NEW RESULTS FROM CLEO-II ON HADRONIC DECAYS OF THE TAU LEPTON

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ABSTRACT

Results on semi-hadronic decays of the τ lepton are presented, from studies of e^+e^- annihilation data obtained at the Cornell Electron Storage Ring with the CLEO-II detector. Branching fractions have been measured for decays to two, three and four hadrons, namely $\tau^- \to \nu_\tau h^- \pi^0$, $\tau^- \to \nu_\tau h^- h^+ h^-$, and $\tau^- \to \nu_\tau h^- h^+ h^- \pi^0$, where $h^\pm$ represents a charged pion or kaon. CLEO-II has also observed decays with charged and/or neutral kaons; preliminary results for branching ratios and structure arising from the decay dynamics are given. Connections are made with predictions derived from theoretical models, the Conserved Vector Current theorem, isospin constraints and sum rules.

1. Introduction

Semi-hadronic decays of the τ lepton provide a unique opportunity to explore the hadronic charged weak current. The leptonic current is well-understood in electroweak theory, and the τ is the only lepton which can decay semi-hadronically. Thus, one can probe the weak and strong dynamics governing the formation of hadronic final states.

A cartoon of semi-hadronic τ decay is shown in Figure 1. The values of q^2 carried by the W are small, so the strong physics is non-perturbative, dominated by resonance formation, and gives rise to final states consisting of light pseudoscalar mesons.

Spin, parity, isospin and charge conjugation symmetries constrain the hadronic states which can form.[1] The spin and parity quantum numbers of a given state select out either the vector or axial vector part of the weak V–A current. Isospin and charge conjugation for Cabibbo-favored ($\bar{u}d$) currents require that vector states produced be G-parity even and axial vector states be G-parity odd, and further restrict them to decay to even and odd numbers of pions respectively. While there is little other theoretical input regarding τ decays to axial vector states, production of non-strange vector states can be related to low energy e^+e^- cross-sections by way of the Conserved Vector Current (CVC) theorem. Also sum-rules can be invoked to relate the vector and axial-vector (or strange and non-strange) hadronic spectral functions (of q^2) which describe the resonant content of the hadronic system.

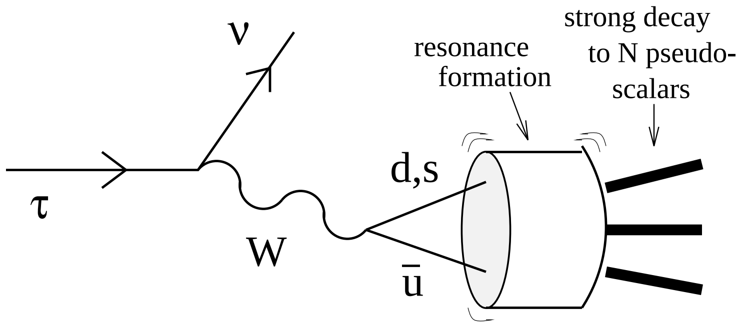

Fig. 1. Simplified picture of semi-hadronic τ lepton decay.

The present experimental situation is somewhat murky however. Only a few τ decays have been studied with sufficient precision to test the elements of the hadronic weak and strong physics described above. Inconsistencies are present, both in regard to the overall picture of τ decay and within the data for several specific decays. Below, I present results from CLEO-II on semi-hadronic τ decay branching fractions. Comments on resonant structure are made where appropriate. This talk is organized as follows: A brief description of the CLEO-II detector is given in Section 2. In Section 3, results are given for decays containing from 2 to 5 hadrons. Results on decays containing one or two kaons are discussed in Section 4.

