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NEW RESULTS ON THE τ LEPTON*

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ABSTRACT

This is a review of new results on the τ lepton. The results include precise measurements of the lifetime, measurements of the decay $\tau^- \rightarrow \pi^- 2\pi^0 \nu_\tau$ with much improved precision, and limits on decay modes containing η mesons, including the second-class-current decay $\tau^- \rightarrow \pi^- \eta \nu_\tau$. The implications of these new results on the discrepancy in the one-charged-particle decay modes are discussed.

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1. INTRODUCTION

The τ lepton has been a subject of extensive study since the discovery[1] in 1975. All measurements[2] indicate that it is a sequential lepton in the standard gauge theory[3] of electromagnetic and weak interactions. The branching ratios for most of the major decay modes have been measured with good precision and all measurements are in good agreement with the theoretical expectations. However, the sum of the measured branching ratios for decay modes with one charged particle in the final state is significantly smaller than the inclusive measurement.[4] Since the theoretical predictions for the branching ratios and the τ lifetime are related to the electron branching ratio, measurement of the lifetime provides an independent measurement of the electron branching ratio. There are several new and precise measurements of the lifetime. We review the results in the next section. We then review the new results on branching ratios. First, we discuss the new measurements of the vector decays, $\tau^- \to \rho^- \nu_\tau$ and $\tau^- \to K^{*-}\nu_\tau$. Next, we discuss the new results on the decay $\tau^- \to \pi^- 2\pi^0 \nu_\tau$, which has now been measured with much improved precision. Also included is a discussion of the decay $\tau^- \to \pi^- 3\pi^0 \nu_\tau$. Then, we survey the theoretical expectations and experimental limits on decay modes containing η mesons, including the limits on the second-class-current decay $\tau^- \to \pi^- \eta \nu_\tau$. We conclude with a discussion of the implications of the new results on the discrepancy in the one-charged-particle decay modes.

2. LIFETIME

Measurement of the τ lifetime provides a direct study of the coupling strength of the τ to the charged weak current. In the standard model, the τ decay $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ proceeds in perfect analogy to the μ decay $\mu^- \to e^- \bar{\nu}_e \nu_\tau$. Assuming $\mu - \tau$ universality of the weak coupling and that the τ neutrino is massless, the τ lifetime is related to the μ lifetime by[5]

$$\begin{aligned} \tau_\tau &= \left(\frac{m_\mu}{m_\tau}\right)^5 \tau_\mu \, B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \\ &= 16.03 \times 10^{-13} \, B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \text{ s} \quad . \end{aligned}$$

With the world average measurement (Sec. 3.1) of the electron branching ratio $B_e = (17.7 \pm 0.4)\%$, the predicted lifetime is $\tau_\tau = (2.83 \pm 0.06) \times 10^{-13}$ s.

Several experiments[6−12] have reported new measurements of the τ lifetime. All measurements are consistent with each other as shown in Fig. 1. The weighted average of the measurements is $\tau_\tau = (3.03 \pm 0.08) \times 10^{-13}$ s, in fair agreement with the theoretical prediction. Over the past few years, the measured lifetime has always been in excellent agreement[13] with the theoretical prediction. This is the first time that the lifetime has shifted. The shift might indicate the underestimate of the quoted error in the weighted average, calculated assuming that all the statistical and systematic errors are independent. The final systematic error could be as large as $\pm 0.15 \times 10^{-13}$ s. The implication of the shift on the discrepancy in the one-charged-particle decay modes will be discussed in Sec. 5.

3. DECAY MODES AND BRANCHING RATIOS

The τ decay is a good laboratory for studying many aspects of the standard model. Since the τ appears to have no internal structure to complicate theoretical calculations, many branching ratios can be predicted with the present understanding of the electroweak interaction. The large lepton mass allows the τ to decay into both purely leptonic states and semi-leptonic states with accompanying hadrons.

The hadronic decay products have distinctive charge conjugation (C) and isospin (and hence G-parity) signatures, a reflection of the quantum number of the charged hadronic weak current. The weak current is classified according to its G-parity:

$$\begin{array}{rll} \text{vector weak current:} & G=+1,\ J^P=1^- , & \text{e.g., } \rho^-(770) \\ \text{axial weak current:} & G=-1,\ J^P=0^-,1^+ , & \text{e.g., } \pi^-,\ a_1^-(1270) \ . \end{array}$$

These are known as the first class currents. Currents with opposite G-parity are called the second class currents[14] and are suppressed by the order α^2 or 10^{-4} in the standard model. Examples of second class current decays are $\tau^- \to a_0^-(980)\nu_\tau$ and $\tau^- \to b_1^-(1235)\nu_\tau$.

In this section, we review the results on branching ratios.

3.1 e AND μ DECAYS

There are no new results on the electron and muon branching ratios. We include the world average measurements[15] for completeness: $B_e = (17.7 \pm 0.4)\%$ and $B_\mu = (17.7 \pm 0.4)\%$.

It is customary to calculate the branching ratios for other decay modes normalized to the electron branching ratio. We will use the world average measurement of B_e in the calculations.

3.2 π AND K DECAYS

The decays $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to K^-\nu_\tau$ involve the coupling of the weak axial-vector current to the pion and kaon, respectively. There are also no new results on these branching ratios. As before we include the world average measurements[15] for completeness: $B_\pi = (10.9\pm0.6)\%$ and $B_K = (0.59\pm0.18)\%$.

3.3 ρ AND K^* DECAYS

The decays $\tau^- \to \rho^-\nu_\tau$ and $\tau^- \to K^{*-}\nu_\tau$ involve the coupling of the weak vector current to $\rho(770)$ and $K^*(890)$, respectively. Measurements of the branching ratios allow studies of the hadronic weak current. The ρ branching ratio can be calculated[5] by using the conserved-vector-current[16] (CVC) hypothesis to relate the coupling strength of the ρ to the weak charged vector current and the electromagnetic neutral vector current. Gilman and Rhie[4] use the measured cross section for $e^+e^- \to \gamma^* \to \rho$ to calculate the electromagnetic coupling and predict that

$$B_\rho/B_e = 1.23 \quad . \tag{2}$$

The Cabibbo-suppressed K^* decay is related[5] to the Cabibbo-favored ρ decay by

$$B_{K^*}/B_\rho = \tan^2\theta_C \cdot f(m_\rho, m_{K^*}, m_\tau) \cdot \frac{g_{K^*}^2}{g_\rho^2} \quad . \tag{3}$$

The factor f corrects for the differences in the available phase spaces. The relationship between g_{K^*} and g_ρ, the coupling strengths of the ρ and K^* to the vector current, depends on whether the SU(3) symmetry is exact or broken. If the symmetry is exact, then $g_{K^*}^2 = g_\rho^2$ and the prediction is

$$B_{K^*}/B_\rho = 0.038 \quad . \tag{4}$$

On the other hand, if the symmetry is broken, then the Das-Mathur-Okubo[17] sum rules give $g_{K^*}^2/m_{K^*}^2 = g_\rho^2/m_\rho^2$ and the prediction becomes

$$B_{K^*}/B_\rho = 0.052 \quad . \tag{5}$$

The MARK III and CRYSTAL BALL collaborations have reported new results[18,19] on ρ branching ratio, $B_\rho = (23.0 \pm 1.3 \pm 1.7)\%$ and $(22.6 \pm 0.5 \pm 1.4)\%$, respectively. The results are in good agreement with the measurements from other experiments.[15] Combining all the measurements yields a weighted average of $B_\rho = (22.8 \pm 0.9)\%$. This gives the ratio

$$B_\rho/B_e = 1.29 \pm 0.06 \quad , \tag{6}$$

in good agreement with the CVC prediction. It is interesting to note that the CRYSTAL BALL detector, a neutral detector with very different systematic errors from the conventional magnetic detectors, obtains a very similar result.

