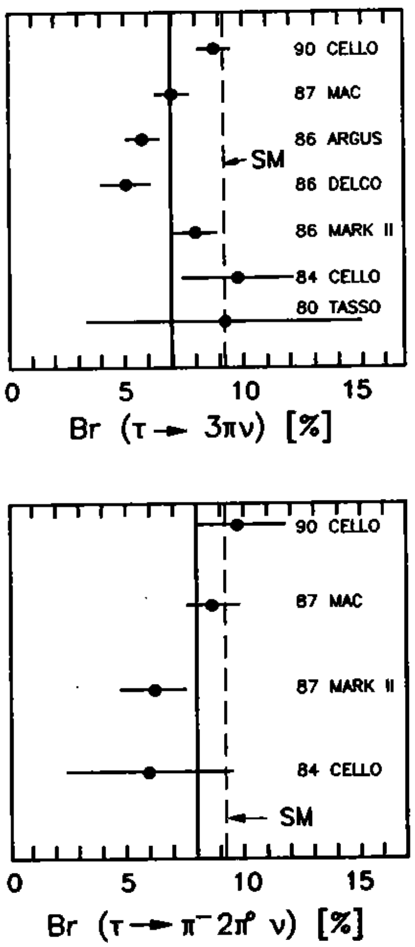


Fig. 8. World data on the branching ratio $\tau \to 3\pi\nu$. In the figure, statistical and systematic errors are added in quadrature. a) τ decay into three charged pions, b) decay into one charged pion and two π^0's. The solid line corresponds to the world average of $B(\tau \to 3\pi\nu) = 6.9$ % and $B(\tau \to \pi 2\pi^0\nu) = 8.0$ %, respectively. The broken lines correspond to the expectations of the standard model (see text).

---

†In the analysis τ events were tagged by a single track in one hemisphere. Typical selection efficiencies are below 1 %. The result depends on the branching ratios for 1-prong decays.

a value of $B(\tau \to \pi 2\pi^0\nu) = (5.6 \pm 0.5 \pm {}^{1.7}_{1.0})\%$, in agreement with the ARGUS number for $\tau \to 3\pi\nu$). One might argue that substantial weight ought to be given to those experiments measuring the complete τ final state (CELLO, ALEPH) where systematics are under much better control. Following this, the calculation of formal world averages for the three-pion final states from all experiments does not seem to be very meaningful.

CELLO and ALEPH find no internal inconsistency in their τ branching ratio measurements, both experiments agree mutually and with the theoretical expectations for the standard sequential nature of the τ lepton, the "τ problem" is absent in these data. Although statistically not significant, there is one peculiarity in both analyses: The branching ratio for $\tau \to \pi 3\pi^0\nu$ is somewhat larger than expected from CVC. While this could lead to a new "τ problem" (on a smaller level) a "natural" explanation, at least for CELLO, might be multihadronic background, accumulating in this particular final state. Background from multihadronic events is usually estimated using the LUND Monte-Carlo [43], but very little is known about the precision of simulation for low hadron multiplicities. CELLO have checked the Monte-Carlo by tagging multihadronic events in one event hemisphere (high charged multiplicity, invariant jet mass larger than m_τ) and by studying the jet properties on the other side. The calculation of the background in the τ sample, however, rests on the assumption of independent jet fragmentation (low multiplicities on *both* sides).

6. Conclusions

A significant deficit of about 6 % in the sum of the known one-prong exclusive decay channels of the τ lepton as compared to the direct measurement of the topological branching ratios shows up when all available data are averaged, assuming independent systematic errors. Most experiments used in the averages have only measured a subset of the exclusive decays. However, all these experiments mutually agree on the individual branching ratios. Evidence is accumulating that this longstanding "τ problem" may be resolved on purely experimental grounds: Recently, the CELLO experiment has performed a simultaneous analysis of all the topological and exclusive branching ratios. In this analysis significant differences with respect to the world averages were found, in particular for the branching ratios of the semihadronic decay channels with 3 pions, which are substantially larger than the respective world averages. At the same time the CELLO measurements favour a higher-than-average branching ratio for $\tau \to e\nu\nu$, in better agreement with the prediction from the τ lifetime measurement. In the CELLO data the 6 % mismatch between the sum of exclusive decay channels leading to one charged particle plus neutrals and the direct measurement has disappeared. The sum of the measured exclusive channels adds up to 100 % within the errors, leaving no room for non-standard decays at the few percent level. Explicit searches for "exotic" one-prong decays were negative. The measured exclusive branching ratios are in agreement with the expectations from

the standard model. Preliminary results from a similar, complete analysis of the τ decays by the ALEPH collaboration at LEP support the CELLO findings. While a solution to the "τ problem" is suggestive, the branching ratios for $\tau \to \pi 3\pi^0\nu$ by CELLO and the new ALEPH data show an interesting, though statistically still insignificant, excess over the naive CVC expectation. This excess deserves some further study.