2. The CLEO-II Detector

CLEO-II[2] is a solenoidal spectrometer and calorimeter operating at the south interaction region of the Cornell Electron Storage Ring (CESR), where τ leptons are produced in pairs through e^+e^- annihilation at $\sqrt{s} \sim 10.6$ GeV, with a ~ 0.91 nb cross section. Since the turn-on of CLEO-II in late 1989, CESR has delivered in excess of 4 fb^{-1} of integrated luminosity, corresponding to ~ 3.6 million τ-pairs. The components of CLEO-II most relevant to the analyses presented here are the 67-layer tracking system and the 7800-element CsI(Tl) crystal calorimeter which are contained within a 1.5T magnetic field, and cover $> 96\%$ of 4π in solid angle. The segmentation and energy resolution of the calorimeter permit reconstruction of $\pi^0 \to \gamma\gamma$ decays with high efficiency for π^0's of all energies: typical π^0 mass resolutions range from 5 to 7 MeV/c^2, and we have observed τ decays containing as many as four fully reconstructed π^0's.[5] Muons above ~ 1 GeV/c are tracked in Iarocci tubes deployed at three depths in the flux return steel. Limited π/K separation is achieved below 1 GeV/c and above 2 GeV/c using dE/dx information from the 51-layer main drift chamber and/or time of flight measurements from scintillation counters located in front of the calorimeter.

3. Decays to Two, Three, Four and Five Hadrons

CLEO-II has directed much effort to precisely measure branching fractions for decays to charged hadrons with and without accompanying π^0's. This focus was motivated by the persistence of the one-prong deficit.[3,4] Earlier work includes studies of τ decays to one charged hadron plus two or more π^0's[5] as well as decays containing η

mesons.[6] We observed for the first time the decay $\tau^- \rightarrow \nu_\tau 2\pi^-\pi^+2\pi^0$,[7] finding a surprisingly large branching fraction ($0.48 \pm 0.04 \pm 0.04\%$). Below I present results for the decays $\tau^- \rightarrow \nu_\tau h^-\pi^0$, $\tau^- \rightarrow \nu_\tau 2h^-h^+[\pi^0]$ and $\tau^- \rightarrow \nu_\tau 3h^-2h^+[\pi^0]$. In these analyses, $h^\pm$ represents a charged hadron (π or K) which we do not attempt to identify.

3.1. The Decay $\tau^- \rightarrow \nu_\tau h^-\pi^0$

The primary semi-hadronic τ decay, $\tau^- \rightarrow \nu_\tau \pi^-\pi^0$, occurs through the vector portion of the hadronic charged weak current. The $\rho(770)$ meson dominates the spectral function responsible for this decay, but contributions from excited ρ's and non-resonant $\pi^-\pi^0$ formation may also be present.

The CVC theorem allows one to relate the $\tau^- \rightarrow \nu_\tau \pi^-\pi^0$ decay width to the iso-vector contribution to the $e^+e^- \rightarrow \pi^+\pi^-$ cross section. A branching fraction of $24.58 \pm 0.93 \pm 0.27 \pm 0.50\%$ is predicted,[8,9] where the errors are from uncertainties in the e^+e^- data, τ lifetime, and knowledge of the radiative corrections. Experimental values range from 22% to 26%,[4] limited in precision by difficulties in π^0-finding and rejection of decays with multiple neutrals (themselves poorly measured until recently).

We have studied the decay $\tau^- \rightarrow \nu_\tau h^-\pi^0$,[10] $h^- \equiv \pi^-, K^-$, using a 1.58 fb^{-1} data sample (1.44×10^6 τ-pairs). We employ three statistically independent methods, determining the branching fraction, $B_{h\pi^0}$, according the following forms:

$$B_{h\pi^0} = \sqrt{\frac{N_{e-h\pi^0} N_{\mu-h\pi^0}}{2N_{e-\mu}N_{\tau\tau}}}, \quad \sqrt{\frac{N_{h\pi^0-h\pi^0}}{N_{\tau\tau}}}, \quad \text{or} \quad \frac{N_{3h-h\pi^0}}{N_{3h-1}}\, B_1. \qquad (1)$$

The N's denote the measured background-subtracted, efficiency-corrected event yields for the given final states (e denotes $\nu e\bar{\nu}$, *etc.*). $N_{\tau\tau}$ is the number of τ-pairs, as determined from the integrated luminosity (known to 1% from studies of Bhabha scattering, $e^+e^- \rightarrow \gamma\gamma$, and $e^+e^- \rightarrow \mu^+\mu^-$), and the theoretical cross-section (also known to 1%). B_1 is the world average topological one-prong branching fraction.

