NEW RESULTS ON NON-STRANGE DECAYS OF THE τ LEPTON

K.K. Gan

Department of Physics, The Ohio State University, Columbus, OH 43210, U.S.A.

This is a review of new results on the τ lepton. For the leptonic decays, this includes precise measurements of the branching ratios and the observation of the decay $\tau^- \to e^-e^+e^-\bar{\nu}_e\nu_\tau$. For the hadronic decays, this includes precise measurements of the branching ratios for the decays to h^-, $h^-\pi^0$, $h^-h^+h^-$, $h^-h^+h^-\pi^0$, and a study of the three-pion system. Also included is a new result on $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ and a search for the decay into seven or more charged particles and into undetected particles. All results are consistent with the Standard Model expectations.

1 Introduction

With the advent of the CLEO II and LEP experiments, there has been a profusion of new results on the τ lepton. The CLEO II detector, with a large data sample and an electromagnetic calorimeter of excellent energy resolution and granularity, excels in the study of rare decays. The LEP experiments, with high detection efficiency and low background, excel in the study of major decay modes. This complementary allows for stringent tests of the Standard Model. This paper is a review of new results on τ decay. We first review the leptonic decays, including the first observation of the decay $\tau^- \to e^-e^+e^-\bar{\nu}_e\nu_\tau$. We then discuss the new results on the decay to h^-, $h^-\pi^0$, and $h^-h^+h^-$, including a study of the three-pion system. This is followed by a discussion on $h^-h^+h^-\pi^0$. We then present the new result on $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ and a search for the decay into seven or more charged particles and into undetected particles.

2 The Leptonic Decay Branching Ratios

The measurement of the leptonic decay branching ratios allow a test of lepton universality, a fundamental assumption of the Standard Model. The electron and muon decay widths can be precisely calculated and the ratio of the two branching ratios is[1],

$$\begin{aligned} \frac{B_\mu}{B_e} &= \left[\frac{g_\mu}{g_e}\right]^2 \cdot (1 - 8x + 8x^3 - x^4 - 12x^2 \ln x) \\ &= \left[\frac{g_\mu}{g_e}\right]^2 \cdot 0.9726, \end{aligned} \tag{1}$$

where g_e and g_μ are the coupling of the leptons to the weak charged current and $x = (m_\mu/m_\tau)^2$. The radiative corrections to the individual decay width is $\sim 0.4\%$, but they cancel out in the ratio[2].

The new results from the LEP experiments[3,4,5,6] are consistent with each other and the current world average[7] as shown in Figs. 1 and 2. The ratio of the average branching ratios[8] is

$$\frac{B_\mu}{B_e} = 0.9736 \pm 0.0069, \tag{2}$$

which gives the following ratio for the couplings,

$$\frac{g_\mu}{g_e} = 1.0005 \pm 0.0036. \tag{3}$$

However, the ratios are computed assuming that there is no correlation between the systematic errors in the measurements. A better test of lepton universality is to calculate the average coupling ratio from the coupling ratios computed by the individual LEP experiments where the correlations have been accounted for:

$$\frac{g_\mu}{g_e} = 1.0007 \pm 0.0037. \tag{4}$$

The ratio is consistent with unity. This represents a test of lepton universality to 0.4% level, a remarkable achievement.

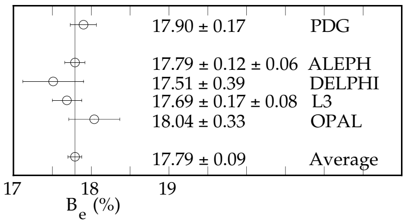

Figure 1: The electron branching ratio.

3 Observation of $\tau^- \to e^-e^+e^-\bar{\nu}_e\nu_\tau$

The decay of the τ into three leptons and two neutrinos is allowed in the Standard Model. The decay proceeds via the emission of a virtual photon with subsequent internal conversion into a pair of electrons or muons as shown in Fig. 3. The contribution from a virtual photon radiated off the W boson is negligible due to the W propagator. The branching ratios for the decays $\tau^- \to e^-e^+e^-\bar{\nu}_e\nu_\tau$

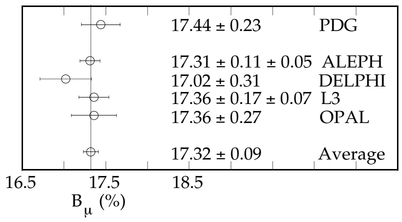

Figure 2: The muon branching ratio.

