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NEW RESULTS ON τ LEPTON FROM CLEO

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ABSTRACT

Several properties of the τ lepton have been measured precisely in e^+e^- annihilation by the CLEO II experiment at the Cornell Electron Storage Ring (CESR). This includes the τ mass and the branching ratios into electron and one charged particle plus multiple π^0's. The implication of these results on the 1-prong decay problem will be discussed.

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* Representing the CLEO II Collaboration

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Abstract

Several properties of the τ lepton have been measured precisely in e^+e^- annihilation by the CLEO II experiment at the Cornell Electron Storage Ring (CESR). This includes the τ mass and the branching ratios into electron and one charged particle plus multiple π^0's. The implication of these results on the 1-prong decay problem will be discussed.

INTRODUCTION

The τ lepton has been the subject of intense investigation in recent years due to the perplexing problem in the decay into one-charged-particle final states[1]. In the comparison of the measured inclusive and the sum of the measured exclusive decay branching ratios, a few percent of the decays are unaccounted for. In addition, there is a discrepancy in the lifetime that may be related to the problem. The measured lifetime is somewhat longer than that expected from the measured leptonic branching ratio assuming lepton universality[2]. Since the lifetime depends on the τ mass to the fifth power, a more precise measurement of the mass may elucidate the problem. With a large data sample and an electromagnetic calorimeter with excellent energy resolution, the CLEO II detector is in an unique position to investigate the problems. In this paper, we present new and precise measurements of the τ mass and the branching ratios into electron and one charged particle plus multiple π^0's.

DETECTOR

The CLEO II detector is a general purpose spectrometer with excellent charged particle and shower energy detection[3]. Charged particles are measured with three cylindrical drift chambers between 5 cm and 95 cm from the e^+e^- interaction point, with a total of 67 layers. This is surrounded by a scintillation time-of-flight system and a CsI(TI) calorimeter with 7800 crystals. These detector systems are installed inside a 1.5 T superconducting solenoidal magnet, surrounded by a proportional tube muon chamber with iron absorbers. The momentum resolution is 1.2% for a 5 GeV charged particle and the energy resolution is 1.5% for a 5 GeV shower.

The data sample was collected around the Υ energy region at the Cornell Electron Storage Ring (CESR). The total integrated luminosity of the data used in the analyses varies from 0.67 to 1.43 fb^{-1}, corresponding to 0.6-1.3×10^6 $\tau^+\tau^-$ produced.

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τ MASS

The τ mass is extracted by measuring the minimum kinematically allowed τ mass in $\tau^+\tau^-$ candidate events. For a given τ mass, the τ direction must lie on a cone around the observed decay product if the energy of the τ is known. In a $\tau^+\tau^-$ event, ignoring initial and final state radiation, the two cones (one inverted) must intersect at two lines. If a smaller tau mass is assumed, the cone angle decreases; eventually, the two cones just touch. This corresponds to the minimum kinematically allowed τ mass.

In order to reconstruct the events, both τ's are required to decay hadronically: one charged particle[4] with up to two π^0's. The π^0's are assigned to the nearest charged particle according to the angle. Events with both τ's decaying into one charged particle with no π^0 are rejected to suppress two-photon background. If one of the charged particles is identified as an electron or muon, it is also rejected. A total of $\sim 29,000$ events passed all cuts.

The minimum mass distribution for the data is shown in Fig. 1. The distribution drops off sharply at the τ mass as expected. The presence of events above the τ mass is mainly due to initial and final state radiation, missed π^0, particle misidentification etc. The mass spectra from the data and Monte Carlo are fitted with an arctangent curve near the edge with a polynomial background. The result of the fit is shown in Fig. 1. Also shown is the fit to a Monte Carlo sample generated with $M_\tau = 1784.1$ MeV/c^2. The shape of the Monte Carlo spectrum is very similar to the data. The result of the fit to the data is $M_\tau = 1776.6 \pm 0.9$ MeV/c^2.