The TPC and HRS collaborations have reported new results[20,21] on K^* branching ratio, $B_{K^*} = (1.5 \pm 0.4 \pm 0.4)\%$ and $(1.9 \pm 0.28 \pm 0.25)\%$, respectively. The results are in good agreement with the MARK II measurement[22] of $B_{K^*} = (1.3 \pm 0.3 \pm 0.3)\%$. The weighted average is $B_{K^*} = (1.6 \pm 0.3)\%$ and yields the ratio,

$$B_{K^*}/B_\rho = 0.070 \pm 0.013 \quad . \tag{7}$$

The result favors a broken SU(3) symmetry (Eq. 5). A more precise measurement is needed before one can draw a definite conclusion.

3.4 3π AND 4π DECAYS

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[23] (PCAC) hypothesis. Unfortunately, the estimate is not very reliable. However, isospin conservation imposes a limit on the relative fraction of the branching ratios for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$: $B_{\pi 2\pi^0} \leq B_{3\pi}$. If the decay is dominated by the $a_1(1270)$ resonance as expected, then $B_{\pi 2\pi^0} = B_{3\pi}$. The world average measurement[15] of $B_{3\pi}$ is $(6.7 \pm 0.4)\%$.

The four-pion decay proceeds through the vector current and can be estimated[5] by CVC. Gilman and Rhie[4] use the measured cross sections for $e^+e^- \to \pi^+\pi^-2\pi^0$ and $e^+e^- \to 2\pi^+2\pi^-$ to calculate the branching ratios for $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \to \pi^-3\pi^0\nu_\tau$, and predict $B_{3\pi\pi^0} = 0.275 \times B_e = 4.9\%$ and $B_{\pi 3\pi^0} = 0.055 \times B_e = 1.0\%$. The world average measurement[15] of $B_{3\pi\pi^0}$ is $(5.0 \pm 0.5)\%$, in good agreement with the CVC prediction.

It is difficult to measure $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ because of the multiple photons in the final states, which demand good energy resolution and granularity for the electromagnetic shower detection. Three years ago, the CELLO collaboration reported measurements[24] of the branching ratios by unfolding the observed photon multiplicity spectrum. The results are

$$\begin{aligned} B_{\pi 2\pi^0} &= (6.0 \pm 3.0 \pm 1.8)\% \\ B_{\pi 3\pi^0} &= (3.0 \pm 2.2 \pm 1.5)\% \quad . \end{aligned} \tag{8}$$

The measurements ignored the contributions from decays containing η mesons such as $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ and $\tau^- \to \pi^-\eta\eta\nu_\tau$.

There are now three new measurements of the branching ratios. The MARK II collaboration[25] extracted the branching ratios by fitting the observed photon multiplicity spectrum of τ candidates with one charged particle and three or more photons. The fit favored additional multiple-neutral-meson decay modes other than $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$. Using the decay $\tau^- \to \pi^- \eta \pi^0 \nu_\tau$ as an example for the multiple-neutral-meson decay modes, the fit yields

$$
\begin{aligned}
B_{\pi 2\pi^0} &= (6.2 \pm 0.6 \pm 1.2)\% \\
B_{\pi 3\pi^0} &= \left(0.0 \pm^{1.4}_{0.0} \pm^{1.1}_{0.0}\right)\% \qquad (9) \\
B_{\pi \eta \pi^0} &= \left(4.2 \pm^{0.7}_{1.2} \pm 1.6\right)\% \quad .
\end{aligned}
$$

The MAC collaboration[26] measured $B_{\pi 2\pi^0}$ by using τ candidates with two energetic photons. The invariant mass of the two photons was required to be greater than 200 MeV/c^2 to reduce contamination from the decay $\tau^- \to \pi^- \pi^0 \nu_\tau$. The result is

$$B_{\pi 2\pi^0} = (8.7 \pm 0.4 \pm 1.1)\% \quad . \qquad (10)$$

The CRYSTAL BALL collaboration measured[19] $B_{2\pi^0}$ using τ candidates with four detected photons. Figure 2a shows the invariant mass distribution of the $\gamma\gamma$ pairs that recoiled against another $\gamma\gamma$ pair which has an invariant mass that is consistent with the π^0 mass. A clear π^0 signal is evident. This is the first direct evidence of this decay mode; the excellent resolution of the CRYSTAL BALL allows the reconstruction of the π^0's amid the large combinatorial background. The result of a fit to the mass spectrum yields

$$B_{\pi 2\pi^0} = (7.4 \pm 0.6 \pm 1.3)\% \quad . \qquad (11)$$

The CRYSTAL BALL also performed a similar analysis on the six-photon sample to measure $B_{\pi 3\pi^0}$. Figure 2b shows the invariant mass distribution of the $\gamma\gamma$ pairs that recoiled against two other $\gamma\gamma$ pairs which both have an invariant mass that is consistent with the π^0 mass. There is no clear evidence for a π^0 signal due to the very large combinatorial background and the limited detection efficiency. A fit to the mass spectrum yields

$$B_{\pi 3\pi^0} = (0.54 \pm 0.28 \pm 1.06)\% \qquad (12)$$

or an upper limit of

$$B_{\pi 3\pi^0} < 2.5\% \qquad (13)$$

at the 95% confidence level.

Within the errors, all measurements of $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ are consistent with the theoretical expectations. The result from MARK II on $B_{\pi\eta\pi^0}$ will be discussed in Sec. 3.7.

Last year, the ARGUS collaboration[27] reported evidence for $\tau^- \to \pi^-\omega\nu_\tau$ in the decay $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$, with a branching ratio of $(1.5 \pm 0.3 \pm 0.3)\%$. This result has now been confirmed[28] by the CLEO collaboration (Fig. 3), which measures a branching ratio of $(1.6 \pm 0.27 \pm 0.41)\%$. CLEO also performed a similar spin-parity analysis on the $\omega\pi$ system and found that the system is consistent with a $J^P = 1^-$ state and that there is no evidence for second class currents, confirming the ARGUS findings.

3.5 5π AND 6π DECAYS

There are no new results on the five- and six-pion decay branching ratios. As before, we include the world average measurements of the branching ratios for completeness: the inclusive five-charged-particle branching ratio[15] is $B_5 = (0.11 \pm 0.03)\%$, and the exclusive branching ratios[29] for the five- and six-pion decays are $B_{5\pi} = (0.051 \pm 0.020)\%$ and $B_{5\pi\pi^0} = (0.051 \pm 0.022)\%$, respectively.

There are no experimental measurements on the decays $\tau^- \to \pi^-4\pi^0\nu_\tau$ and $\tau^- \to \pi^-5\pi^0\nu_\tau$. However, isospin invariance imposes[4] the limits: $B_{\pi 4\pi^0} \leq \frac{3}{4} B_{5\pi} = (0.038 \pm 0.015)\%$ and $B_{\pi 5\pi^0} \leq \frac{9}{7} B_{5\pi\pi^0} = (0.066 \pm 0.028)\%$.

