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Search for τ-lepton decays to seven or more pions with BABAR

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We report the results of searches for several decay modes of the τ-lepton with ≥ 7 pions in the final state using 207×10^6 τ-pairs collected with the BABAR detector. For the decays with 7 charged pions in the final state we find the following 90% CL upper limits: $\mathcal{B}(\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau) < 3.0\times10^{-7}$, $\mathcal{B}(\tau^- \to 4\pi^-3\pi^+\nu_\tau) < 4.3\times10^{-7}$, and $\mathcal{B}(\tau^- \to 4\pi^-3\pi^+\pi^0\nu_\tau) < 2.5\times10^{-7}$. We also search for the decay $\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau$ and report a 90% CL upper limit of $< 3.4\times10^{-6}$ for its branching fraction. Finally, we search for the exclusive final state $\tau^- \to 2\omega\pi^-\nu_\tau$ and find a 90% CL upper limit for its branching fraction of $< 5.4\times10^{-7}$.

1. Introduction

The study of the decay of the τ-lepton into final states containing hadrons allows for detailed tests of the dynamics of the strong interaction. To date, these studies include τ decays into final states with up to six pions[1] [1]. While kinematically allowed the decay of the τ into seven or more pions has yet to be observed. Previous experiments reported upper limits for the all charged pion mode $\tau^- \to 4\pi^-3\pi^+\nu_\tau$ [2] as well as the mode with two π^0's, $\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau$ [3]. In this paper we present results on several searches for τ decay modes with seven or more pions exploiting the very large data sample accumulated by the BABAR experiment.

There is very little in the theoretical literature concerning the decay rate of the τ-lepton to states with $\geq$7 pions. In Ref. [4] the authors calculate the ratio $\mathcal{B}(\tau^- \to 7(\pi)^-\nu_\tau)/\mathcal{B}(\tau^- \to 5(\pi)^-\nu_\tau) = 6\times10^{-9}$. Using the measured $\mathcal{B}(\tau^- \to 5(\pi)^-\nu_\tau)$ [5] we find $\mathcal{B}(\tau^- \to 7(\pi)^-\nu_\tau) \approx 10^{-12}$, immeasurably small by today's experiments. Here the authors have assumed that the $7(\pi)^-$ state decay is pure phase space and does not contain any resonant substructure. The decay rate may be enhanced if it proceeds through resonances.

Another 7π final state of interest is $3\pi^-2\pi^+2\pi^0$. There are no predictions for the decay rate into this final state. However, calculations based on isospin symmetry [6] suggest that $\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau$ should be dominated by $\tau^- \to 2\omega\pi^-\nu_\tau$.

2. Data Sample, BABAR Detector, and MC Simulation

The analyses described here use data recorded with the BABAR detector at the PEP-II asymmetric e^+e^- collider operated at the Stanford Linear Accelerator. The data sample consists of 232 fb^{-1} of data collected at center of mass (CM) energies of 10.58 GeV and 10.54 GeV. The number of produced τ pairs, $N_{\tau\tau}$, is $(206.5\pm4.7)\times10^6$ where the τ pair cross section is taken as $\sigma_{\tau\tau} = (0.89\pm0.02)$ nb [7].

A complete description of the BABAR detector can be found in Ref. [8] and so only a brief sketch will be given here. The momentum of a charged particle is measured using a 5-layer double sided silicon strip vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5-T solenoidal magnetic field. Electromagnetic energy is measured using a calorimeter (EMC) with

[1]Whenever a mode is given its charged conjugate is also implied.

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6580 CsI(Tl) crystals. Hadrons are identified using a ring imaging Cherenkov detector in combination with ionization energy loss measurements from the SVT and DCH. Muons are identified using resistive plate chambers interspaced in the magnetic flux return iron. The four-momenta of all particles are reconstructed in the laboratory frame and then boosted to the CM using the known beam energies.

Since we are searching for decay modes that have yet to be observed we rely on Monte Carlo (MC) simulations to estimate our signal efficiencies. We also use MC simulations to develop criteria for background rejection as well as estimating the level of background remaining in our sample. However, whenever possible we use data for the final background estimate. The production of τ pairs is simulated with the KK generator [9] while non-signal τ decays are modeled with TAUOLA [10] using measured decay rates [11]. Signal events were generated with uniform density throughout the available phase space. GEANT 4 [12] is used to model the performance of the BABAR detector.