Table 1: Summary of results for $\tau^- \to e^-e^+e^-\bar{\nu}_e\nu_\tau$ and $\mu^-e^+e^-\bar{\nu}_\mu\nu_\tau$. The background in both channels is estimated to be < 0.4 events at 68% C.L. The branching ratios are expressed in unit of 10^{-5}.

	$e^-e^+e^-$	$\mu^-e^+e^-$
Data	5	1
BR (CLEO)	$2.8 \pm 1.4 \pm 0.4$	<3.6 @ 90%CL
BR (FORM)	4.457 ± 0.006	2.089 ± 0.003
BR (Dicus+Vega)	4.15 ± 0.06	1.97 ± 0.02

and $\mu^-e^+e^-\bar{\nu}_\mu\nu_\tau$ are expected to be at the 10^{-5} level (Table I). The branching ratios calculated by CLEO[9] using the symbolic manipulation program FORM[10] are $\sim 7\%$ higher than the calculation by Dicus and Vega[11]. An independent calculation would be useful to resolve the difference. The internal conversion into a muon pair is suppressed by two orders of magnitude[9,11] and hence beyond the reach of any experiment. The CLEO II experiment has observed[9] the decay $\tau^- \to e^-e^+e^-\bar{\nu}_e\nu_\tau$ and set an upper limit on $\tau^- \to \mu^-e^+e^-\bar{\nu}_\mu\nu_\tau$ (Table I). The result is consistent with both calculations. It is remarkable that we are now sensitive to rare decays at the 10^{-5} level.

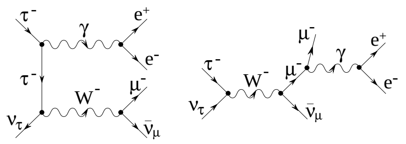

Figure 3: Feynman diagrams for $\tau^- \to \mu^-e^+e^-\bar{\nu}_\mu\nu_\tau$.

4 Branching Ratio of $\tau^- \to h^-\nu_\tau$

The decays $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to K^-\nu_\tau$ involve the coupling of the weak axial-vector current to pion and kaon, respectively. The branching ratio for $\tau^- \to \pi^-\nu_\tau$ can be calculated[1] from that for $\pi^- \to \mu^-\bar{\nu}_\mu$,

$$\frac{B(\tau^- \to \pi^-\nu_\tau)}{B(\pi^- \to \mu^-\bar{\nu}_\mu)} = \left[\frac{g_\tau}{g_\mu}\right]^2 \cdot \frac{\tau_\tau}{\tau_\pi} \cdot \frac{1}{2}\frac{m_\tau^3}{m_\pi m_\mu^2}\frac{(1-m_\pi^2/m_\tau^2)^2}{(1-m_\mu^2/m_\pi^2)^2} \quad (5)$$

where τ_π and τ_τ are the π and τ lifetimes[7,12]. The rate for $\tau^- \to K^-\nu_\tau$ is related to that for $K^- \to \mu^-\bar{\nu}_\mu$ by a similar expression. A measurement of the branching ratio for $\tau^- \to h^-\nu_\tau$, where $h = \pi$ or K, provides a test of lepton universality. The new results[13,14,15,16] on the branching ratio are shown in Fig. 4 together with the PDG value[7], where the contribution of K_L from K^* had been subtracted. The results are consistent with the expectation[17,18] from the Standard Model, including radiative corrections. This tests the $\mu - \tau$ universality to $\sim 1\%$.

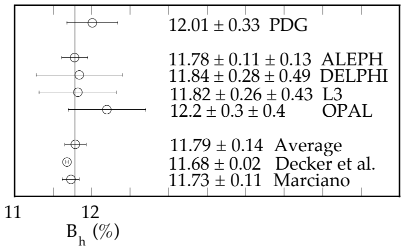

Figure 4: Branching ratios for $\tau^- \to h^-\nu_\tau$.