3.6 $\pi\eta$ DECAY

The decay $\tau^- \to \pi^-\eta\nu_\tau$ is of particular interest in the standard model of electroweak interaction. The $\pi\eta$ system has parity

$$P(\pi\eta) = P(\pi)P(\eta)(-1)^J = (-1)(-1)(-1)^J = (-1)^J \quad ,$$

and thus the system has $J^P = 0^+$ or 1^-. However, the G-parity of the system

$$G(\pi\eta) = G(\pi)G(\eta) = (-1)(+1) = -1 \quad ,$$

and thus is opposite to that for a first class current. The decay is strongly suppressed in the standard model. In the isospin limit with equal masses for the light quarks, second class currents vanish altogether. Isospin violations are naturally expected to be of order α, the fine structure constant, so a branching ratio of order 10^{-4} for the decay is possible. Therefore observation of a sizable branching ratio could indicate the existence of second class currents. Of course, it could also indicate G-parity violation in the strong interaction hadronization process after the virtual W decays into quarks, or other non-standard decay mechanism. The simplicity of the decay process, $\tau^- \to \pi^-\eta\nu_\tau \to \pi^-\gamma\gamma\nu_\tau$, provides a clean laboratory for the search[30] for second class currents. This is in sharp contrast to the searches[31] in nuclear β decay and muon capture, which are at small momentum transfer and complicated by nuclear form factors.

Recently, the HRS collaboration reported evidence[32] for the decay (see Fig. 4) with a branching ratio of

$$B_{\pi\eta} = (5.1 \pm 1.0 \pm 1.2)\% \quad . \tag{14}$$

It is rather difficult,[33,34] even in non-standard models, to account for such a large branching ratio of a few percent as reported. Since then, many experiments[19,28,35–39] have searched for the decay and fail to confirm the HRS finding. Limits obtained from the experiments are summarized in Table 1. Figure 5 shows an example of a search by the MARK II collaboration.[39]

The HRS collaboration also searched[36] for the η signal using the decay $\eta \to \pi^+\pi^-\pi^0$ in a subsequent analysis. The experiment searched for an enhancement in the $\pi^+\pi^-$ invariant mass distribution of τ candidates with three charged particles and one or more photons. The low Q^2 of the η decay restricts the invariant mass to be in a relatively narrow range,

$$\begin{array}{ccccc} 280 & < & m_{\pi^+\pi^-} & < & 410 \text{ MeV/c}^2 \\ m_{2\pi} & & & & m_\eta - m_\pi \end{array} \quad .$$

The invariant mass rises slowly from the lower kinematic limit at 280 MeV/c^2 to a peak near 380 MeV/c^2, and then drops steeply to the upper kinematic bound at 410 MeV/c^2. The analysis took advantage of the excellent momentum resolution of the HRS without using the electromagnetic calorimeter information. No enhancement at 380 MeV/c^2 was observed, resulting in an upper limit of 2.3% at the 95% confidence level.

The second-class-current decay should also give rise[33,40] to an SU(3) related decay, $\tau^- \to K^-K^0\nu_\tau$. The TPC collaboration has searched[20] for the decay but to no avail, resulting in an upper limit of $B_{KK^0} < 0.26\%$ at the 95% confidence level. With the assumption of an approximate flavor SU(3) symmetry,[40] the TPC limit corresponds to $B_{\pi\eta} < 5.1 \times B_{KK^0} < 1.3\%$.

In conclusion, there is no evidence for second class currents. It appears that the η signal observed by HRS is a statistical fluctuation.[36]

3.7 $2\pi\eta$ Decay

The decay $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ is allowed in the standard model and is expected to proceed through the $\rho(1600)$ resonance. The branching ratio for the decay can be calculated using the measured cross section for $e^+e^- \to \eta\pi^+\pi^-$ together with the CVC hypothesis. The cross section has been measured by the Neutral Detector collaboration[41] at Novosibirsk and the DM1 collaboration[42] at DCI. The cross section is consistent with zero for center-of-mass energy below 1.35

GeV and has a broad maximum in the 1.5 – 1.6 GeV region, as shown in Fig. 6. The solid line is the result of a fit[41] taking into account $\rho(1600)$. Using the fitted line as an estimate of the cross section, Gilman predicts[43] the branching ratio to be $B_{\pi\eta\pi^0} = 0.15\%$.

It is difficult to measure the branching ratio because of the multiple photons in the final state. As discussed in Sec. 3.4, the MARK II collaboration,[25] using the decay as an example of the multiple-neutral-meson decay modes, obtained $B_{\pi\eta\pi^0} = (4.2 \pm^{0.7}_{1.2} \pm 1.6)\%$ from the fit. This is significantly larger than the theoretical prediction. This, however, is not a meaningful comparison as the decay is used as an example of the multiple-neutral-meson decays and the detector is insensitive to the η signal due to the limited mass resolution and the large combinatorial problem. Note that the results on $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ are relatively insensitive to the assumption.

The HRS search[36] for the η signal using the $\pi^+\pi^-$ invariant mass technique is also valid for $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ because the search is relatively insensitive to the number of π^0's accompanying the η. Therefore the upper limit for the branching ratio is $B_{\pi\eta\pi^0} < 2.3\%$ at the 95% confidence level. The CLEO collaboration used[28] the same technique and set an upper limit of 2.1%.

The CRYSTAL BALL collaboration searched for the decay in both an exclusive[19] and an inclusive analysis.[44] The exclusive analysis searched for an η signal in the four-photon sample. No enhancement was observed as shown in Fig. 2a, resulting in an upper limit of $B_{\pi\eta\pi^0} < 2.5\%$ at the 95% confidence level. The inclusive analysis searched for an η signal in τ candidates with two or more photons. The inclusive sample has somewhat more background , but much larger detection efficiency, and hence a more stringent limit, $B_{\pi\eta\pi^0} < 0.9\%$.

3.8 $3\pi\eta$ DECAY

There are no firm theoretical predictions on the branching ratios for the decays $\tau^- \to \pi^-\eta\pi^+\pi^-\nu_\tau$ and $\tau^- \to \pi^-\eta 2\pi^0\nu_\tau$. However, the two branching ratios are related by isospin invariance: $B_{\pi\eta 2\pi^0} \leq B_{3\pi\eta}$.

The HRS collaboration also used the $\pi^+\pi^-$ invariant mass technique[36] to set an upper limit on $B_{3\pi\eta}$. The experiment searched for $\pi^+\pi^-$ combinations with invariant mass less than 410 MeV/c^2 in the six τ candidates with five charged particles and one or more photons. All the candidates were found to contain at least one valid combination. Attributing all the candidates to the η decay yields the limit $B_{3\pi\eta} < 0.4\%$ at the 95% confidence level. From isospin invariance, therefore, $B_{\pi\eta 2\pi^0} < 0.4\%$.

As in the previous section, the limit on $B_{3\pi\eta}$ also applies for the case where the η is accompanied by π^0's. Note that the *experimental* limit on $B_{\pi\eta 2\pi^0}$ is 2.3% from the HRS collaboration[36] and 2.1% from the CLEO collaboration.[28]

3.9 $\pi 2\eta$ DECAY

There is also no firm theoretical prediction on the branching ratio for $\tau^- \rightarrow \pi^- 2\eta\nu_\tau$. However, there is an experimental limit[36] on the decay from the HRS collaboration using the $\pi^+\pi^-$ invariant mass technique.

The experiment searched in the 5-prong sample for events that contained at least two separate $\pi^+\pi^-$ combinations with invariant mass less than 410 MeV/c^2 and found one event. This results in the upper limit of $B_{\pi 2\eta} < 0.6\%$ at the 95% confidence level. As before, this limit also applies if the η's are accompanied by π^0's.

The CRYSTAL BALL collaboration[19] also searched for $\tau^- \rightarrow \pi^- 2\eta\nu_\tau$, with both η's decaying into $\gamma\gamma$, in the four-photon sample. No η enhancement was observed, resulting in upper limit of $B_{\pi 2\eta} < 1.4\%$ at the 95% confidence level. The null result[44] in the search for an inclusive η signal was also used to place a limit on the decay, $B_{\pi 2\eta} < 2.5\%$. This limit is less stringent because of the larger background.