Due to space constraints, we merely give the results below, and refer the reader elsewhere[10] for experimental details. The three methods agree; combining them we find:

$$B_{h\pi^0} = 25.87 \pm 0.12\,(\text{stat.}) \pm 0.42\,(\text{syst.})\,\%, \qquad (2)$$

based on samples totalling $\sim 44,000$ reconstructed $\tau^- \rightarrow \nu_\tau h^-\pi^0$ decays. The dominant systematic errors (common to all three methods) are those due to π^0-finding efficiency (0.9%) and the veto on events with additional energy deposition in the calorimeter applied to reject backgrounds (0.9%).

This result is higher than most other measurements,[4] but is consistent with recent values obtained at LEP by OPAL,[11] L3,[12] and Aleph[13] which also tend to be high. Subtracting the measured contribution from $\tau^- \rightarrow \nu_\tau K^-\pi^0$,[14] we find $B_{\pi^\pm\pi^0} = 25.36 \pm 0.44\%$, in good agreement with the CVC prediction.

3.2. The Decays $\tau^- \rightarrow \nu_\tau h^-h^+h^-[\pi^0]$

As with the decay described above, our understanding of τ decay into final states with three charged particles has been confused by conflicting experimental data.[4] The CLEO-II observation of decays containing two π^0's with a branching fraction around

0.5%[7] has implications for 3-prong results from other experiments. Below, I present preliminary results from CLEO-II on branching fractions for the decays $\tau^- \to \nu_\tau h^- h^+ h^-$ and $\tau^- \to \nu_\tau h^- h^+ h^- \pi^0$.

The decay $\tau^- \to \nu_\tau h^- h^+ h^-$ is expected to occur through the axial-vector current. Hence theoretical constraints are limited. The hadronic system is expected to be dominated by the $a_1(1260)$, which gives rise to both $\pi^-\pi^+\pi^-$ and $\pi^-\pi^0\pi^0$ final states. However channels with charged kaons are also known to contribute.

Because the decay $\tau^- \to \nu_\tau h^- h^+ h^- \pi^0$ has an even number of final state mesons, the vector current is expected to play the primary role. Due to severe Cabibbo and phase-space suppression for modes containing kaons, the four-pion final state is expected to dominate. Thus, predictions can be made from $e^+e^- \to 4\pi$ data through application of the CVC theorem. Two such calculations give the branching fraction to be $4.3 \pm 0.3\%$[15] and $4.8 \pm 0.7\%$.[16] Experimental results cluster around the 5% level.

At CLEO-II, branching fractions are obtained from analyses of the following event types: $3h^\pm$–$3h^\pm$, ℓ–$3h^\pm$ and ℓ–$3h^\pm\pi^0$, where ℓ represents an electron or muon.[17] The branching fractions are determined from measured quantities as follows:

$$B_{3h^\pm} = \sqrt{\frac{N_{3h^\pm-3h^\pm}}{N_{\tau\tau}}} \quad \text{or} \quad \frac{N_{\ell-3h^\pm}}{N_{\tau\tau}B_\ell}, \qquad B_{3h^\pm\pi^0} = \frac{N_{\ell-3h^\pm\pi^0}}{N_{\tau\tau}B_\ell}, \tag{3}$$

where as before the N's represent background-subtracted, efficiency-corrected event yields, $N_{\tau\tau}$ is the number of produced tau-pairs (1.44×10^6), and B_ℓ represents the leptonic branching fraction. The much smaller $3h^\pm$–$3h^\pm$ sample (2,030 events as opposed to 17,479 in the ℓ–$3h^\pm$ sample) gives a nearly comparable statistical error because of the square root. Also systematic errors associated with event-related efficiencies are smaller by a factor of 2 than in the ℓ–$3h^\pm$ analysis.