3. Tau Decays to 7 Charged Pions

In this section we briefly describe the $\tau^- \rightarrow 7(\pi)^-(\pi^0)\nu_\tau$ analyses as complete details can be found in Refs. [13] and [14]. The candidate selection starts with events where eight well measured charged tracks with a net charge of zero are reconstructed. Photons are reconstructed from EMC clusters and are required to have an energy $\geq$70 MeV, more than three crystal hits and a lateral energy profile consistent with a photon. The event is divided into two hemispheres using a plane perpendicular to the thrust axis [15]. The thrust is calculated using all charged tracks and photons in the event and is required to be >0.9. Further, we require all events to satisfy the "1-7 topology", one track in one hemisphere ("tag side"), and the remaining 7 tracks in the other hemisphere ("signal side").

Photon conversions in the detector material pose a serious source of additional tracks which can contribute to the event selection. This source is greatly reduced by requiring that charged tracks be identified as pions as well as requiring that that the invariant mass of any two oppositely charged tracks on the signal side be inconsistent with that expected from a photon conversion. The pion identification requirement also eliminates background $e^+e^- \rightarrow q\bar{q}$ events with kaons.

In order to further suppress $e^+e^- \rightarrow q\bar{q}$ events the tag side is required to satisfy one of the following criteria: 1) an identified muon or electron with $\leq$ 1 photon; 2) the charged track is not a lepton and no additional photons; or 3) a reconstructed ρ meson and no additional photons.

In order to better discriminate between signal events and background from $e^+e^- \rightarrow q\bar{q}$ events we use the pseudo mass [16] (M^*) of the signal side rather than its invariant mass ($m_{7\pi}$). The pseudo mass is calculated using the known beam energy, E_{beam}, and the measured 7-prong momentum ($P_{7\pi}$) and energy ($E_{7\pi}$) from:

$$M^{*2} = 2(E_{beam} - E_{7\pi})(E_{7\pi} - P_{7\pi}) + m^2_{7\pi} \quad (1)$$

The pseudo mass calculation assumes that the neutrino's flight direction is given by the combined momentum vector of the 7-prong and its energy is approximated by ($E_{beam} - E_{7\pi}$). In Fig. 1 the pseudo mass distribution is shown for signal and background MC events.

We define the signal region for $\tau^- \rightarrow 4\pi^-3\pi^+\nu_\tau$ and $\tau^- \rightarrow 4\pi^-3\pi^+\pi^0\nu_\tau$ to be $1.3 \leq M^* \leq 1.8$ GeV/c^2. From MC studies we determine the efficiencies for $\tau^- \rightarrow 4\pi^-3\pi^+\nu_\tau$ and $\tau^- \rightarrow 4\pi^-3\pi^+\pi^0\nu_\tau$ events in the signal region to be $(9.4\pm0.1\pm0.6)\%$ and $(9.3\pm0.1\pm0.6)\%$ respectively. The first errors are statistical while the second are systematic. Since the two efficiencies are consistent with each other we use an average efficiency of $(9.4 \pm 0.6)\%$ for both modes.

Both MC and data studies indicate that the main background source is from $e^+e^- \rightarrow q\bar{q}$ events. In order to determine the number of these background events in our data sample we fit the pseudo mass distribution in the signal free region $1.8 < M^* < 2.6$ GeV/c^2 and use the fit parameters to calculate the number of expected background events in the signal region. Background from τ events as predicted from the MC are subtracted before the fit is done. This method of es-

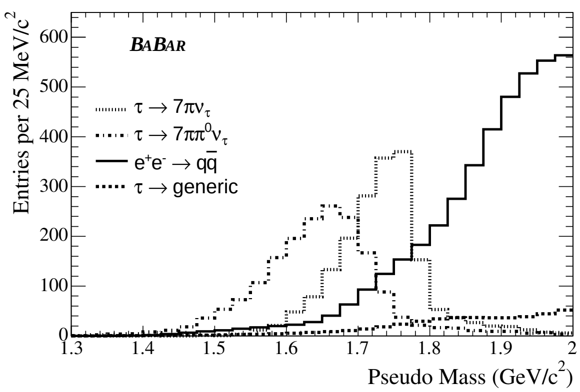

Figure 1. MC pseudo mass distributions of the seven charged tracks for signal, generic τ, and $e^+e^- \to q\bar{q}$ events. Backgrounds are normalized to data luminosity while signal modes assume a branching fraction of $2{\times}10^{-5}$.