4. τ NEUTRINO MASS

Previously, the upper limit[45] on the τ neutrino mass was 70 MeV/c^2. The limit was obtained by the ARGUS collaboration from an analysis of the energy spectrum of three-charged-pion decays. The experiment has obtained[46] a new limit from a study of the mass spectrum of five-charged-particle decays. The limit is 35 MeV/c^2 at the 95% confidence level. Future e^+e^- experiments should have the sensitivity to about 10 MeV/c^2 in the τ neutrino mass, before being limited by the error in the τ mass measurement[47] of ± 3.2 MeV/c^2.

5. COMPARISON OF INCLUSIVE AND EXCLUSIVE BRANCHING RATIOS

In this section, we discuss the implications of the new results on the discrepancy in the one-charged-particle decay modes. Table 2 summarizes the experimental measurements and theoretical expectations for the exclusive branching ratios. All measurements are in good agreement with the expectations. The world average inclusive measurements[15] of the one- and three-charged-particle branching ratios are $B_1 = (87.0 \pm 0.3)\%$ and $B_3 = (12.9 \pm 0.3)\%$, respectively.[48] The sum of the two exclusive three-charged-particle branching ratios is in fair agreement with the inclusive measurement. For the one-charged-particle final states, the sum of the exclusive branching ratios is significantly less than the inclusive measurement. Thus, there is still a discrepancy between the measured inclusive one-charged-particle branching ratio and the new sum of exclusive measurements.

One possible explanation for the discrepancy is that the major decay branching ratios should each be a few percent larger than what was measured. The new results on $\tau^- \to \pi^-\pi^0\nu_\tau$ and $\tau^- \to \pi^-2\pi^0\nu_\tau$ do not support the speculation. The results on $\tau^- \to \pi^-\pi^0\nu_\tau$ from MARK III and CRYSTAL BALL (Sec. 3.3) are in good agreement with other measurements and the CVC prediction. The results on $\tau^- \to \pi^-2\pi^0\nu_\tau$ from MARK II, MAC, and CRYSTAL BALL (Sec. 3.4) are consistent with each other and the expectation assuming isospin invariance. The results on $\tau^- \to \pi^-2\pi^0\nu_\tau$ are of particular importance in view of the fact that this is the last major decay mode to be measured with good precision. The CELLO measurement[24] of $B_{\pi 2\pi^0} = (6.0 \pm 3.0 \pm 1.8)\%$ in 1984 could easily resolve the discrepancy given the large error, although it is difficult to understand theoretically why $B_{\pi 2\pi^0}$ is as large as 12 or 13%. These new results rule out this possibility.

On the other hand, the new measurements of τ lifetime indicate that the major decay branching ratios should be a few percent larger. The world average measurement of the lifetime (Sec. 2) is somewhat larger than the prediction based on the world average measurement of the electron branching ratio. The lifetime measurement corresponds to $B_e = (18.9 \pm 0.5)\%$. If the actual values of the major decay branching ratios correspond to this value of B_e, then the actual sum of the exclusive branching ratios would be considerably larger and removes any serious discrepancy between the inclusive and the exclusive measurements. However, it is very difficult to understand why all the major exclusive branching ratios currently measured are significantly below their actual values. But then, there have been times in physics when a quantity was consistently measured slightly wrong because the "follow-the-crowd" effect led experimenters to seek and correct errors in just one direction. In view of the fact that measurement of the lifetime is far more complicated than measurements of the exclusive branching ratios, the lifetime measurements can only be regarded as an indication.

There is a similar indication from a study[49] by the MARK II collaboration. The experiment measured all the exclusive branching ratio by classifying all the τ candidates into one of the known decay modes and found that B_e, B_μ, and B_ρ are larger than the world averages. Unfortunately, due to the large errors in the measurements, the results can only be regarded as an indication.

It is unlikely that the branching ratio for $\tau^- \to \pi^-3\pi^0\nu_\tau$ is large enough to account for the discrepancy. The branching ratio[4] is predicted to be 1%. The experimental "measurements" from MARK II and CRYSTAL BALL (Sec. 3.4) indicate that the branching ratio is not large.

It is also unlikely that the branching ratios for decay modes containing η mesons are large enough to resolve the discrepancy. The largest decay mode is expected to be $\tau^- \to \pi^-\eta\pi^0\nu_\tau$. The branching ratio is predicted[43] to be $B_{\pi\eta\pi^0} = 0.15\%$ by Gilman using the measured cross section for $e^+e^- \to \eta\pi^+\pi^-$.

It is interesting to examine how far we can increase $B_{\pi\eta\pi^0}$ due to possible errors in the measured cross section. Using the dotted line in Fig. 6 to represent the cross section, instead of the solid line which fits the data, yields $B_{\pi\eta\pi^0} = 0.24\%$. This is a generous estimate of the maximum branching ratio. If the dashed line is used, which is significantly above the measured cross section below 1.4 GeV, then $B_{\pi\eta\pi^0} = 0.66\%$. This can be regarded as the absolute maximum. Therefore the theory predicts that $B_{\pi\eta\pi^0}$ is not large enough to account for the discrepancy. This prediction is supported by experimental measurements (Sec. 3.7) — the CRYSTAL BALL collaboration set an upper limit of $B_{\pi\eta\pi^0} < 0.9\%$ at the 95% confidence level.[44]

The limits on other decay modes containing η mesons are also stringent as summarized in Table 2. The experimental limits are inclusive as they are relatively insensitive to the number of π^0's accompanying the η's. There are also rough calculations of branching ratios containing η mesons using Chiral-Effective-Lagrangian methods (or current algebra). The calculations find that the branching ratios are small.[50] In summary, the decay modes containing η mesons are not large enough to account for the discrepancy.

Yet there is a possible experimental solution to the problem although it defies conventional theoretical explanations. Two experiments have measured the inclusive branching ratio with multiple neutral mesons in the final states. The TPC collaboration extracted[51] the branching ratio by measuring the number of τ candidates with one charged particle and three or more photons, with the invariant mass of at least one $\gamma\gamma$ combination consistent with the π^0 mass. The experiment assumed that the τ candidates were dominated by the decays $\tau^- \rightarrow \pi^- 2\pi^0 \nu_\tau$, $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$ and $\tau^- \rightarrow \pi^- \eta \pi^0 \nu_\tau$ and obtained a weighted sum measurement of

$$B_{\pi 2\pi^0} + 1.6 B_{\pi 3\pi^0} + 1.1 B_{\pi\eta\pi^0} = (13.9 \pm 2.0 \pm 1.9)\% \quad .$$

This is somewhat larger than the theoretical prediction of $\sim 8.5\%$. The MARK II collaboration, in the special study[49] discussed earlier, extracted an inclusive branching ratio by measuring the number of τ candidates with two or more energetic photons. Ignoring the decay modes containing η mesons, the experiment found

$$B_{\pi 2\pi^0} + B_{\pi 3\pi^0} = (12.0 \pm 1.4 \pm 2.5)\% \quad .$$

This is also somewhat larger than the theoretical expectation of $\sim 7.7\%$. As discussed in Sec. 3.4, the experiment performed a further analysis[25] to extract the exclusive branching ratios by fitting the observed photon multiplicity spectrum. The fit favored additional multiple-neutral-meson decays other than $\tau^- \rightarrow \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$. Using the decay $\tau^- \rightarrow \pi^- \eta \pi^0 \nu_\tau$ as an example for the multiple-neutral-meson decays, the fit yields

$$B_{2\pi^0} = (6.2 \pm 0.6 \pm 1.2)\%$$

$$B_{3\pi^0} = (0.0 \pm^{1.4}_{0.0} \pm^{1.1}_{0.0})\%$$

$$B_{\pi\eta\pi^0} = (4.2 \pm^{0.7}_{1.2} \pm 1.6)\% \quad .$$

The excessive branching ratio for $B_{\pi\eta\pi^0}$ implies that there are more events with multiple neutral mesons than expected.