The absolute energy and momentum scales of the detector are calibrated using $K_S \to \pi^+\pi^-$, $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $\Lambda \to p^+\pi^-$, $\psi \to \mu^+\mu^-$, and $\pi^0 \to \gamma\gamma$. These and other major source of systematic errors are summarized in Table 1. Also shown is the effect of a ν_τ of 35 MeV/c^2. Combining these systematic errors in quadrature yields $M_\tau = 1776.6 \pm 0.9 \pm 1.5^{+0.9}_{-0.0}$ MeV/c^2. The result is significantly smaller the world average[2] but consistent with the recent results from BES[5] and ARGUS[6].

Table 1. Systematic errors in M_τ.

	Δ	ΔM_τ(MeV/c^2)
Energy	$\pm 0.30\%$	± 1.2
Momentum	$\pm 0.10\%$	± 0.8
Beam Energy	$\pm 0.03\%$	± 0.1
Cuts and Fit	–	± 0.5
M_{ν_τ}	< 35 MeV/c^2	$+0.9$

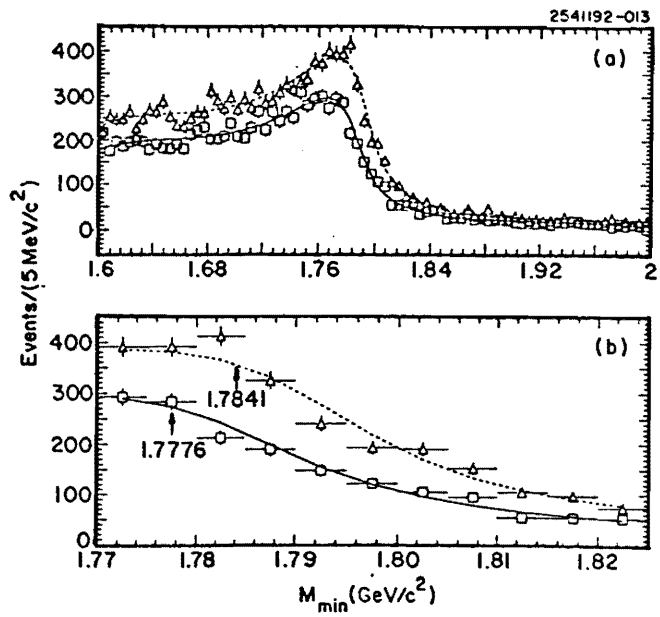

Figure 1. (a) The minimum mass spectra of the data and Monte Carlo (Δ). The lines show the fit discussed in the text. (b) an expanded view of (a).

Electron Branching Ratio

The branching ratio for $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ is measured[7] using e vs. e events,

$$B_e^2 = \frac{N_{ee}}{\epsilon\sigma L} \quad ,$$

where N_{ee} is the number of e vs. e events observed after correcting for the background, ϵ is the detection efficiency, σ is the cross section, and L is luminosity. This measurement has the advantage that the systematic errors on the acceptance, cross section, and luminosity are halved. The analysis takes advantage of the large data set and the hermetic CsI calorimeter and uses stringent selection criteria to suppress Bhabha and two-photon backgrounds. The suppression is achieved by requiring the acoplanarity angle between the two charged tracks to be in the range, $0.15 < \xi < 1.50$. The Bhabha contamination is further eliminated by rejecting any event that contains a photon with energy greater than $\sim$ 500 MeV. The two-photon background is further reduced by requiring the transverse momentum of events to be greater than 22% of the beam energy and the momentum of both tracks must be greater than 10% of the beam energy. The momentum of both tracks and the missing momentum of the events must point into the central region of the detector. The electron candidate is defined as a particle with shower energy to momentum ratio in the range, $0.85 < E/P < 1.10$, and specific ionization no more than two standard deviations below that expected for an electron.