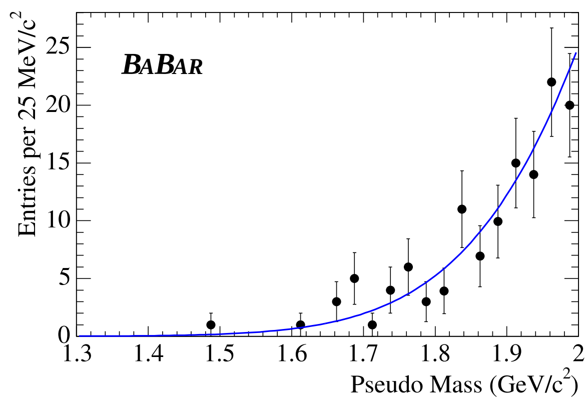

Figure 2. Pseudo mass distribution for $\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau$ events passing all selection criteria. The curve is from a fit to the pseudo mass distribution in the region $1.8 < M^* < 2.6$ GeV/c^2.

timating the $e^+e^- \to q\bar{q}$ background is validated using a signal free sample of 1-8 data events. Results from the background studies predict 20.3 events from $e^+e^- \to q\bar{q}$ and 1.3 events from τ's, the largest source being the $\tau \to 5\pi\pi^0\nu_\tau$ mode.

In Table 1 all contributions to the systematic error are tabulated. The total uncertainty in the $e^+e^- \to q\bar{q}$ background is 0.8 events while the uncertainty in the τ related background is 1.0 event. Thus we predict a total of 21.6±1.3 background events.

The pseudo mass distribution of data candidates passing the $\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau$ selection criteria is shown in Fig. 2. The curve represents the extrapolation of the fit from the non-signal region, $1.8 < M^* < 2.6$ GeV/c^2, into the signal region, $1.3 < M^* < 1.8$ GeV/c^2. There are 24 events in the signal region, consistent with the background estimate of 21.6±1.3.

As there is no evidence for a signal we calculate a Bayesian upper limit at 90% confidence level (CL) using a uniform prior in the branching fraction, background, and efficiency. We find:

$$\mathcal{B}(\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau) < 3.0 \times 10^{-7} \text{ @ } 90\% \text{ CL.}$$

We also calculate the sensitivity of the analysis by setting the observed number of events (N_{obs}) equal to the background prediction (N_{exp}) and find $\mathcal{B}^{N_{obs}=N_{exp}}(\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau) < 2.5 \times 10^{-7}$ Our result is considerably smaller than the previous upper limit, $\mathcal{B}(\tau^- \to 4\pi^-3\pi^+(\pi^0)\nu_\tau) < 2.4 \times 10^{-6}$, from [2].

We can also modify the analysis to search for the exclusive decays $\tau^- \to 4\pi^-3\pi^+\nu_\tau$ and $\tau^- \to 4\pi^-3\pi^+\pi^0\nu_\tau$ by vetoing events with photons on the signal side or requiring a reconstructed π^0 on the signal side. After modifying the selection criteria accordingly we find a selection efficiency of (5.5±0.3)% and (3.6±0.3)% for $\tau^- \to 4\pi^-3\pi^+\nu_\tau$ and $\tau^- \to 4\pi^-3\pi^+\pi^0\nu_\tau$, respectively. The total background in the $\tau^- \to 4\pi^-3\pi^+\nu_\tau$ ($\tau^- \to 4\pi^-3\pi^+\pi^0\nu_\tau$) sample is estimated to be 3.9±0.8 (8.2±0.5) events. We observe 8 events in the signal region for $\tau^- \to 4\pi^-3\pi^+\nu_\tau$ and 7 events for $\tau^- \to 4\pi^-3\pi^+\pi^0\nu_\tau$ leading to the following 90% upper limit CLs:

$$\mathcal{B}(\tau^- \to 4\pi^-3\pi^+\nu_\tau) < 4.7 \times 10^{-7} \text{ @ } 90\% \text{ CL}$$

$$\mathcal{B}(\tau^- \to 4\pi^-3\pi^+\pi^0\nu_\tau) < 2.5 \times 10^{-7} \text{ @ } 90\% \text{ CL.}$$

The sensitivities for the two modes are

$\mathcal{B}^{N_{obs}=N_{exp}}(\tau^- \to 4\pi^-3\pi^+\nu_\tau) < 2.2 \times 10^{-7}$ and $\mathcal{B}^{N_{obs}=N_{exp}}(\tau^- \to 4\pi^-3\pi^+\pi^0\nu_\tau) < 4.2 \times 10^{-7}$.