There is another indication of an excess from the MAC collaboration.[26] As discussed in Sec. 3.4, the experiment extracted the branching ratio for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ by measuring the number of τ candidates with one charged particle and two energetic photons. The result is

$$B_{\pi 2\pi^0} = (8.7 \pm 0.4 \pm 1.1)\% \quad .$$

This is somewhat larger than the expectation from isospin invariance, $B_{\pi 2\pi^0} = B_{3\pi} = (6.7 \pm 0.4)\%$. As the experiment is very sensitive to feed down from other multiple-neutral-meson decays, the result indicates that there may be an excess of multiple-neutral-meson decays.

Therefore three experiments seem to observe an excess of multiple-neutral-meson decays, although defying conventional explanations, that could at least partially account for the discrepancy. It remains an experimental challenge to see whether we can convincingly establish the existence of an excess and, if it exists, determine which modes comprise it and whether there are any exotic decay modes.

It should be emphasized that not a single experiment sees a significant discrepancy in the one-charged-particle decays, as it is just at the limit of the statistical and systematic errors of one experiment. Combining results from different experiments reinforces the discrepancy, but then there is concern about the "follow-the-crowd" effect. Yet it is still an intriguing puzzle that may require major detective work. Here are some suggestions:

(1) More precise measurements of the exclusive branching ratios and lifetime. This is especially interesting in the light of the shift in the lifetime.

(2) More precise measurement of the branching ratio for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$. This decay mode is important in resolving the discrepancy because this is the largest decay mode with multiple neutral mesons. This large branching ratio also allows a precise test of isospin invariance.

(3) Measurement of the branching ratio for $\tau^- \to \pi^- 3\pi^0 \nu_\tau$. There is *no* measurement yet of this decay; all "measurements" thus far suffer from

very limited statistics. Measurement of a larger than expected branching ratio would be a violation of the CVC hypothesis; this would also explain the apparent excess in the multiple-neutral-meson decays and at least partially account for the discrepancy.

(4) For detectors with limited energy resolution or granularity for electromagnetic shower detection, a precise measurement of the inclusive branching ratio for decay modes with multiple neutral mesons is still of great interest because of the apparent excess.

(5) Observation of the decay $\tau^- \rightarrow \pi^-\eta\pi^0\nu_\tau$. This is difficult if the branching ratio is as small as 0.15% as predicted[43]; improvement in the limit is still useful.

(6) Improved limit for the decay $\tau^- \rightarrow \pi^-\eta 2\pi^0\nu_\tau$. The experimental limit[28] (Sec. 3.8) on this decay is $B_{\pi\eta 2\pi^0} < 2.1\%$ at the 95% confidence level; isospin invariance imposes the limit $B_{\pi\eta 2\pi^0} < 0.4\%$. It is very difficult to improve the experimental limit because the neutral final state of the decay contains at least six photons. The HRS $\pi^+\pi^-$ invariant mass technique offers the best chance for improvement.

(7) Improved limit for the decay $\tau^- \rightarrow \pi^- 2\eta\nu_\tau$. Improved limit for the decay is still useful although the current limit[36] (Sec. 3.9) of $B_{\pi 2\eta} < 0.6\%$ is already quite stringent. Again, the HRS $\pi^+\pi^-$ invariant mass technique offers the best possibility for improvement.

(8) Global analysis of all decay modes in a single experiment. This requires a large data sample to obtain a definitive answer on whether there is a discrepancy, assuming that systematic problems are under control.

(9) Study the properties of the charged particles in the one-charged-particle decays.[13] Look for any deviations from expectations in the momentum distribution, time-of-flight information, and ionization power $(\frac{dE}{dx})$, particularly in events with multiple photons. Investigate whether the charged particles with multiple photons are consistent with being pions and kaons. These studies are of particular importance in view of the apparent excess of multiple-neutral-meson decays.

We can expect new results from SPEAR, CESR and DORIS in the near future. New results on the new data collected last year at the higher energy PETRA are eagerly awaited. Because of the discrepancy, even a 10% measurement of the cross section at the yet higher energy TRISTAN and SLC/LEP is also interesting.

6. CONCLUSION

In 1984, Gilman and Rhie[4] brought the discrepancy in the one-charged-particle decay to the attention of elementary particle physicists. At the DPF meeting at Oregon the following year, all major decay modes were remeasured with much improved precision and the discrepancy was reaffirmed.[13] A year later, at the 1986 Berkeley Conference, decay modes containing η mesons, reported by the HRS and CRYSTAL BALL collaborations, were offered as a possible solution.[52] A few months later, the HRS collaboration presented[32] evidence that the η decays were dominated by the strongly suppressed second-class-current decay $\tau^- \rightarrow \pi^-\eta\nu_\tau$. At this Topical Conference, many experiments reported limits that contradicted the HRS finding, including the CRYSTAL BALL collaboration, which after a more detailed analysis,[19,44] found that there was no evidence for the η. Also reported were stringent limits on other decay modes containing η mesons, including the largest decay mode expected, $\tau^- \rightarrow \pi^-\eta\pi^0\nu_\tau$. These results rule out the η decay modes as a possible solution to the problem. The result on $\tau^- \rightarrow \pi^-\eta\pi^0\nu_\tau$ is also supported by Gilman's calculation[43] which predicts a surprisingly small branching ratio. Also reported at this conference are much improved measurements of another major decay mode, $\tau^- \rightarrow \pi^-2\pi^0\nu_\tau$, by MARK II, MAC and CRYSTAL BALL. The branching ratio is consistent with the isospin invariance expectation and thus excludes this decay mode as a possible solution to the discrepancy. With the new understandings, it becomes difficult to account for the measurements of the somewhat larger than expected inclusive branching ratio for multiple neutral mesons. The apparent excess of multiple-neutral-meson decays, if confirmed, could at least partially account for the discrepancy. Also presented at this conference were new and precise measurements of the τ lifetime. The lifetime is found to be longer than the theoretical prediction. This indicates that all the major decay branching ratios might be each a few percent larger than presently measured. This, although difficult to understand experimentally, could be a potential solution to the discrepancy.

In conclusion, despite the tremendous progress in the last few years, the discrepancy is still unresolved and, if anything, has deepened.

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Table 1. Upper limits on the branching ratio in percent for $\tau^- \rightarrow \pi^-\eta\nu_\tau$.

Limit	Confidence Level (%)	Technique	Experimental Group	Reference
2.5	90	$\eta \rightarrow \gamma\gamma,\ \pi^+\pi^-\pi^0$	MARK III	35
2.3	95	$\eta \rightarrow \pi^+\pi^-(\pi^0)$	HRS	36
1.8	95	$\eta \rightarrow \pi^+\pi^-\pi^0$	CLEO	28
1.7	95	$\eta \rightarrow \gamma\gamma, \pi^+\pi^-\pi^0$	CELLO	37
1.3	95	$\eta \rightarrow \pi^+\pi^-\pi^0$	ARGUS	38
1.0	95	$\eta \rightarrow \gamma\gamma$	MARK II	39
0.3	95	$\eta \rightarrow \gamma\gamma$	CRYSTAL BALL*	19
1.3	95	$\tau^- \rightarrow K^-K^0\nu_\tau$	TPC	20

*Preliminary

Table 2. Experimental measurements and theoretical expectations for the branching ratios.