A total of 3970 events satisfies the selection criteria. The detection efficiency includes three components: acceptance, $\epsilon_a = (11.17 \pm 0.07 \pm 0.15)\%$, electron identification efficiency, $\epsilon_e = (95.76 \pm 0.10 \pm 0.32)\%$, and trigger efficiency, $\epsilon_t = (99.00 \pm 0.13 \pm 0.22)\%$, where the first error is statistical and the second systematic. The two latter efficiencies are very high. The major lost of the acceptance is due to the requirement on the transverse momentum of the event and the momentum on the individual track. The systematic error in the acceptance includes two components, a relative $\pm 1.0\%$ uncertainty in detector modeling and a $\pm 0.8\%$ uncertainty for simulation of tau decay. Decay radiation causes a relative efficiency reduction of $\sim$ 10%, mostly due to the softening of the electron momentum spectrum. Both the electron identification and trigger efficiencies have been measured from the data using radiative Bhabhas.

The backgrounds in the events are small and have been calculated using Monte Carlo. The backgrounds from the two-photon processes, $e^+e^-e^+e^-$, and $e^+e^-\tau^+\tau^-$, are estimated to be $f_{eeee} = (0.62 \pm 0.16 \pm 0.31)\%$ and $f_{ee\tau\tau} = (0.38 \pm 0.09 \pm 0.19)\%$. The migration background from other τ decay is $f_{\tau\tau} = (0.63 \pm 0.15 \pm 0.32)\%$. The Bhabha contamination is estimated to be $f_{ee} = (0.0^{+0.3}_{-0.0})\%$.

The luminosity has been measured using two independent processes, $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$, in which the cross sections can be precisely calculated. From a comparison of two luminosity measurements, the error on the average luminosity is estimated to be $\pm 1.5\%$.

After correcting for the detection efficiency and backgrounds, the result on the electron branching ratio is $B_e = (17.49 \pm 0.14 \pm 0.22)\%$. The systematic error also includes the uncertainty in the τ production cross section, estimated to $\sim \pm 1\%$ (relative). The precision of this measurement is comparable with the world average[2] of all other experiments combined but the measured value is somewhat lower than the world average. The branching ratio is significantly lower than the prediction from lepton universality, $B_e = (18.68 \pm 0.37)\%$, based on the current world average of the lifetime[2] and τ mass[8].

The excellent calorimeter also allows for the search for decay radiation. Figure 2 shows the photon energy spectrum observed in the data. The Monte Carlo calculation without the decay radiation severely underestimates the number of photons observed. The spectrum is well reproduced by the Monte Carlo with decay radiation. Decay radiation accounts for $\sim$ 42% of the photons with energy

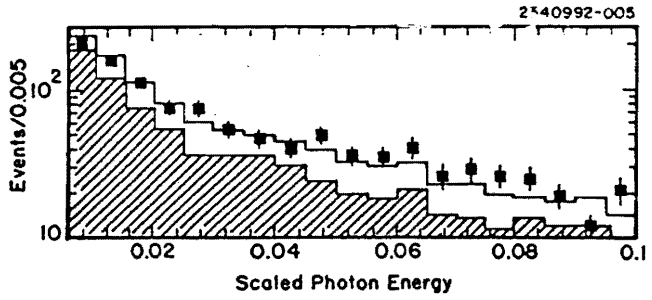

Figure 2. The energy spectrum of the highest energy photon in e vs. e events, normalized to the beam energy. The upper histogram shows the Monte Carlo prediction with decay radiation. The hashed histogram shows the prediction without the radiation.

$>$ 100 MeV. Others sources for the photons are bremsstrahlung ($\sim$ 41%) in the detector material, initial/final state radiation ($\sim$ 15%), and other τ decay background ($\sim$ 2%). The excess of events without decay radiation is $238 \pm 26 \pm 19$. This is the first direct observation of decay radiation in τ decay.

$h^-\pi^0$ Branching Ratio

The branching ratio for $\tau^- \to h^-\pi^0\nu_\tau$ is measured using $h^+\pi^0$ vs. $h^-\pi^0$ events. As in the case of the B_e measurement, many of the systematic errors are halved. Each event is required to be in the central region (barrel) of the detector, $|\cos\theta| < 0.71$. The acolinearity angle of the two charged tracks must be less than 90^0. To suppress two-photon and Bhabha backgrounds, the momentum of each charged track must be greater than 10% of the beam energy and the momentum of at least one track must be less than 85% of the beam energy. The total visible energy of the events must be greater than 40% of the center-of-mass energy and the transverse momentum of the events must be greater than 200 MeV/c.