In Figure 2(a,b), we plot the invariant mass spectra for the hadronic system in the $\tau \to \nu_\tau h^- h^+ h^-$ event samples, taking the pion mass for the hadrons. These samples are relatively background-free as demonstrated by the scarcity of events with $M_{3h} > M_\tau$: non-τ backgrounds are estimated to comprise $4.7 \pm 0.9\%$ in the $3h^\pm$–$3h^\pm$ sample and only $0.2 \pm 0.2\%$ in the ℓ–$3h^\pm$ sample. In Figure 2(c), the presence of π^0's is demonstrated in events containing two energy clusters unassociated with the charged tracks.

The combined results obtained from these event samples are:

$$B_{3h^\pm} = 9.82 \pm 0.09\,(\text{stat.}) \pm 0.34\,(\text{syst.})\,\% \tag{4}$$

$$B_{3h^\pm\pi^0} = 4.25 \pm 0.09\,(\text{stat.}) \pm 0.26\,(\text{syst.})\,\%. \tag{5}$$

While the statistical errors are significantly smaller than those previously attained, the systematic errors are comparable to or slightly worse than recent reports from LEP.[20] Uncertainties in modelling track-finding efficiency (2–2.5%), in effects of cuts on unaccounted-for energy deposition applied to suppress backgrounds (3–4%), and in the π^0-reconstruction efficiency for $3h^\pm\pi^0$ events (3%) dominate the systematic errors. These errors are preliminary, and they should shrink after further study.

The $\tau^- \to \nu_\tau h^- h^+ h^-$ result is significantly higher than the PDG '94 average value of $8.0 \pm 0.4\%$,[4] supporting the recent preliminary value reported by Aleph ($9.57 \pm 0.24 \pm 0.22\%$). After correcting for modes containing kaons, CLEO-II results in both channels[5,10] indicate $B_{3\pi^\pm} \approx B_{\pi^\pm 2\pi^0}$, as expected.

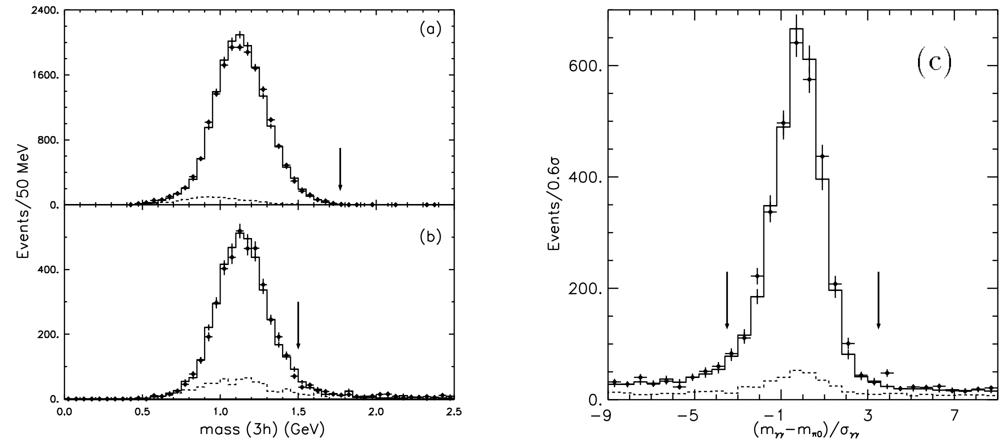

Fig. 2. Invariant mass spectra for $\tau^- \to \nu_\tau h^- h^+ h^-$ decays, taking $M_h = M_\pi$, for lepton-tagged events (a) and $3h^\pm$–$3h^\pm$ (b) event samples. In (c) is shown the quantity $(M_{\gamma\gamma} - M_{\pi^0})/\sigma_{M_{\gamma\gamma}}$ for events in the lepton tagged $\tau^- \to \nu_\tau h^- h^+ h^- \pi^0$ candidate sample. The data (points) are shown along with the expectations for signal plus background from the Monte Carlo[18,19] (solid histogram). Also shown are the expected contributions from backgrounds (dashed histogram). Arrows indicate the location of cuts.