Decay Mode	Branching Ratio (%)	
	Experimental	Theory
1-prong:		
e	17.7 ± 0.4	17.7
μ	17.7 ± 0.4	17.2
π	10.9 ± 0.6	10.7
K	0.6 ± 0.2	0.7
ρ	22.8 ± 0.9	21.8
K^*	1.6 ± 0.3	1.1
$\pi 2\pi^0$	7.5 ± 0.7	6.7
$\pi 3\pi^0$	"1.0"	1.0
$\pi\eta\pi^0$	<0.9	0.15
$\pi\eta 2\pi^0$	<2.1	<0.4
$\pi 2\eta$	<0.6	
$\pi 4\pi^0 + \pi 5\pi^0$		<0.10
Total	79.8 ± 1.5	
3-prong:		
3π	6.7 ± 0.4	
$3\pi\pi^0$	5.0 ± 0.5	4.9
Total	11.7 ± 0.6	
5-prong:		
$5\pi + 5\pi\pi^0$	0.11 ± 0.03	

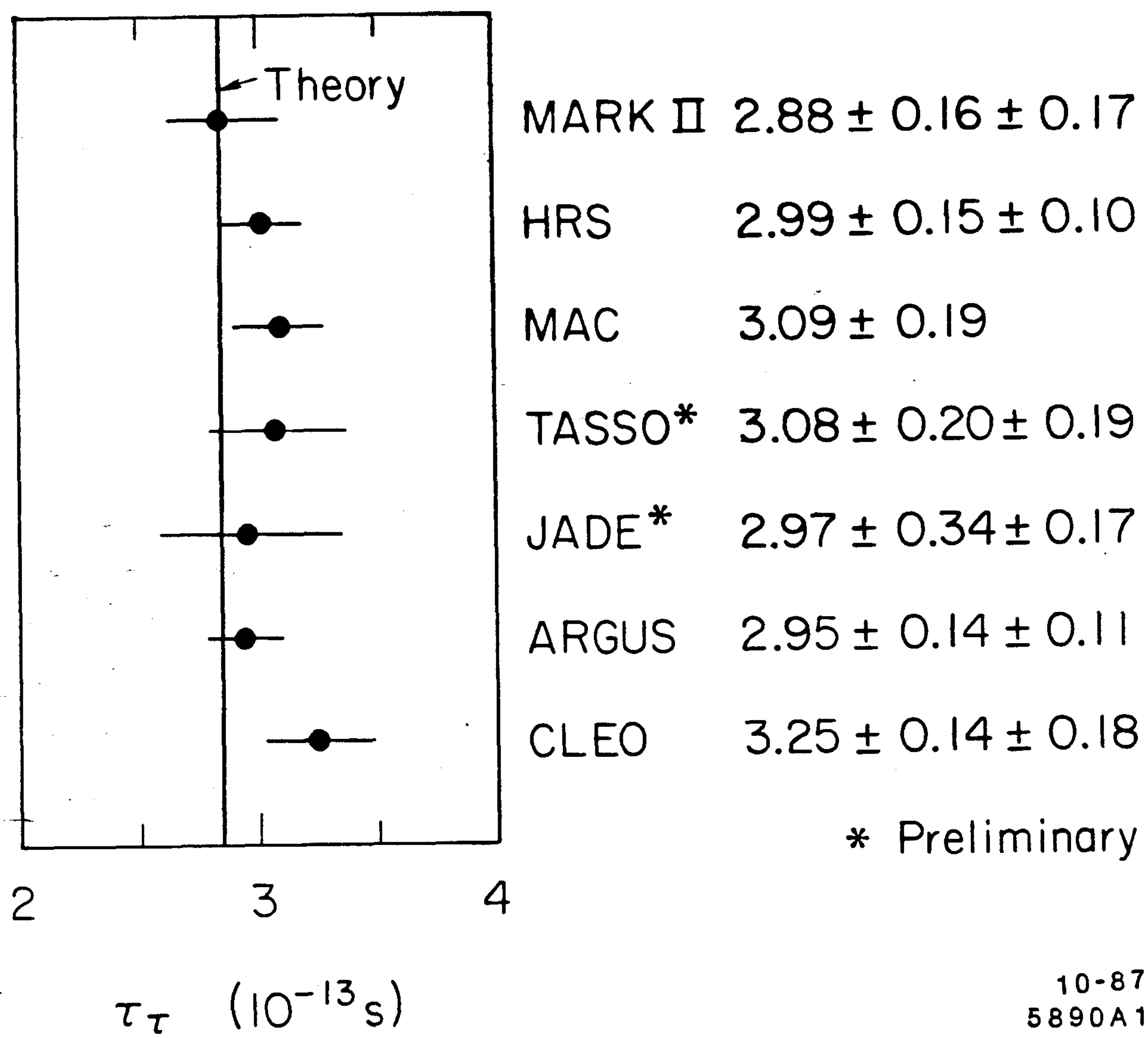

Fig. 1. τ Lifetime Measurements.