The π^0 candidates are reconstructed from the photons in the barrel. The invariant mass of each π^0 candidate must be within four standard deviations of the nominal mass, $|S_{\gamma\gamma} = (m_{\gamma\gamma} - m_{\pi^0})/\sigma_{\gamma\gamma}| < 4$. The photon energy is required to be greater than 40 MeV and the π^0 momentum is required to be greater than 10% of the beam energy. Events with unused photons are rejected: barrel photons with energy greater than 100 MeV or endcap photons ($0.71 < |\cos\theta| < 0.95$) with energy greater than 200 MeV.

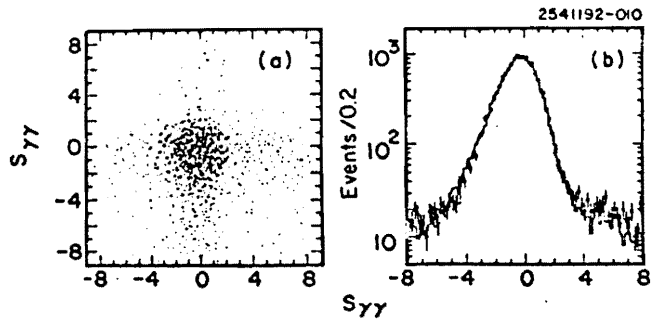

Figure 3. (a) The two-photon invariant mass distribution, in unit of $S_{\gamma\gamma} = (m_{\gamma\gamma} - m_{\pi^0})/\sigma_{\gamma\gamma}$, of one photon pair vs. the other in the data. (b) The two-photon invariant mass distribution for all photon pairs. The histogram shows the Monte Carlo prediction.

A total of 6835 events pass the selection criteria. The two-photon invariant mass distribution, in unit of $S_{\gamma\gamma}$, of the events is shown in Fig. 3. A clear enhancement at $\pi^0 - \pi^0$ mass is observed. The signal is extracted by performing a two-dimensional fit, allowing for $\pi^0\gamma\gamma$ and $\gamma\gamma\gamma\gamma$ backgrounds.

The detection efficiency is estimated to be $\epsilon = (6.92 \pm 0.08)\%$ using Monte Carlo. A small correction has been applied to account for the imperfection in the Monte Carlo simulation. The correction is extracted from the data and includes tracking, trigger, and unused photon veto efficiencies. The systematic error in the detection efficiency has been investigated by comparing kinematic distributions of the data with the Monte Carlo, and by varying the cuts used to select the events. From these studies,

the systematic error is estimated to be ±3% (relative).

The dominant background is the migration background from other τ decays. The major source of the migration background is $\tau^- \to \pi^- 2\pi^0 \nu_\tau$. The Monte Carlo estimates that the total migration background to be $f_{\tau\tau} = (14.0 \pm 0.3 \pm 0.5)\%$. The systematic error is due to the uncertainty in the branching ratios for the migration background. An addition error of ±1.0% is assigned to $f_{\tau\tau}$ to account for the uncertainty in the relative detection efficiencies for the various decay modes. The hadronic background is estimated to be $f_{qq} = (0.25 \pm 0.14)\%$ and the background from $e^+e^- \to e^+e^-\tau^+\tau^-$ is estimated to be $f_{ee\tau\tau} = (0.11 \pm 0.05)\%$.

After correcting for the detection efficiency and background contamination, the result on the branching ratio is $B_{h\pi^0} = (24.83 \pm 0.15 \pm 0.53)\%$. The systematic error includes the relative uncertainty of ±1.5% in the luminosity and ±1.6% in the τ production cross section. The measured branching ratio is consistent with the world average[2], but with better precision. After correcting[2] for $\tau^- \to K^{*-}\nu_\tau \to K^-\pi^0\nu_\tau$, the branching ratio for $\tau^- \to \pi^-\pi^0\nu_\tau$ is $B_{\pi\pi^0} = (24.35 \pm 0.55)\%$. Normalizing to the world average value for B_e (including the CLEO result presented in this paper) yields $B_{\pi\pi^0}/B_e = 1.38 \pm 0.03$. This is in excellent agreement with the prediction from CVC[9], $B_{\pi\pi^0}/B_e = 1.33 \pm 0.07$, after correcting for the new τ mass[8].