5 Branching Ratio of $\tau^- \to h^-\pi^0\nu_\tau$

The decay $\tau^- \to \pi^-\pi^0\nu_\tau$ involves the coupling of the weak vector current to the ρ meson. The branching ratio can be calculated[1] by using the conserved-vector-current (CVC) hypothesis[19] to relate the coupling strength of the ρ to the weak charged vector current and the electromagnetic neutral vector current. This isospin invariance of the quark current couplings to the gauge bosons is a feature of the Standard model. A measurement of the branching ratio for $\tau^- \to \pi^-\pi^0\nu_\tau$ therefore provides a test of the Standard Model. Most of the experiments performed only an inclusive measurement, $\tau^- \to h^-\pi^0\nu_\tau$. The new results[13,14,15] are shown in Fig. 5. Also shown are the theoretical expectations which are the sum of the CVC predictions[20,21,22] and the measured branching ratio[23] for $\tau^- \to K^-\pi^0\nu_\tau$. The CVC predictions are calculated using the measured cross section for $e^+e^- \to \pi^+\pi^-$. All the measurements are consistent with each other and the theoretical expectations, including radiative corrections. This test of the Standard Model is now limited by the uncertainty in the measurement of the cross section. A more precise measurement of the cross section is eagerly awaited.

6 Study of the Decay $\tau^- \to h^-h^+h^-\nu_\tau$

The three-pion decay of the τ is mediated by the axial-vector part of the weak interaction. The branching ratio can be estimated using the partially-conserved-axial-current[24] (PCAC) hypothesis. Unfortunately, the esti-

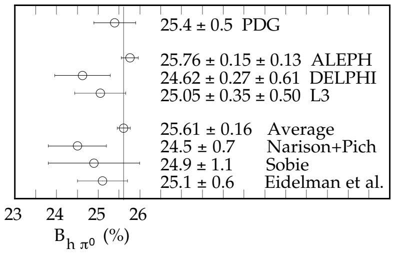

Figure 5: Branching ratios for $\tau^- \to h^-\pi^0\nu_\tau$.

mate is not very reliable. However, isospin conservation imposes a limit on the relative fraction of the branching ratios for $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-2\pi^0\nu_\tau$: $B_{\pi 2\pi^0} \leq B_{3\pi}$. If the decay is dominated by the a_1 resonance as expected, then $B_{\pi 2\pi^0} = B_{3\pi}$, neglecting a small phase space correction. Most of the experiments performed only an inclusive measurement, $\tau^- \to h^-h^+h^-\nu_\tau$. The new results[13,14,25,26] are consistent with each other but significantly higher than the old values[7,23] as shown in Fig. 6. The new results are probably more reliable because they are in good agreement with the average branching ratio for $\tau^- \to h^-2\pi^0\nu_\tau$, a decay of very different detection systematic problems.

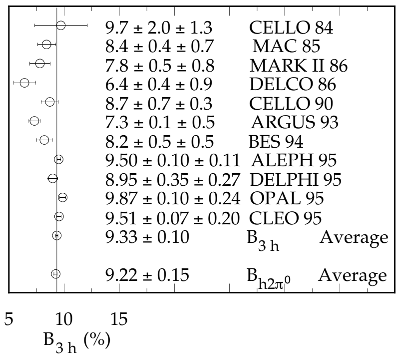

Figure 6: Branching ratios for $\tau^- \to h^-h^+h^-\nu_\tau$ and the average branching ratio for $\tau^- \to h^-2\pi^0\nu_\tau$.

The OPAL experiment has measured[27] the hadronic structure functions in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ using a general description of hadronic τ decays proposed by Kuhn and Mirkes[28]. The structure functions measured are model independent under the reasonable assumptions of G-parity conservation and absence of scalar currents in order to reduce the numbers of functions from 16 to 4. The models of Kuhn and Santamaria (KS)[29] and of Isgur et al. (IMR) both fit the data quite well. The parity violating asymmetry parameter γ_{VA} is simultaneously determined as shown in Table II. Also shown are the parameters obtained using the KS and IMR models and the parameter measured by ARGUS[31] using the IMR model. All measurements are consistent with the Standard Model prediction of $\gamma_{VA} = 1$ for left-handed ν_τ.