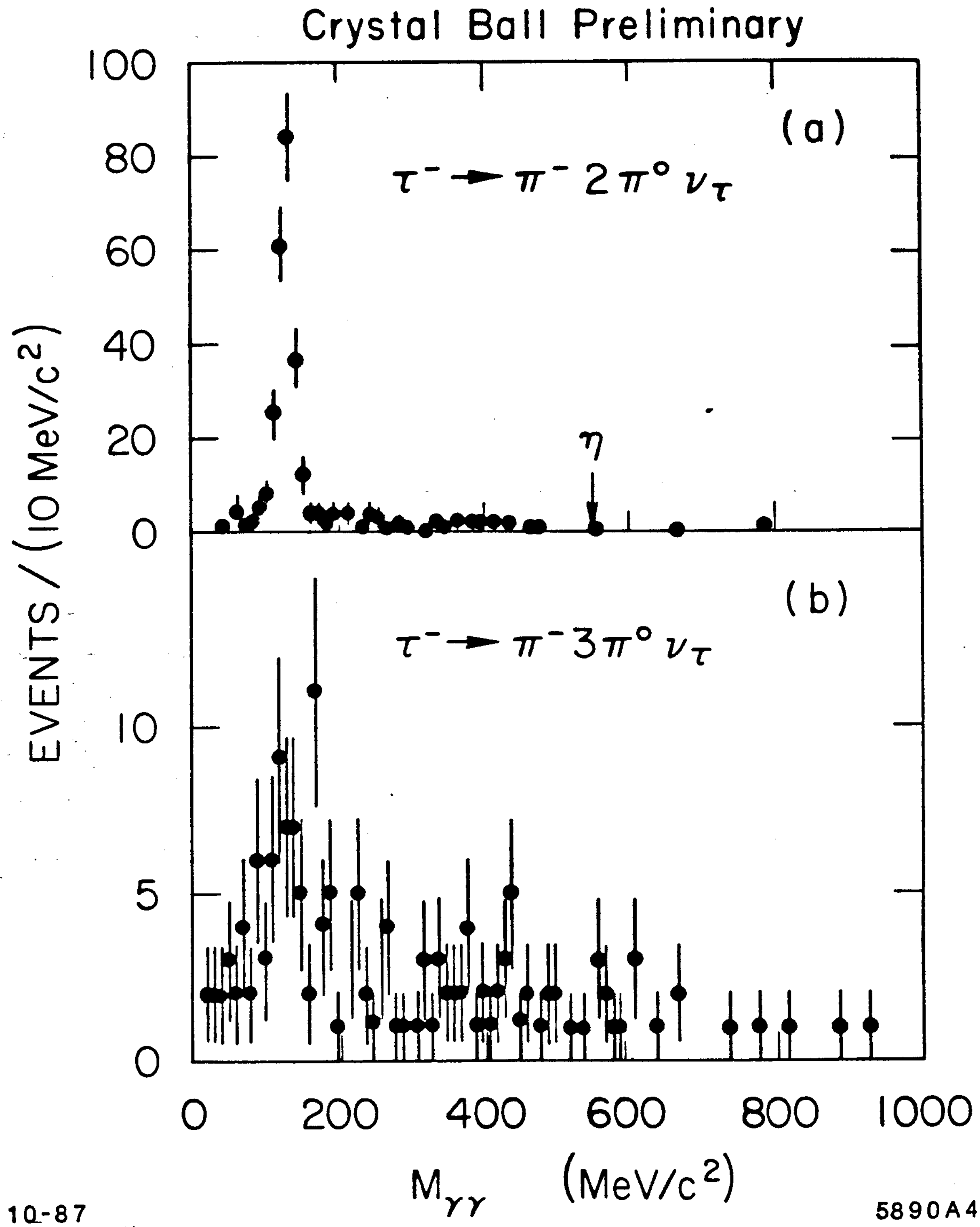

Fig. 2. Invariant mass distribution of the $\gamma\gamma$ pairs that recoiled against (a) another $\gamma\gamma$ pair which has an invariant mass that is consistent with the π^0 mass, (b) two other $\gamma\gamma$ pairs which both have an invariant mass that is consistent with the π^0 mass.

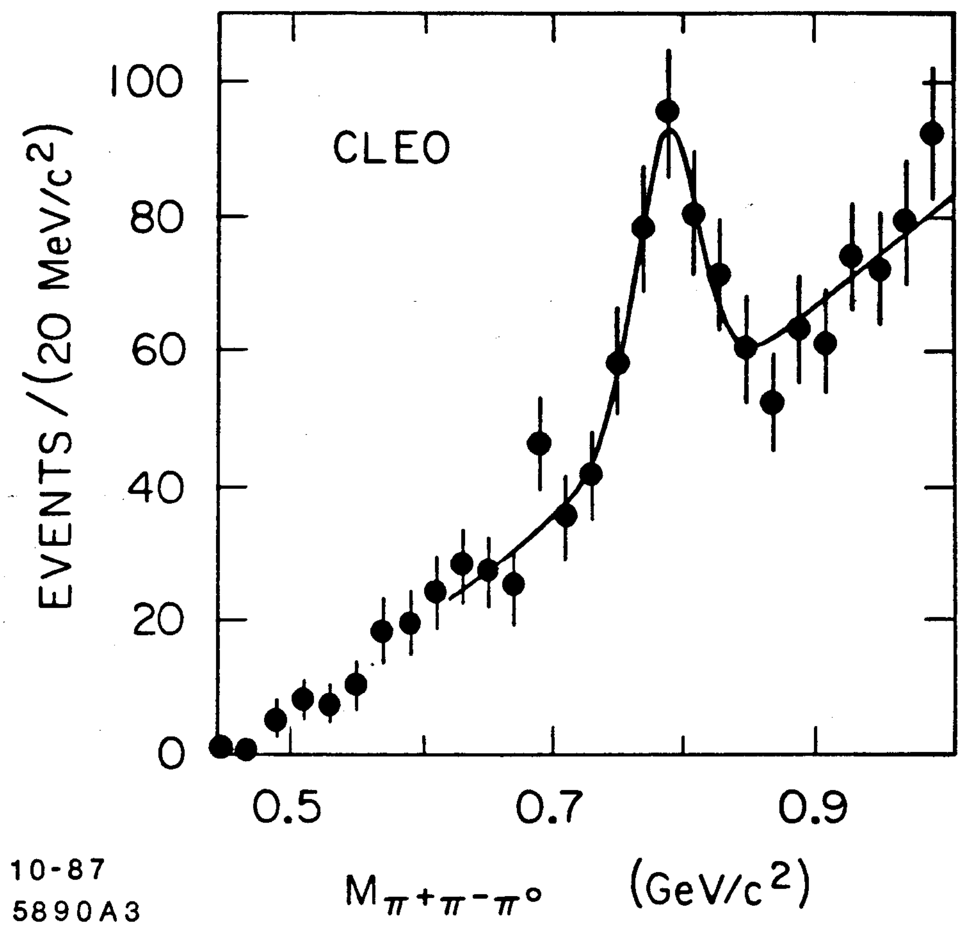

Fig. 3. Invariant mass distribution of $\pi^+\pi^-\pi^0$ combinations in the candidates for the decay $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$. The line is a fit to the distribution.[28]

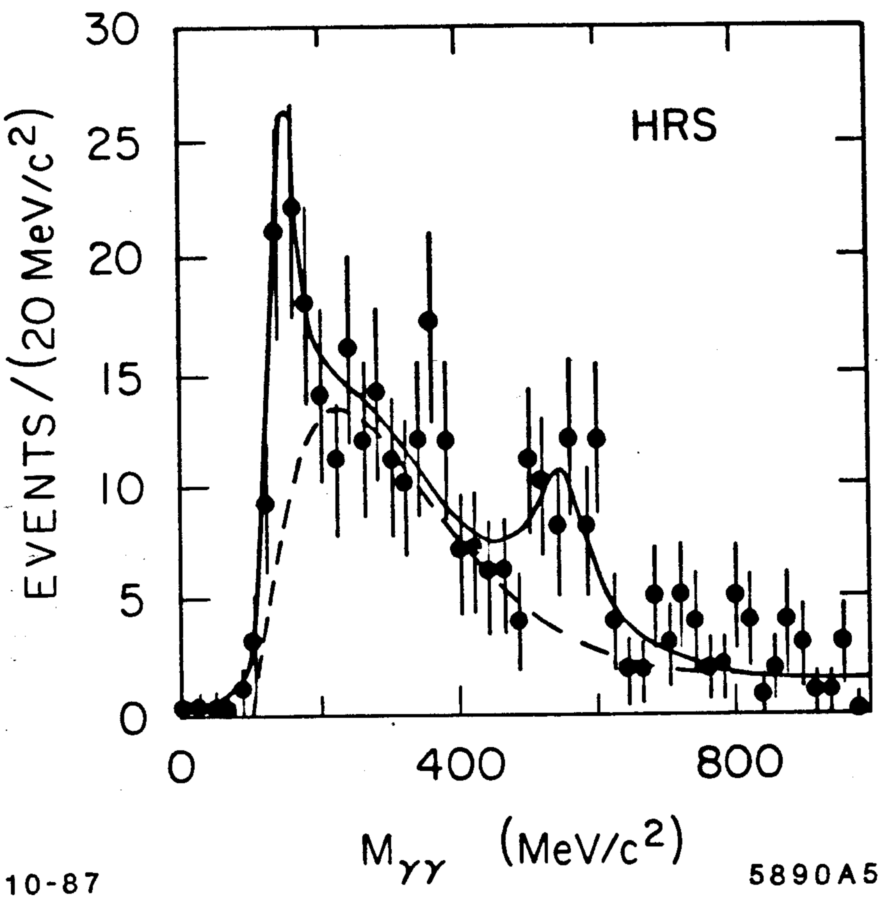

Fig. 4. Invariant mass distribution of $\gamma\gamma$ pairs in τ candidates with one charged particle and two or more photons. The solid line is a fit to the distribution with a background function (dashed line) plus the signal contributions at the π^0 and η masses.

