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New Results on τ Lepton

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Abstract. This is a review of new results on the τ lepton. The lifetime has been measured with improved precision, allowing the test of lepton universality to 0.2% level. There are several new measurements of the branching ratios for the hadronic decays, including much improved measurements for the Cabibbo-suppressed decays. All results are consistent with the Standard Model expectations.

1 Introduction

The τ lepton provides a unique laboratory to test the Standard Model. Its large mass allows the lepton to decay into both lighter leptons and hadrons, providing many venues to challenge the Standard Model. This includes the test of lepton universality, Conserved-Vector-Current (CVC) hypothesis [1], and isospin symmetry. In this paper, I will first review the new measurements of the lifetime and then the branching ratios for hadronic decays.

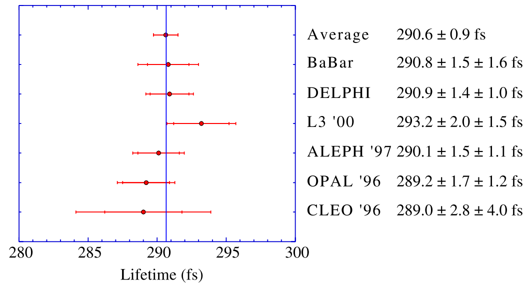

Fig. 1. Measurements of the τ lifetime.

2 Lifetime

In the Standard Model, the coupling of the τ lepton to the W boson is the same as those for the lighter leptons, e and μ. The universality of the couplings can be tested by comparing the measurement of the τ lifetime (τ_τ) and leptonic branching fractions [2]:

$$\tau_\tau = \tau_\mu \left(\frac{g_\mu}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \qquad (1)$$

$$\tau_\tau = \tau_\mu \left(\frac{g_e}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) f\left(\frac{m_\mu^2}{m_\tau^2}\right) \qquad (2)$$

where the phase space factor is given by

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x = 0.9726, \qquad (3)$$

where τ_μ is the μ lifetime, m_μ and m_τ is the mass of the μ and τ, and g_e, g_μ and g_τ is the coupling of the W boson to e, μ, and τ. Lepton universality corresponds to $g_e = g_\mu = g_\tau$.

Both DELPHI and BaBar have reported preliminary measurements of the τ lifetime. The DELPHI experiment [3] used three techniques to measure the lifetime:

- 3-prong decay length
- 1-prong vs 1-prong impact parameters:
  - impact parameter difference: $d_1 - d_2$
  - miss distance: $d_1 + d_2$

The measurements of lifetime using the two impact parameter techniques have 36% correlation and this has been taken into account by the experiment to extract a new measurement of the lifetime.

BaBar has reported a preliminary measurement of the lifetime using the 3-prong decay length method. The experiment performed a blind analysis which is highly desirable for this kind of high precision measurement.

The current status of the lifetime measurements is shown in Fig. 1. It is reassuring to see that all measurements are consistent with the result from a blind analysis. There is a good prospect for higher precision measurements by BaBar and Belle given their large data samples.

The average measured lifetime is plotted against the average measured leptonic branching ratios [4] in Fig. 2. Also shown are the Standard Model predictions assuming lepton universality. The measurements are consistent with lepton universality. Alternatively we can use the measurements to extract the following ratios of couplings:

$$\frac{g_\mu}{g_\tau} = 0.9990 \pm 0.0023$$

$$\frac{g_e}{g_\tau} = 0.9988 \pm 0.0021$$

Both ratios are consistent with the Standard Model expectation to a precision of 0.2%, a remarkable achievement.

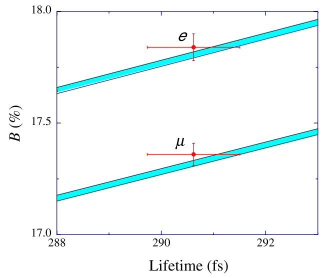

Fig. 2. Measurements of the leptonic branching ratios vs τ lifetime. The lines show the predictions based on lepton universality with the width given by the uncertainty in the τ mass.

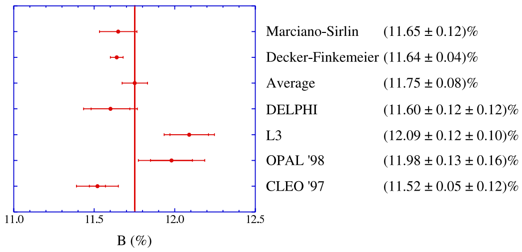

Fig. 3. Branching ratio for $\tau^- \to h^- \nu_\tau$.