$h^- n\pi^0$ Branching Ratios

The branching ratios for $\tau^- \to h^- n\pi^0\nu_\tau$, for $n = 2$, 3, and 4, have been measured by normalizing to the branching ratio for $\tau^- \to h^-\pi^0\nu_\tau$. This has the advantage that many systematic errors cancel in the ratios. The decay candidates are selected using two different tags: the e and μ tags and the 3-prong tag. Since some of the systematic errors associated with the different tags are very different, this allows a powerful cross check of the measurements. The lepton tags have negligible hadronic background in comparison with the 3-prong tag. However, 3-prong tag has a robust trigger due to the higher multiplicity.

The candidates are required to have 1-1 or 1-3 topology. The 1-3 topology is defined by the plane perpendicular to the highest momentum track. The acolinearity angle of the two tracks in 1-1 events must be less than 90^0 in order to suppress two-photon background. The total energy of the events must be greater than $\sim 25\%$ of the beam energy and the total shower energy must be less than $\sim 80\%$ of the beam energy.

The electron tag is identified by comparing the shower energy deposition in the calorimeter with the momentum measured in the drift chambers and from specific ionization in the drift chambers. The minimum electron momentum allowed is 0.5 GeV/c. The muon tag is identified by requiring the track to traverse at least three absorption length of iron. The minimum muon momentum requirement is 1.0 GeV/c. QED backgrounds in the leptonic tags are suppressed by the requiring the net missing momentum to point into the detector and the transverse momentum of the events to be greater than 200 MeV/c. In the 3-prong tag, the invariant mass of all the detected particles in each hemisphere must be less than 1.7 GeV/c^2. The hadronic events are further reduced by the requirement on the missing mass of the events, $0.5 < [(E_{cm} - E_{vis})^2 - P_{vis}^2]^{\frac{1}{2}} < 7.5$ GeV/c^2. There should be no more than two photons in the 3-prong hemisphere. Radiative Bhabha events with converted photons are rejected by allowing no more than one electron in each event.

The π^0 candidates are reconstructed from the photons in the barrel region ($|\cos\theta| < 0.80$) of the calorimeter. The minimum pho-

ton energy allowed is 60 MeV. For the lepton tags, photons within 20^0 of the lepton direction are ignored. In addition, one of the photons in each π^0 candidate must have an energy greater than 80 MeV and the opening angle of the two photons must be less than 135^0. The momentum vector of each π^0 candidate must lie within 90^0 of the charged track. The energy of any unused photon is required to be less than 100 MeV. In order to increase the detection efficiency for $\tau^- \rightarrow h^- 4\pi^0 \nu_\tau$, the minimum photon energy requirement is lowered from 60 to 30 MeV for this decay. For the 3-prong tag, the 1-prong hemisphere is required to contain an even number of photons and events with unused photons are rejected (60 MeV in the barrel and 100 MeV in the endcap, $0.80 < |\cos\theta| < 0.95$).

The $n\pi^0$ candidate is selected based on the combination with lowest reduced chi-square:

$$\chi^2 = \frac{1}{n}\sum_{i=1}^{n} \frac{(m^i_{\gamma\gamma} - m_{\pi^0})^2}{\sigma_i^2} \quad ,$$

where $m^i_{\gamma\gamma}$ is the mass of the ith π^0 candidate. The resolution for the mass, σ_i, is typically between 6 to 8 MeV/c^2. The two-photon invariant mass spectrum for $\tau^- \rightarrow h^- \pi^0 \nu_\tau$ is shown in Fig. 4(a), for the lepton tags. A clear π^0 signal with very little background is observed. A four standard deviation cut on the mass is used to defined the normalization sample. In Fig. 4(b-d), the χ^2 for the other three π^0 multiplicities are shown, also with a lepton tag. An enhancement at zero χ^2 is observed for all three photon multiplicities. The number of events for each tag are summarized in Table 2. The invariant mass spectra of the $\pi^- n\pi^0$ candidates from all tags are shown in Fig. 5. There are few events with mass above the τ mass.