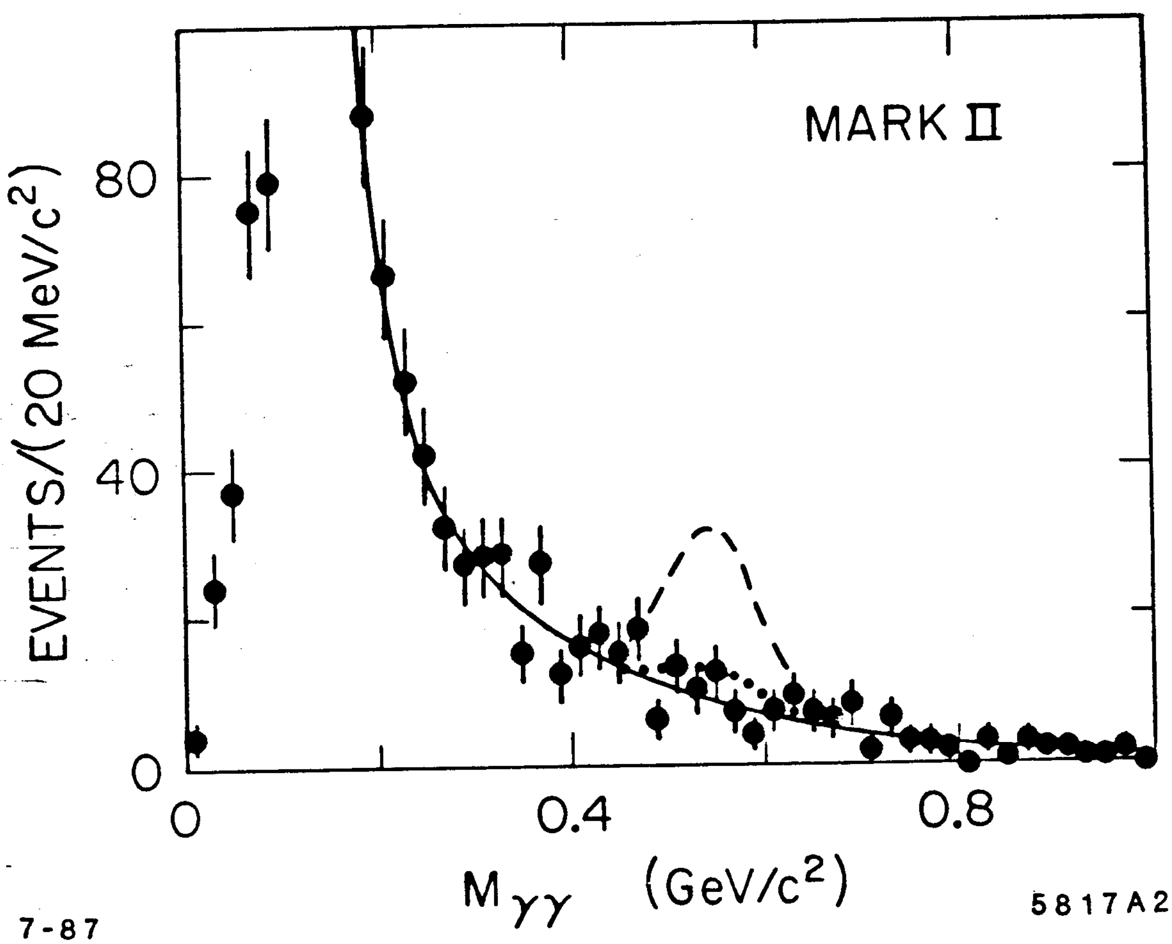

Fig. 5. Invariant mass distribution of $\gamma\gamma$ pairs in τ candidates with one charged particle and two photons. The solid line is the best fit to the data. The dashed line corresponds to the HRS branching ratio of $B_{\eta\pi} = 5.1\%$ and the dotted line corresponds to the upper limit of $B_{\eta\pi} < 1.0\%$.

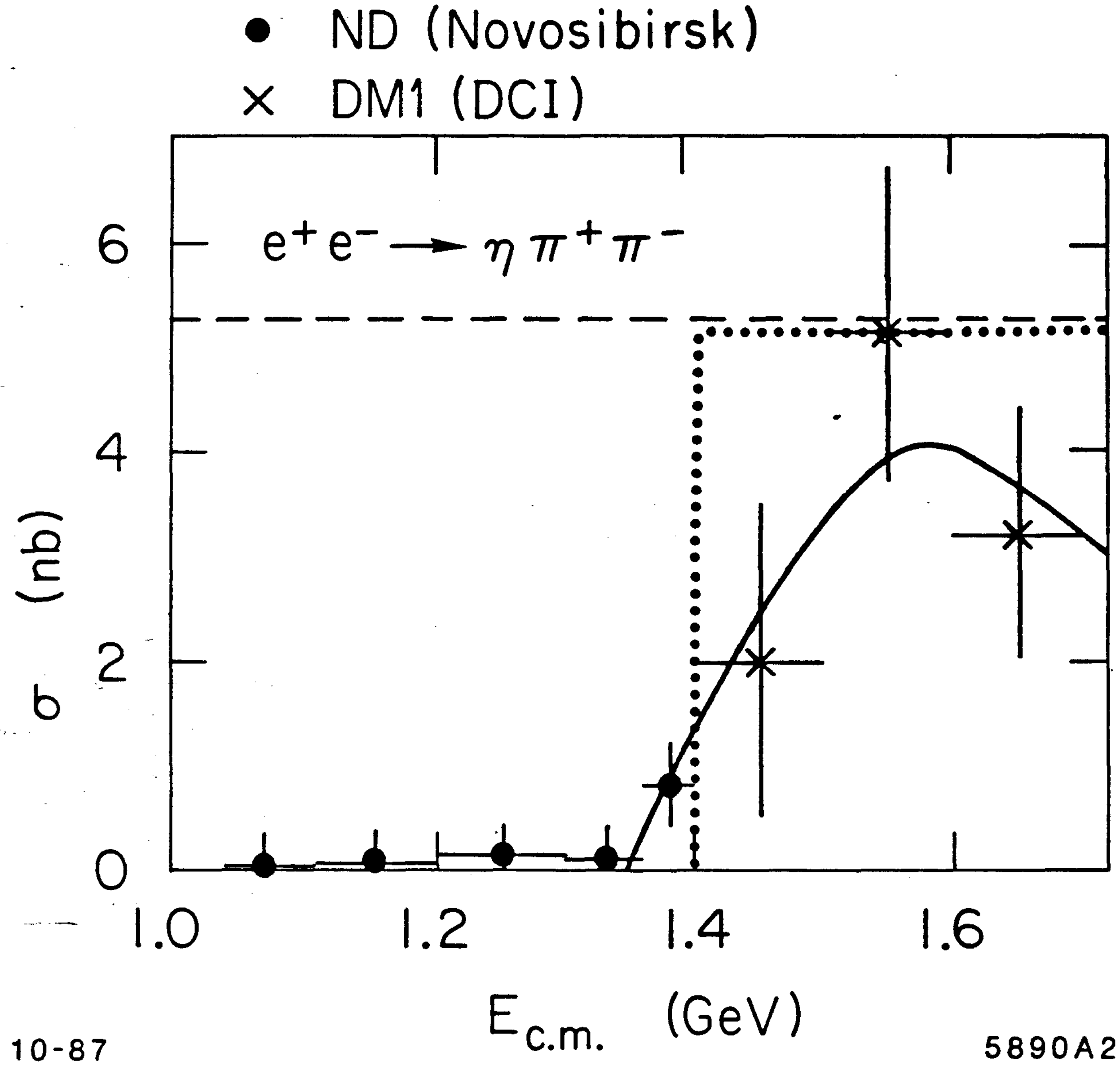

Fig. 6. Measurement of the cross section for $e^+e^- \rightarrow \eta\pi^+\pi^-$. The lines are explained in the text.