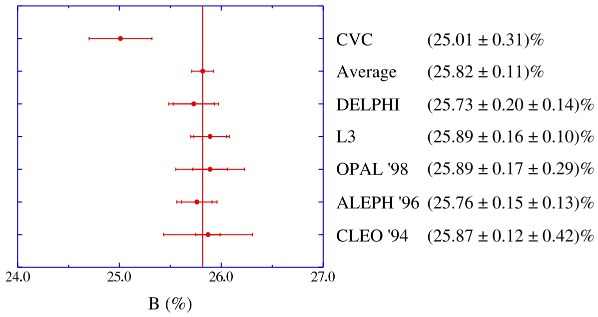

Fig. 4. Branching ratio for $\tau^- \to h^- \pi^0 \nu_\tau$.

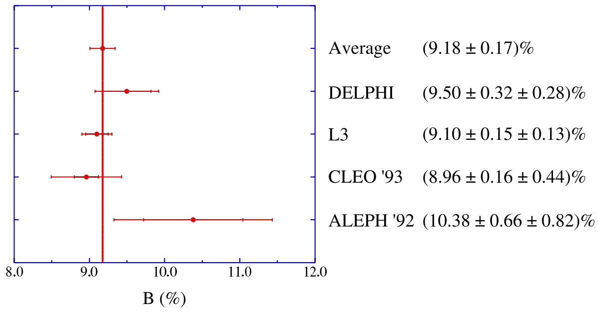

Fig. 5. Branching ratio for $\tau^- \to h^- 2\pi^0 \nu_\tau$.

3 Hadronic Decays

The τ lepton can decay into many hadronic states due to its large mass. The large number of hadronic channels allows the study of many aspects of the Standard Model, including the test of lepton universality, CVC, and isospin symmetry. In this section, I will review the new results from DELPHI [5], L3 [6], and CLEO III [7]. The first two experiments measure the inclusive branching ratios while CLEO III measures the exclusive branching ratios with π/K identification.

3.1 Branching ratio of $\tau^- \to h^- \nu_\tau$

The decay $\tau^- \to \pi^- \nu_\tau$ involves the coupling of the weak current to the pion. The branching ratio for $\tau^- \to \pi^- \nu_\tau$ can be calculated [2] from that of $\pi^- \to \mu^- \bar{\nu}_\mu$,

$$\frac{B(\tau^- \to \pi^- \nu_\tau)}{B(\pi^- \to \mu^- \bar{\nu}_\mu)} = \left[\frac{g_\tau}{g_\mu}\right]^2 \frac{\tau_\tau}{\tau_\pi} \frac{1}{2} \frac{m_\tau^3}{m_\pi m_\mu^2} \frac{(1 - m_\pi^2/m_\tau^2)^2}{(1 - m_\mu^2/m_\pi^2)^2} \quad (4)$$

where τ_π and m_π is the π lifetime and mass, respectively. A measurement of the branching ratio provides a test of $\mu - \tau$ universality. Most of the experiments performed only an inclusive measurement, $B(\tau^- \to h^- \nu_\tau)$ with $h = \pi$ or K. The new results [5,6] are shown in Fig. 3. There is considerable spread among the measurements, with χ^2 of 9.9 for 3 DOF (CL = 2%). The average branching ratio is consistent with the expectation [8] from the Standard Model, including radiative corrections.

3.2 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 [2] by using the CVC hypothesis 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, $B(\tau^- \to h^- \pi^0 \nu_\tau)$. The new results [5,6] are shown in Fig. 4. Also shown is the theoretical expectation which is a sum of the CVC predictions [9] and the measured branching ratio [4] for $\tau^- \to K^- \pi^0 \nu_\tau$. The CVC prediction is based on a reanalysis of the measured cross section for $e^+ e^- \to \pi^+ \pi^-$, with a more proper treatment of the radiative corrections. All the τ measurements are consistent with each other but the average is somewhat higher than the CVC expectation.

3.3 Branching ratio of $\tau^- \to h^- 2\pi^0 \nu_\tau$

The current state of $B(\tau^- \to h^- 2\pi^0 \nu_\tau)$ is summarized in Fig. 5, including the two new measurements [5,6]. All the measurements are consistent with each other. Correcting for the small contribution of $\tau^- \to K^- 2\pi^0 \nu_\tau$ yields the exclusive branching ratio, $B(\tau^- \to \pi^- 2\pi^0 \nu_\tau) = (9.12 \pm 0.17)\%$.