The above results represent an order of magnitude improvement for the inclusive mode and the first upper limits for the exclusive modes. Unfortunately, the experimental sensitivities are not close to the theoretical expectations.

4. $\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau$

In this section we describe the $\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau$ analysis. Complete details can be found in Refs. [14] and [17]. The selection criteria for this analysis are very similar to those used for the $\tau^- \to 7(\pi)^-\nu_\tau$ search, the main differences being that we demand two reconstructed π^0's on the signal side and a total of six charged tracks with net charge zero in the event. Candidate events must satisfy the 1-5 topology. As before the signal region is defined using the pseudo mass rather than the invariant mass. The four momenta of the two π^0's as well as the 5 charged pions are used in the pseudo mass calculation.

The signal region is defined as $1.3 \leq M^* \leq 1.8$ GeV/c^2. From MC studies we find the signal efficiency to be $(0.66 \pm 0.05)\%$ where the uncertainty in the efficiency is a combination of statistical and systematic errors (as detailed in Table 2).

From MC studies we find that the dominant background in our signal region is from τ decays with the largest contribution from $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ followed by $\tau^- \to 2\pi^-\pi^+2\pi^0\nu_\tau$ for a total of 4.3±1.0 events. The $q\bar{q}$ background, 2.2 events, is estimated by fitting the data M^* distribution in a non-signal region ($1.8 \leq M^* \leq 3.3$ GeV/c^2) and extrapolating into the signal region. The systematic error estimates in the background contributions are given in Table 2. In order to validate the $q\bar{q}$ background estimate method we apply it to a sample of events that does not contain τ's. This sample is obtained by requiring that there are at least three photons with energy $\geq$ 300 MeV not associated with a π^0 on the tag side of the event. We find good agreement between the expected number of events (11.8) and the observed event count (12). Finally, we validate the entire method by measuring the $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$ branching fraction and find a value consistent with the PDG value [5]. In

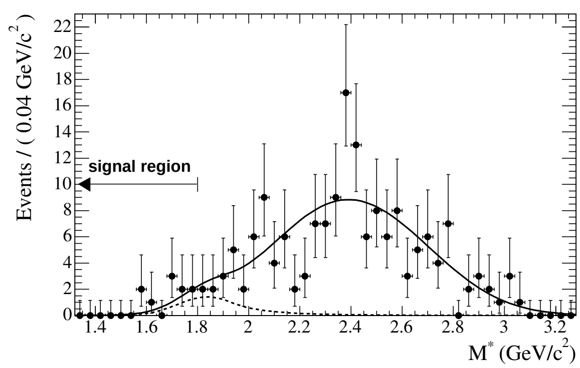

Figure 3. Pseudo mass distribution for $\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau$ events passing all selection criteria. The solid curve represents the total expected background while the dashed curve gives the τ background contribution.

Fig. 3 the pseudo mass distribution of candidates passing all selection criteria is shown. We find 10 events in the signal region, consistent with the expectation of 6.5 background events. As there is no evidence for a signal we calculate a 90% CL upper limit using:

$$\mathcal{B}(\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau) < \frac{\lambda_{N_{signal}}}{2 \times N_{\tau\tau} \times \epsilon} ,$$

where $\lambda_{N_{signal}}$ is the upper limit on the number of signal events at the 90% CL, $N_{\tau\tau}$ is the number of produced τ pair events, and ϵ is the signal efficiency. Using a limit calculator program [18] we find $\lambda_{N_{signal}} = 9.2$ events leading to:

$$\mathcal{B}(\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau) < 3.4 \times 10^{-6} \text{ @ } 90\% \text{ CL}.$$

This new upper limit represents a factor of 30 improvement over the previous upper limit, $\mathcal{B}(\tau^- \to 3\pi^-2\pi^+2\pi^0\nu_\tau) < 1.1 \times 10^{-4}$ [3].

In addition to the above inclusive result we also searched for the exclusive mode $\tau^- \to 2\omega\pi^-\nu_\tau$ where the ω's decay via $\omega \to \pi^+\pi^-\pi^0$. We expect

Table 1
Systematic error components for $\tau^- \to 4\pi^- 3\pi^+ (\pi^0)\nu_\tau$.