Table 2: Measurements of γ_{VA}.

Experiment	Model	γ_{VA}
OPAL		$1.08^{+0.46+0.14}_{-0.41-0.25}$
OPAL	KS	$0.87 \pm 0.27^{+0.05}_{-0.06}$
OPAL	IMR	$1.10 \pm 0.31^{+0.13}_{-0.14}$
ARGUS	IMR	$1.25 \pm 0.23^{+0.15}_{-0.08}$

7 Branching Ratio of $\tau^- \to h^-h^+h^-\pi^0\nu_\tau$

The decay $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ proceeds through the vector current and the branching ratio can be estimated[1] using CVC. Again, the experimenters performed only an inclusive measurement, $\tau^- \to h^-h^+h^-\pi^0\nu_\tau$. The new measurements[13,25,26] are shown in Fig. 7. Also shown are the CVC predictions[20,21] calculated using the measured e^+e^- cross section for four-pion final states. All the measurements are consistent with each other and the theoretical expectations, including radiative corrections. Once again, this test of the Standard Model is now limited by the uncertainty in the measurement of the cross section.

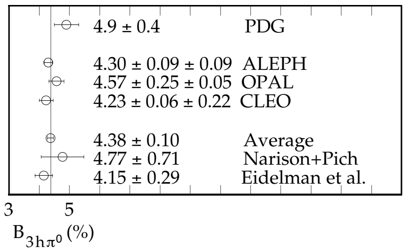

Figure 7: Branching ratios for $\tau^- \to h^-h^+h^-\pi^0\nu_\tau$.

8 Branching Ratio of $\tau^- \to \pi^-\eta\pi^0\nu_\tau$

The decay $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ proceeds through the vector current since the G-parity of the $\pi\eta\pi^0$ system is positive. However, in the chiral limit, the vector current couples exclusively to even numbers of pseudo-scalars. The decay is thus a chiral anomaly of QCD. The calculations of the decay rate have large uncertainties[32]. The CVC hypothesis provides a more reliable estimate of the rate[20,21]. The decay was first observed by CLEO II[33] in 1992 and has now been observed by ALEPH[34] as well. The two measurements are consistent with each other and the CVC expectations as shown in Fig. 8.

9 Search for Exotic τ Decay

The ALEPH experiment[35] has searched for τ decay into seven or more charged particles and into undetected par-

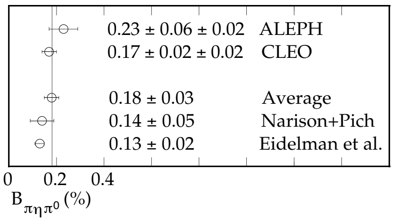

Figure 8: Branching ratios for $\tau^- \to \pi^-\eta\pi^0\nu_\tau$.

ticles. The experiment tags $\tau^+\tau^-$ events using one of the τ decays without looking at the other τ. This search is made possible by the high-energy boost which separates the two τ's into a back-to-back topology with little background. No τ candidate with seven or more charged particles is found, resulting in the following upper limit,

$$B(\tau^- \to (\geq 4h^-3h^+)(\geq 0 \text{ neutrals})\nu_\tau) < 1.2 \times 10^{-4}, \quad (6)$$

at the 95% C.L. This limit is more stringent then the limit set by HRS[36] on the decay into seven charge particles, $B(\tau^- \to 4h^-3h^+ \geq 0$ neutrals $\nu_\tau) < 1.9 \times 10^{-4}$ at the 90% C.L. For the decay into undetected particles, 17 candidates are found with an expected background of 11.5 ± 2.0 events. This corresponds to an upper limit of

$$B(\tau^- \to \text{“}undetected\text{”}) < 8.9 \times 10^{-4}, \quad (7)$$

at the 95% C.L.