Correspondingly, the $\tau^- \to \nu_\tau h^- h^+ h^- \pi^0$ result is somewhat lower than previous results, although still agreeing with the CVC predictions noted earlier. Summing the two results along with the result for $B_{3h^\pm 2\pi^0}$[7] and accounting for common errors, we obtain a total 3-prong τ branching fraction of $14.55 \pm 0.13 \pm 0.59\%$. This is consistent with the PDG average value of $14.32 \pm 0.27\%$[4] for the topological branching fraction.

3.3. Five-Prong Tau Decays

CLEO-II has measured branching fractions for decays into final states with five charged particles.[21] The results are

$$B(\tau^- \to \nu_\tau 3\pi^- 2\pi^+ + \geq 0\,\text{neutrals}) = 0.097 \pm 0.005 \pm 0.011\,\% \tag{6}$$
$$B(\tau^- \to \nu_\tau 3\pi^- 2\pi^+) = 0.077 \pm 0.005 \pm 0.009\,\% \tag{7}$$
$$B(\tau^- \to \nu_\tau 3\pi^- 2\pi^+ \pi^0) = 0.019 \pm 0.004 \pm 0.004\,\%, \tag{8}$$

the most precise to date.

4. Decays to Final States Containing Kaons

The production of final states containing kaons represents a largely unexplored sector of τ lepton decay. In the following sections, I present results[14,23] from CLEO-II on decays with one, two, or three final state mesons of which at least one is a kaon.

4.1. The Decay $\tau^- \to \nu_\tau K^-$

The decay $\tau^- \to \nu_\tau K^-$ is completely specified in electroweak theory through analogy with kaon decay. The branching ratio, accounting for radiative effects, is predicted to be $0.74 \pm 0.01\%$.[9] CLEO-II has measured it to be $0.66 \pm 0.07 \pm 0.09\%$.[14]

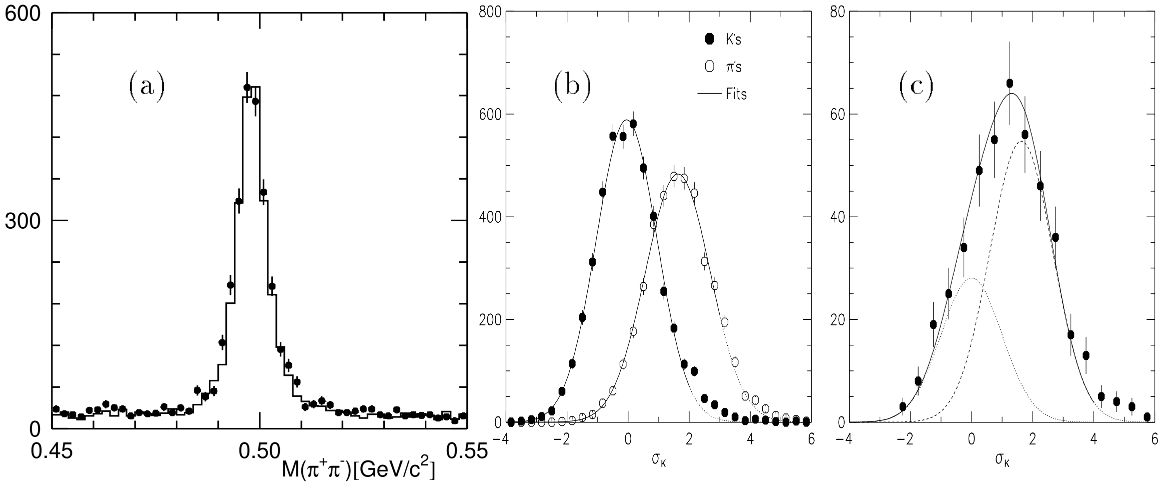

Fig. 3. (a) Invariant mass of $\pi^+\pi^-$ pairs forming detached vertices in the $\tau^- \to \nu_\tau h^- K^0_S$ candidate data (points) and Monte Carlo (histogram) samples. (b) Plots of σ_K (see text) for π's and K's with momenta above 2 GeV/c, identified from kinematics in $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$ decays. (c) Plot of σ_K for the charged hadron accompanying the K^0_S in $\tau^- \to \nu_\tau h^- K^0_S$, where $p_h > 2$ GeV/c, fit to a sum (solid curve) of Gaussians parameterizing the dE/dx response to pions (dashed) and kaons (dotted) taken from the D^* data shown in (b).