Experiments with efficient detection of all τ final states, such as CELLO and ALEPH, might be given a higher weight when possible inconsistencies in the τ decay pattern are discussed. But it must be kept in mind that the world data on the τ branching ratios, formed from all other experiments, still indicate a significant deficit of identified one-prong decays. It thus seems inevitable to perform further high precision experiments of the CELLO/ALEPH type. Evidently, besides continuing the efforts at the existing machines, a τ-charm factory would be the ultimate tool for new insights on this subject.

Acknowledgement

I would like to thank the organizers of this workshop, in particular M. Davier, for this pleasant meeting. Many stimulating discussions with my collegues, in particular E. D. Bloom, K.K. Gan, J. Smith and A. Pich, during this workshop are gratefully acknowledged.

References

[1] M. Perl et al., Phys. Rev. Lett. 35 (1975) 1489

[2] S. L. Glashow, Nucl. Phys. 22 (1961) 579; A. Salam, Elementary Particle Theory, ed. N. Swartholm (Stockholm: Almquist and Wiksell) 1968, p. 367; S. Weinberg, 1967 Phys. Rev. Lett. 19 (1967) 1264, Phys. Rev. Lett. 27 (1971) 1688

[3] A. Pich, FTUV/89-21 and 89-22, see also proceedings of this workshop

[4] C. Kiesling, Tests of the Standard Theory of Electroweak Interactions, Springer Tracts in Modern Physics, Vol. 112, 1988

[5] A. Rouge, ALEPH 90-185, R. Alemany et al., ALEPH 90-186, F. Zomer et al., ALEPH 90-188

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

[7] H. B. Thacker and J. J. Sakurai, Phys. Lett. 36B (1971) 103

[8] F. J. Gilman and D. H. Miller, Phys. Rev. D17 (1978) 1846

[9] M. Perl, proceedings of the 1989 International Symposium on Lepton and Photon Interactions at High Energies, Stanford, p.89

[10] B. C. Barish and R.Stroynowski, Phys. Rep. 157 (1988) 1

[11] K. K. Gan and M. Perl, Int. J. Mod. Phys. A3 (1988) 531

[12] K. G. Hayes and M. L. Perl, Phys. Rev. D38 (1988) 3351

[13] D. Wegener, Proc. of the XXIVth International Conference on High Energy Physics, Munich, 1988, p. 877

[14] C. Kiesling, "τ Physics", in: High Energy Electron Positron Physics, eds. A. Ali and P. Söding, World scientific, Singapore, 1988, p. 716

[15] F. J. Gilman and S. H. Rhie, Phys. Rev. D31 (1985) 1066

[16] S. Abachi et al., Phys. Rev. D40 (1989) 902

[17] H.-J. Behrend et al., Phys. Lett. B222 (1989) 163

[18] E. Fernandez et al., Phys. Rev. Lett. 54 (1985) 1624

[19] W. Ruckstuhl et al., Phys. Rev. Lett. 56 (1986) 2132

[20] Review of Particle Properties, Phys. Lett. B239 (1990) 1

[21] T. N. Pham, C. Roiesnel and T. N. Truong, Phys. Lett. 78B (1978) 623

[22] H. Kagan, see proceedings of this workshop

[23] J. Kühn and S. Santamaria, MPI-PAE/PTh 17/90

[24] K. Hayes, proceedings of the Tau-Charm Factory Workshop, SLAC-Report-343, 1989, p.90

[25] F. J. Gilman , Phys. Rev. D35 (1987) 3541

[26] M.Derrick et al., Phys. Lett. 189B (1987) 260

[27] K.K. Gan, see proceedings of this workshop

[28] CLEO collaboration, contribution to the Singapore conference on High Energy Physics, 1990

[29] R. Stroynowski, see proceedings of this workshop

[30] V. Jain, see proceedings of this workshop, and CLEO preprint CLNS 90/997

[31] H.-J. Behrend et al., Z. Phys. C46 (1990) 537

[32] H.-J. Behrend et al., Phys. Lett. 114B (1982) 282

[33] H.-J. Behrend et al., Phys. Lett. 127B (1983) 270

[34] H.-J. Behrend et al., Z. Phys. C23 (1984) 103

[35] H.-J. Behrend et al., Phys. Lett. B200 (1988) 226

[36] H. J. Behrend et al., Physica Scripta 23 (1981) 610

[37] C. Kiesling, "τ decays: The solution to a longstanding problem ?", proceedings of the XXIVth Rencontre de Moriond, 1989, and MPI-PAE/Exp.El. 206, July 1989

[38] S. Scholz, Ph. D. Thesis, Technische Universität München, 1990

[39] Z. Zhang, see proceedings of this workshop

[40] J. Smith, see proceedings of this workshop

[41] H. Albrecht et al., Phys. Lett. 185B (1987) 223

[42] D. Antreasyan et al., DESY 91-001, January 1991

[43] B. Anderson et al., Phys. Rep. 97 (1983) 31