10 Conclusion

In conclusion, we have reached a new level of sensitivity in τ physics. Lepton universality is now tested to the level of 0.4%. We are now sensitive to branching ratios at the level of 10^{-5}. Unfortunately, there is no hint of physics beyond the Standard Model.

11 Acknowledgments

This work was supported in part by the OJI program of the U.S. Department of Energy. The author wishes to thank R. Kass for the careful reading of this manuscript.

12 References

1. Y.S. Tsai, Phys. Rev. D **4**, 2821 (1971).
2. W.J. Marciano and A. Sirlin, Phys. Rev. Lett. **61**, 1815 (1988).
3. D. Buskulic *et al.*, CERN-PPE/95-127, submitted to Z. Phys. C.
4. P. Abreu *et al.*, Phys. Lett. B **357**, 715 (1994).
5. J. Alcaraz, Nucl. Phys. B (Proc. Suppl.) **40**, 237 (1995).
6. R. Akers *et al.*, Z. Phys. C **66**, 543 (1995).
7. Review of Particle Properties, L. Montanet *et al.*, Phys. Rev. D **50** (1994).
8. All average branching ratios are computed from the new results presented in this paper and the results tabulated by PDG[7], with the assumption that the new results supersede the previous publications by the same experiments.
9. CLEO Collaboration, CLNS 95/1370, to be submitted to Phys. Rev. Lett.
10. J.A.M. Vermaseren, The Symbolic Manipulation Program FORM, KEK-TH-326, 1992 (unpublished).
11. D.A. Dicus and R. Vega, Phys. Lett. B **338**, 341 (1994).
12. M. Davier, Nucl. Phys. B (Proc. Suppl.) **40**, 395 (1995).
13. D. Buskulic *et al.*, CERN-PPE/95-140, submitted to Z. Phys. C.
14. DELPHI contribution to this conference, DELPHI 95-66.
15. M. Acciarri *et al.*, Phys. Lett. B **345**, 93 (1995).
16. A.S. Schwarz, Proc. XVI International Symposium on Lepton and Photon Interactions, Cornell, 1993, eds. P. Drell and D. Rubin, AIP Press (1994), p. 671.
17. W.J. Marciano and A. Sirlin, Phys. Rev. Lett. **71**, 3629 (1993).
18. R. Decker and M. Finkemeier, Nucl. Phys. B (Proc. Suppl.) **40**, 453 (1995).
19. R.P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).
20. S. Narison and A. Pich *et al.*, Phys. Lett. B **304**, 359 (1993).
21. S.I. Eidelman and V.N. Ivanchenko, Nucl. Phys. B (Proc. Suppl.) **40**, 131 (1995).
22. R.J. Sobie, Z. Phys. C **65**, 79 (1995).
23. B.K. Heltsley, Nucl. Phys. B (Proc. Suppl.) **40**, 413 (1995).
24. J. Bernstein *et al.*, Nuovo Cimento **17**, 757 (1960).
25. R. Akers *et al.*, CERN-PPE/95-070, submitted to Z. Phys. C.
26. R. Balest *et al.*, CLNS 95/1347, submitted to Phys. Rev. Lett.
27. R. Akers *et al.*, Z. Phys. C **67**, 45 (1995).
28. J.H. Kuhn and E. Mirkes, Z. Phys. C **56**, 661 (1992).
29. J.H. Kuhn and A. Santamaria, Z. Phys. C **48**, 445 (1990).
30. N. Isgur, C. Morningstar, and C. Reader, Phys. Rev. D **39**, 1357 (1989).
31. H. Albrecht *et al.*, Z. Phys. C **58**, 61 (1993).
32. G. Kramer and W.F. Palmer, Z. Phys. C **39**, 423 (1988) and references therein.
33. M. Artuso *et al.*, Phys. Rev. Lett. **69**, 3278 (1992).
34. P. Bourdon, ALEPH contribution to this conference, EPS0424.
35. ALEPH contribution to this conference, EPS0453.
36. B.G. Bylsma *et al.*, Phys. Rev. D **35**, 2269 (1987).