Signal efficiency		
	Tracking efficiency	5.2%
	1-prong τ BF	0.5%
	Particle ID	2.7%
	Limited MC statistics	0.7%
	Total	6.0%
τ Background		
	Limited MC statistics	75%
	$\mathcal{B}(\tau \to 5\pi\nu)$	7%
	$\mathcal{B}(\tau \to 5\pi\pi^0\nu)$	15%
	Total	77%
$q\bar{q}$ Background		
	Fit parameters	3.4%
	Number of events fitted	2.0%
	Fit range	0.1%
	Total	4%
Luminosity $\times$ cross section		2.3%

to have increased sensitivity in this decay mode as the allowed signal region, $1.7 \leq M^* \leq 1.8$ GeV/c^2, is considerably smaller than the signal region of $\tau^- \to 3\pi^- 2\pi^+ 2\pi^0 \nu_\tau$.

The event selection is re-optimized for this analysis. We require the reconstruction of two ω's in an event with the requirement $0.76 \leq M_{\pi^+\pi^-\pi^0} \leq 0.80$ GeV/c^2. The reconstruction of two ω's suppresses backgrounds while at the same time allows us to loosen many of the selection criteria. As a result the $\tau^- \to 2\omega\pi^-\nu_\tau$ signal efficiency, $(1.53 \pm 0.13)\%$, is considerably larger than that of $\tau^- \to 3\pi^- 2\pi^+ 2\pi^0 \nu_\tau$.

The background in our sample is estimated using a combination of data and MC to be $0.4^{+1.0}_{-0.4}$ events with the sole contribution from $\tau^- \to \omega 2\pi^-\pi^+\nu_\tau$. In Fig. 4 the pseudo mass distribution of candidates passing all selection criteria is shown. We find one event in the signal region. We use the same upper limit calculation procedure as in the $\tau^- \to 3\pi^- 2\pi^+ 2\pi^0 \nu_\tau$ analysis and find $\lambda_{N_{signal}} = 3.4$ events leading to:

$$\mathcal{B}(\tau^- \to 2\omega\pi^-\nu_\tau) < 5.4 \times 10^{-7} \text{ @ } 90\% \text{ CL}.$$

This represent the first experimental upper limit for this τ decay mode.

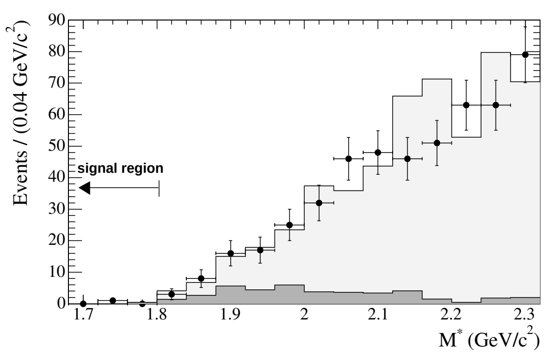

Figure 4. Pseudo mass distribution for $\tau^- \to 2\omega\pi^-\nu_\tau$ events passing all selection criteria. The light histogram shows the total background with the $q\bar{q}$ component scaled to agree with the data. The dark histogram is the expected τ background.

Table 2
Systematic error components for $\tau^- \to 3\pi^- 2\pi^+ 2\pi^0 \nu_\tau$.

Signal efficiency		
	Tracking efficiency	3.9%
	Reconstruction of $2\pi^0$	6.6%
	Single photon	1.8%
	Particle ID	1.7%
	Limited MC statistics	1.8%
	Total	8.3%
τ Background		
	Tracking, Neutrals, PID, π^0	8.4%
	$\mathcal{B}(\tau \to 5\pi\pi^0\nu)$	14.9%
	Fitting	16.7%
	$\tau \to 5\pi\pi^0\nu$ background	3.6±0.9 evts
	$\tau \to 3\pi 2\pi^0\nu$ background	0.7±0.5 evts
$q\bar{q}$ Background		$2.2^{+1.7}_{-1.0}$ evts
Luminosity × Cross section		2.3%

5. Summary and Conclusions

We have reported the results of several searches for τ decays modes with seven or more pions in the final state. Although each of the searches reported here has an upper limit at least an order of magnitude lower than previous searches no evidence of a signal has been found. It may very well be that the observation of the τ into seven or more pions is beyond the reach of the current b (and τ) factories.

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