3.4 Branching ratio of $\tau^- \to h^- h^+ h^- \nu_\tau$

The new results by DELPHI [5] and L3 [6] on $B(\tau^- \to h^- h^+ h^- \nu_\tau)$ together with the results from other experiments are summarized in Fig. 6. All the measurements are consistent with each other.

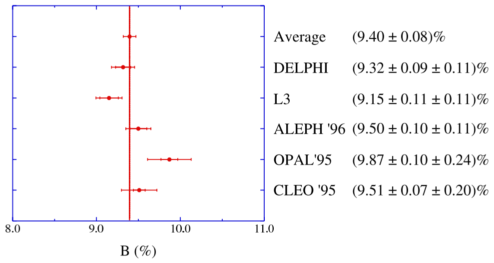

Fig. 6. Branching ratio for $\tau^- \to h^- h^+ h^- \nu_\tau$.

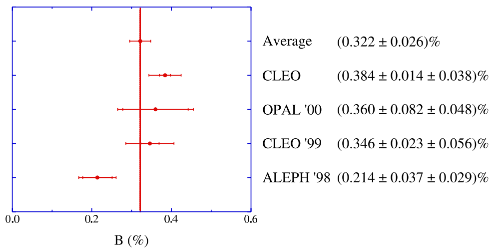

Fig. 7. Branching ratio for $\tau^- \to K^- \pi^+ \pi^- \nu_\tau$.

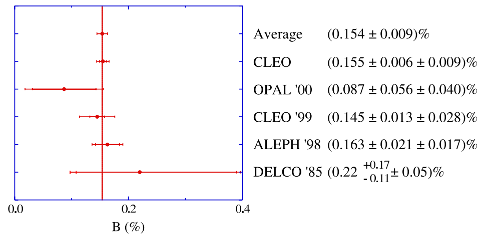

Fig. 8. Branching ratio for $\tau^- \to K^- K^+ \pi^- \nu_\tau$.

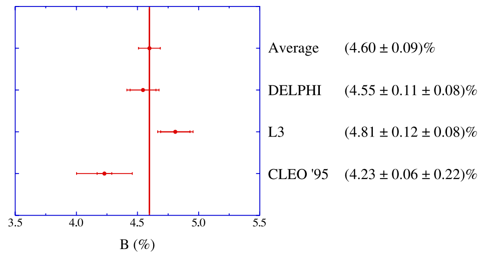

Fig. 9. Branching ratio for $\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$.

3.5 Branching ratio of $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$

The CLEO III experiment uses their ring imaging Cherenkov detector (RICH) to separate π/K and obtains the first measurement of the exclusive branching ratio [7]: $B(\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau) = (9.13 \pm 0.05 \pm 0.46)\%$. Comparing this result with that in Sec. 3.3, it is evident that they are consistent with isospin symmetry: $B(\tau^- \to \pi^- 2\pi^0 \nu_\tau) \leq B(\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau)$.

3.6 Branching ratio of $\tau^- \to K^- \pi^+ \pi^- \nu_\tau$

The CLEO III experiment has also measured the branching ratio for $\tau^- \to K^- \pi^+ \pi^- \nu_\tau$ [7]. This result together with those of other experiments are summarized in Fig. 7. The measurements are consistent with each other.

3.7 Branching ratio of $\tau^- \to K^- K^+ \pi^- \nu_\tau$

CLEO III has also measured the branching ratio for $\tau^- \to K^- K^+ \pi^- \nu_\tau$ [7]. This result is consistent with other experiments but is significantly more precise as shown in Fig. 8. The experiment also set an upper limit on the three-koan decay, $B(\tau^- \to K^- K^+ K^- \nu_\tau) < 0.0037\%$ at the 90%CL.

The sum of the three exclusive 3-prong branching ratios, $\approx (9.6 \pm 0.5)\%$, is consistent with the inclusive result shown in Sect. 3.4, indicating internal consistency of the measurements.

3.8 Branching ratio of $\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$

The new results by DELPHI [5] and L3 [6] on $B(\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau)$ together with the result by CLEO are summarized in Fig. 9. All the measurements are consistent with each other. If we neglect the small contribution from decays with kaons, the weighted average is significantly ($\approx 4\sigma$) above the CVC prediction [10], $(3.63 \pm 0.21)\%$, based on the measured cross section for $e^+ e^- \to 4\pi$. More precise measurements of the branching ratio and cross section are needed to resolve the discrepancy.

4 Conclusion

We have reached a new level of sensitivity in τ physics. Lepton universality is now tested to the level of 0.2%. We have begun a new era of τ physics with kaons and can expect new results from CLEO III, BaBar, and Belle. There is no hint of physics beyond the Standard Model.

Acknowledgements
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