4.2. Decays of the Type $\tau^- \to \nu_\tau [Kh]^-$

Like the decay $\tau^- \to \nu_\tau \pi^- \pi^0$, decays of the type $\tau^- \to \nu_\tau [Kh]^-$ are expected to occur through the vector part of the weak current. The K^-K^0 final state has zero net strangeness, and CVC predictions based on $e^+e^- \to \pi^+\pi^-$ data and SU(3) symmetry give branching fractions of $0.11 \pm 0.03\%$[15] and 0.16 ± 0.02.[16] A recent analysis by Aleph[22] gives $B_{K^-K^0} = 0.29 \pm 0.12 \pm 0.03\%$. The $K^-\pi^0$ and $\pi^-\bar{K}^0$ final states are expected to appear in the ratio 1 : 2 from isospin, with a spectral function dominated by the $K^*(892)$ resonance. In this case, the Das-Mathur-Okubo (DMO) sum rule[24] allows one to predict $B_{[\pi K]^-}$ from the measured value of $B_{\pi^-\pi^0}$ discussed earlier.

At CLEO-II, all three final states (K^-K^0, $K^-\pi^0$ and $\pi^-\bar{K}^0$) have been observed, using dE/dX (and time-of-flight for $K^-\pi^0$) for charged kaon identification, and detection of $K^0_S \to \pi^+\pi^-$ decay for neutral kaons. The $K^-\pi^0$ decay branching fraction has been measured with limited statistics to be $0.51 \pm 0.10 \pm 0.07\%$, in the analysis[14] described in the previous section. A higher-statistics study of the $\pi^-\bar{K}^0$ decay based on 2.96 fb^{-1} of data (2.71×10^6 τ-pairs) is described below, in which the K^-K^0 decay is also extracted.

We select events of a 1–3 charged-track topology in which two oppositely charged tracks of the '3' form a vertex separated from the e^+e^- interaction point by at least 5 mm. In Figure 3(a), the presence of $K^0_S \to \pi^+\pi^-$ decays is demonstrated by plotting the invariant mass of the detached tracks as pions. After background subtraction, we have $1,938 \pm 126$ candidates for the decay $\tau^- \to \nu_\tau h^- K^0_S$.

For momenta above 2 GeV/c, dE/dx gives $\sim 2\sigma$ π/K separation, as shown in 3(b) for kinematically selected π's and K's from $D^0 \to K^-\pi^+$ data. Selecting $\tau^- \to \nu_\tau h^- K^0_S$