The backgrounds are small and have been calculated using both Monte Carlo and data. The background ($f_{\gamma\gamma}$) from two unrelated photons forming a π^0 candidate is estimated from

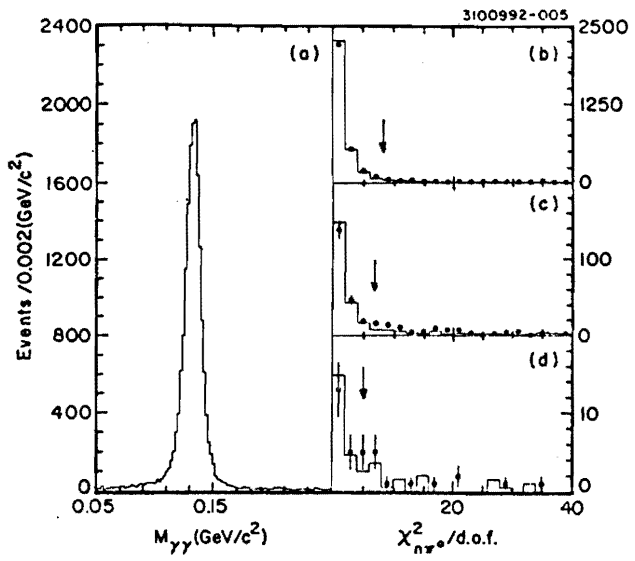

Figure 4. (a) The two-photon mass spectrum of the $1\pi^0$ candidates for lepton tags. (b-d) The χ^2distribution for the 2, 3, and 4 π^0 candidates for lepton tags. The histograms show the Monte Carlo expectations.

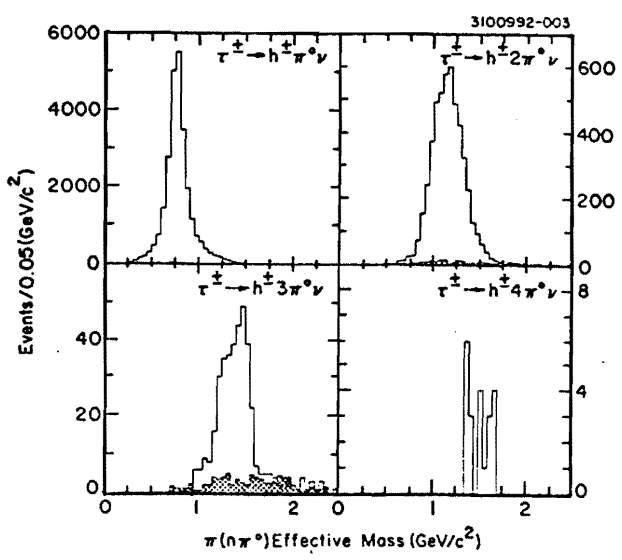

Figure 5. (a) The $\pi^- n\pi^0$ invariant mass spectrum for the 1, 2, 3, and 4 π^0 candidates. The hatched histograms shows the hadronic background expectation. Only the lepton tag is shown in (d).

Table 2. Numbers of events, backgrounds, detection efficiencies, and branching ratios for the $n\pi^0$ candidates in the various tags.

Mode (X)	Tag	Events	Backgrounds (%) $f_{\tau\tau}$	$f_{q\bar{q}}$	f_τ	Relative Eff.(%)	$\frac{B(\tau^- \to X)}{B(\tau^- \to h^-\pi^0\nu_\tau)}$
$h^-\pi^0\nu_\tau$	e	8935	2.2 ± 0.1	< 0.1	4.3 ± 0.1	100	1
	μ	7470	2.3 ± 0.1	< 0.1	4.6 ± 0.2	100	1
	$3h$	8511	2.0 ± 0.1	2.6 ± 0.1	3.4 ± 0.2	100	1
$h^-2\pi^0\nu_\tau$	e	1639	4.1 ± 0.3	< 0.4	3.6 ± 0.2	53.8 ± 0.8	0.336 ± 0.011
	μ	1434	3.7 ± 0.3	< 1.0	4.4 ± 0.3	53.3 ± 0.8	0.356 ± 0.012
	$3h$	1561	2.9 ± 0.2	5.1 ± 0.4	3.0 ± 0.2	51.2 ± 0.7	0.347 ± 0.011
$h^-3\pi^0\nu_\tau$	e	111	11 ± 2	< 6	12.4 ± 1.7	25.4 ± 0.9	0.041 ± 0.004
	μ	100	11 ± 2	< 6	11.4 ± 1.7	27.0 ± 1.0	0.042 ± 0.005
	$3h$	95	14 ± 2	22 ± 3	6.6 ± 1.2	19.5 ± 0.8	0.039 ± 0.007
$h^-4\pi^0\nu_\tau$	e	9	14 ± 6	< 10	5.7 ± 3.2	16.8 ± 1.1	0.005 ± 0.002
	μ	12	15 ± 6	< 10	4.3 ± 2.3	18.9 ± 1.3	0.007 ± 0.003
	$3h$	4	45 ± 27	< 45	6 ± 6	6.3 ± 0.9	$< 0.012(90\%CL)$

the tail of the χ^2 distributions. The hadronic background ($f_{q\bar{q}}$) in the lepton tag is calculated using Monte Carlo and in the 3-prong tag, the background is estimated from the data. The migration background from other π^0 multiplicities is estimated using the Monte Carlo.

The dominant source of systematic error is the $n\pi^0$ finding efficiency. This has been estimated by varying the cuts on photon energy, angle, and multiplicity and by comparing the branching ratios with the results obtained in a semi-inclusive analysis of the energy spectrum of the unused photons. The signal extraction technique is investigated by comparing the results with n-dimensional side-band subtraction technique. The hadronic background estimate is studied using hadronic events of 3-3 topology from the data.

After correcting for the backgrounds and detection efficiencies, the final results are $B_{h2\pi^0}/B_{h\pi^0} = 0.345 \pm 0.006 \pm 0.016$, $B_{h3\pi^0}/B_{h\pi^0} = 0.041 \pm 0.003 \pm 0.005$, and $B_{h4\pi^0}/B_{h\pi^0} = 0.006 \pm 0.002 \pm 0.002$, where the first error is statistical and the second systematic.

Using the world average of $B_{h\pi^0} = (23.8 \pm 0.8)\%$, the absolute branching ratios are

$$B_{h2\pi^0} = (8.21 \pm 0.15 \pm 0.38 \pm 0.28)\%$$
$$B_{h3\pi^0} = (0.98 \pm 0.07 \pm 0.12 \pm 0.03)\%$$
$$B_{h4\pi^0} = (0.15 \pm 0.04 \pm 0.05 \pm 0.01)\%$$

These results are more precise than, but consistent with, the current world averages. The results on $B_{h3\pi^0}$ and $B_{h4\pi^0}$ represent the first measurement of these decays by *exclusive* reconstruction. These two measurements are consistent with the theoretical expectation from CVC and isospin[1].

CONCLUSIONS

In conclusion, the τ mass and the branching ratios into electron and one charged particle plus multiple π^0's have been measured precisely by the CLEO II experiment. The results

are consistent with the world averages and the precision of the branching ratio measurements is comparable or better than the world averages of all other experiments. The measured branching ratios into e and $h\pi^0$ are somewhat lower than the results from ALEPH[11]. However, the measured branching ratios into $h2\pi^0$ and $h3\pi^0$ are significantly below the "quasi-exclusive" branching ratios measured by ALEPH and more consistent with their "exclusive" measurements. The sum of the four measured branching ratios is $\sim$ 51.5%, compared with $\sim$ 55.2% for the ALEPH's "quasi-exclusive" results and $\sim$ 54.8% for the "exclusive" results. Our measured precise sum is $\sim$ 4% below ALEPH which observed no 1-prong problem. This difference is significant in comparison with the $\sim$ 5-7% "missing 1-prong". This difference needs to be satisfactory resolved if we think we understand the τ lepton.

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