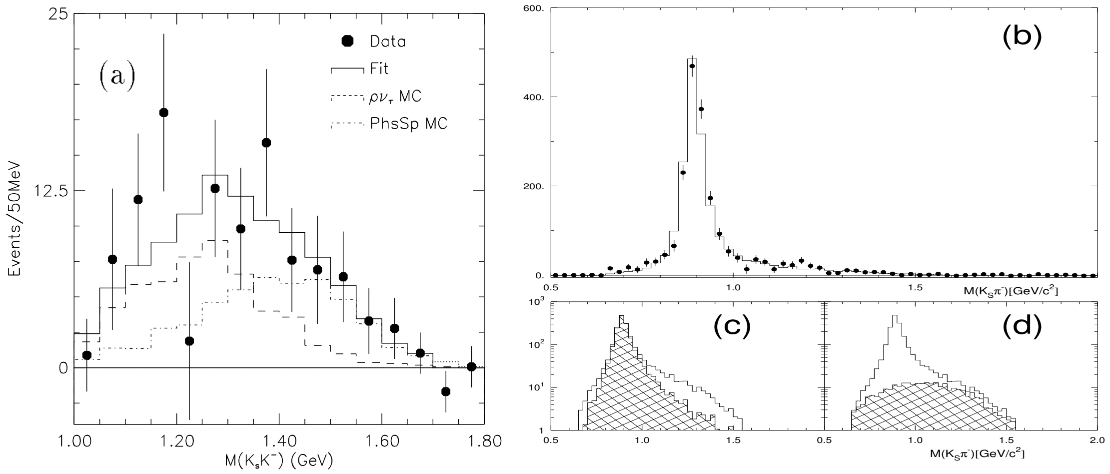

Fig. 4. (a) Invariant mass of $K^-K^0_S$ system for $\tau^-\to\nu_\tau K^-K^0_S$ candidate events in the data (points), along with a fit (solid histogram) to ρ^- (dashed) and phase space (dotted) contributions as determined through Monte Carlo simulation. (b) Plot of $M_{\pi-K^0}$ for $\tau^-\to\nu_\tau h^-K^0_S$ candidates in the data (points), along with a sum (solid histogram) of distributions obtained from $\tau^-\to\nu_\tau K^{*-}(892)$ and $\tau^-\to\nu_\tau K^-K^0_S$ Monte Carlo samples (shown separately in (c) and (d), respectively), where the latter is determined according to the mixture of ρ and phase-space constributions shown in (a).

events with $p_h > 2$ GeV/c, we plot in Figure 3(c) the difference between the measured dE/dx and that expected for kaons, divided by experimental resolution, (denoted σ_K), and fit to a linear combination of response functions for π's and K's.

We obtain the following preliminary branching fractions from these studies:

$$B(\tau^-\to\nu_\tau h^-K^0) = 0.977 \pm 0.023 \pm 0.108\,\% \qquad (9)$$
$$B(\tau^-\to\nu_\tau K^-K^0) = 0.123 \pm 0.023 \pm 0.023\,\%, \qquad (10)$$

The result for B_{K-K^0} is lower than that from Aleph, and consistent with expectations from CVC. In Figure 4, we plot the invariant masses of the $K^-K^0_S$ and $h^-K^0_S$ systems in these event samples. The $K^-K^0_S$ system is softer than that predicted by a phase-space model, and may have some resonant content such as in the 'ρ' model, based on the $\tau^-\to\nu_\tau\pi^-\pi^0$ spectral function. The $h^-K^0_S$ system, after accounting for the admixture of $K^-K^0_S$ events, is consistent with saturation by $\tau^-\to\nu_\tau K^{*-}(892)$, as shown in Fig. 4(b), permitting a test of the DMO sum rule. Using the CLEO-II results on $h^-\pi^0$, $K^-\pi^0$, h^-K^0 and K^-K^0 final states we find $B_{K^*}/B_\rho = (0.98 \pm 0.03 \pm 0.13) \times \tan^2\theta_C$, where the DMO sum rule prediction is $0.93 \tan^2\theta_C$ in the narrow-width approximation.

4.3. Decays of the Type $\tau^-\to\nu_\tau[Kh\pi]^-$

Space constraints forbid a detailed discussion of the very interesting 3-meson final states containing one or two kaons, and only the results can be presented below. CLEO-II has observed the decays $\tau^-\to\nu_\tau h^-K^0_S\pi^0$, $\tau^-\to\nu_\tau K^-K^0_S\pi^0$, and $\tau^-\to\nu_\tau\pi^-K^0_SK^0_S$, the first two being studied in a fashion similar to what was described in the previous

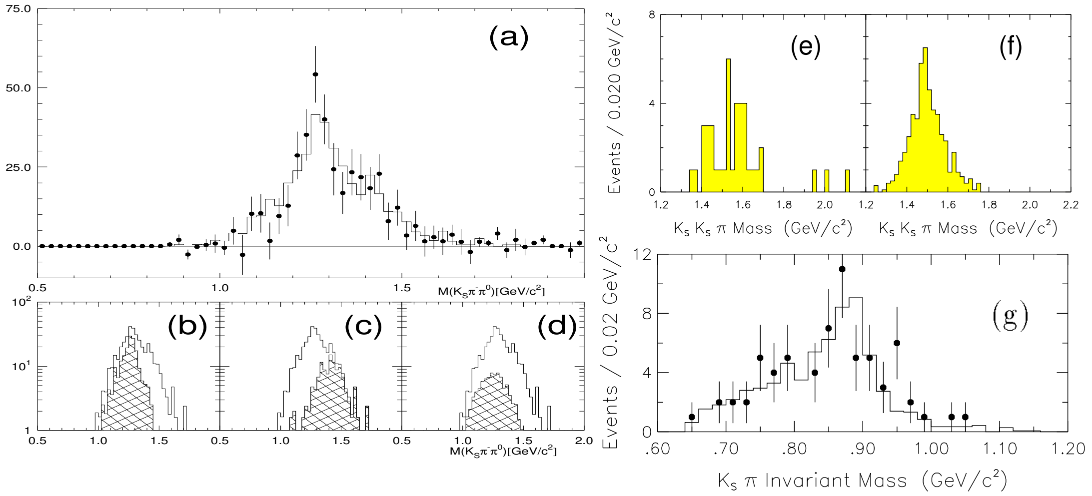

Fig. 5. (a) Plot of $M_{\pi^- K^0 \pi^0}$ for $\tau^- \to \nu_\tau h^- K_S^0 \pi^0$ candidates in the data (points), along with a fit (solid histogram) to distributions obtained from $\tau^- \to \nu_\tau K_1{}^-(1270)$, $\tau^- \to \nu_\tau K_1{}^-(1400)$, and $\tau^- \to \nu_\tau K^- K^0 \pi^0$ Monte Carlo samples (shown separately in (b), (c), (d) respectively), with the latter fixed according to the measured branching fraction. In (e) and (f) the $K_S^0 K_S^0 \pi^-$ invariant mass is plotted for $\tau^- \to \nu_\tau \pi^- K_S K_S$ candidate events in the data and Monte Carlo respectively, where the latter is based on the model of Decker *et al.*[26] In (g), we plot the $K_S \pi^-$ submass (two entries per event) for data (points) and Monte Carlo.

section. We obtain the following preliminary results:

$$B(\tau^- \to \nu_\tau h^- K^0 \pi^0) = 0.519 \pm 0.035 \pm 0.062\,\% \tag{11}$$
$$B(\tau^- \to \nu_\tau K^- K^0 \pi^0) = 0.129 \pm 0.050 \pm 0.032\,\% \tag{12}$$
$$B(\tau^- \to \nu_\tau \pi^- K^0 \bar{K}^0) = 0.083 \pm 0.017 \pm 0.017\,\%, \tag{13}$$

where the last result assumes that the $\pi^- K^0 \bar{K}^0$ system manifests itself as $\pi^- K_S K_S$ 25% of the time. The decay $\tau^- \to \nu_\tau \pi^- \bar{K}^0 \pi^0$ is thought to proceed via the strange axial vector $K_1(1270)$ and $K_1(1400)$ resonances. As shown in Figure 5(a-d), we find that both contribute, with a preliminary fit favoring $K_1(1270)$ production, contrary to indications from TPC/2γ[25] in the all-charged channel, (although the admixture of $K^- K_S \pi^0$ events in our $h^- K_S \pi^0$ sample makes this difficult to quantify).

The resonant structure for the non-strange $[KK\pi]^-$ system is unknown. Our results support crudely a recent model based on chiral perturbation theory,[26] as shown in Figure 5(e-g) for the $\pi^- K_S K_S$ event sample. However the branching fraction for the $K^- K^0 \pi^0$ channel and indications for substructure containing K^{*0} and K^{*-} in this channel are at variance with the predictions of this model.

5. Conclusion

To conclude, CLEO-II has obtained new results for many semi-hadronic τ decay channels. Many aspects of these processes are for the first time being tested through precision measurements of branching fractions and studies of spectral functions and resonant substructure. We anticipate many more results from CLEO in years to come.

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