

Search for $\tau^- \rightarrow 4\pi^- 3\pi^+(\pi^0)\nu_\tau$ Decays

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A search for the decay of the τ lepton to seven charged pions and at most one π^0 was performed using the BABAR detector at the PEP-II e^+e^- collider. The analysis uses data recorded on and near the $\Upsilon(4S)$ resonance between 1999 and 2003, a total of 124.3 fb^{-1} . We observe 7 events with an expected background of 11.9 ± 2.2 events and calculate a preliminary upper limit of $\text{BR}(\tau^- \rightarrow 4\pi^- 3\pi^+(\pi^0)\nu_\tau) < 2.7 \times 10^{-7}$ at 90 % CL. This is a significant improvement over the previous limit established by the CLEO Collaboration.

1. INTRODUCTION

The decay of the τ lepton to seven charged particles ¹ (7-prong decay) has not been observed to date. If observed, it may lead to an improved τ neutrino mass limit due to the phase space limitations of the decay. The current experimental upper limit of $\text{BR}(\tau^- \rightarrow 4\pi^- 3\pi^+(\pi^0)\nu_\tau) < 2.4 \times 10^{-6}$ at 90% confidence level was set by the CLEO Collaboration [1]. However, theoretical calculations, using an effective chiral Lagrangian to estimate the matrix element, show that, provided the decay does not occur through narrow resonances, the 7-prong τ decay rate is almost completely dominated by its tiny phase space, which leads to the theoretical upper limit of $\text{BR}(\tau^- \rightarrow 4\pi^- 3\pi^+(\pi^0)\nu_\tau) < 6 \times 10^{-11}$ [2]. However, if the decay is dominated by resonances like $a_1(1240)$, $a_2(1320)$, $\pi(1300)$, similar to the case of $\tau \rightarrow 6\pi\nu_\tau$ [3] decays where η and ω resonances play an important role, the decay rate may be expected to be much larger.

This analysis ² is based on data recorded by the BABAR detector at the PEP-II asymmetric-energy e^+e^- storage ring operated at the Stan-

ford Linear Accelerator Center. The data sample consists of 124.3 fb^{-1} recorded at $\sqrt{s} = 10.58 \text{ GeV}$ and 10.54 GeV between 1999 and 2003. With the expected cross-section for τ pairs at the luminosity-weighted $\sqrt{s}$ of $\sigma_{\tau\tau} = 0.89 \text{ nb}$ [4], this data sample contains over 220 million τ decays.

The BABAR detector is described in detail in Ref. [5]. Charged particle momenta are measured with a 5-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH). A calorimeter consisting of 6580 CsI(Tl) crystals is used to measure electromagnetic energy, a ring-imaging Cherenkov detector (DIRC) is used to identify charged hadrons, and the instrumented magnetic flux return (IFR) is used to identify muons. The charged particle tracking system, the electromagnetic calorimeter and the Cherenkov detector are inside a 1.5 T superconducting magnet.

Monte Carlo samples were used for background and signal decay studies. The KK2F [6] generator simulates the process $e^+e^- \rightarrow \tau^+\tau^-$ according to the electroweak interactions. Signal 7-prong τ decays were generated using phase space with a V-A interaction. The other (tag) τ -lepton in the event decays generically. These decays are simulated with the TAUOLA [7] package using branching ratios for the τ decay modes, which

¹Throughout this paper, whenever a mode is given its charge conjugate is also implied.

²All tables, plots and results in this paper are preliminary.

are set by fitting the world data from PDG02 [8] applying a unitarity constraint. More than 200 million τ -pairs, twice the size of the data, were simulated for this analysis. Continuum $q\bar{q}$ Monte Carlo sample, corresponding to 80 fb^{-1} , was generated using the JetSet package [9]. All Monte Carlo background samples are scaled to the data luminosity according to their production cross sections.

The goal of this analysis is to isolate a sample of 7-prong τ decays, which we call the signal. The invariant mass of signal events is expected to be slightly below the τ mass of $1.777 \text{ GeV}/c^2$ due to the undetected neutrino. The signal in data is established by counting events in the signal region between 1.3 and $1.8 \text{ GeV}/c^2$, and subtracting the number of expected background events. This analysis was performed “blinded” for events of the 1-7 topology with $M_{7\text{prong}} \leq 2 \text{ GeV}/c^2$, which means these data events were not studied during background estimate and the evaluation of the systematic errors.

2. EVENT SELECTION

The main background to 7-prong τ decays comes from hadronic ($e^+e^- \rightarrow q\bar{q}$) and τ migration processes. The τ migration stems from the decays $\tau^- \rightarrow 3\pi^-2\pi^+\pi^0\nu_\tau$, $\tau^- \rightarrow 2\pi^-\pi^+2\pi^0\nu_\tau$ and $\tau^- \rightarrow 2\pi^-\pi^+\pi^0\nu_\tau$, where π^0 mesons decay to $\gamma\gamma$ and the photons undergo conversions in the detector material.

The event selection criteria were developed to suppress these backgrounds while maintaining a high signal efficiency level. The selection consists of a pre-selection, designed to reject the majority of easily distinguishable background events, and a main selection, developed as a result of more detailed studies of signal and background properties.

In the pre-selection, the overall multiplicity is limited to less than or equal to 10 charged tracks in the event. The event is divided into two hemispheres based on the plane perpendicular to the thrust axis. The thrust is calculated in the center of mass system using all charged tracks and neutral clusters in the event. The number of tracks in each hemisphere is used to determine the topol-

ogy of the event. Tracks from the interaction region are required to have a distance of closest approach in the transverse plane to the beam axis (DOCA_{XY}) of not more than 1.5 cm and an absolute value of the distance of closest approach in the z -direction smaller than 10 cm. The invariant mass of each pair of oppositely charged tracks is required to be larger than $5 \text{ MeV}/c^2$ to reject photon conversions. Low momentum tracks with $\theta_{lab} \simeq \pi/2$ can pass through the interaction region multiple times, resulting in copies of the initial track with similar momenta. These tracks are easily removed from an event due to their low and similar momenta and $\cos \theta_{lab}$.

We demand seven tracks in one hemisphere, which is called the signal side, and one track in the other hemisphere called the tagging side. In addition, the tagging side track and four tracks on the 7-prong signal side are required to have at least 12 drift chamber hits each. Transverse momentum of each track has to be larger than $100 \text{ MeV}/c$. The net charge of these eight tracks has to be zero. The thrust magnitude of an event is required to be greater than 0.93, reducing background from $q\bar{q}$ events by more than 95%. The number of photons is restricted to less than six per hemisphere. Photon candidates, which are neutral clusters that are not a part of a cluster matching the charged track, are required to have at least 70 MeV energy and more than 3 crystal hits in the calorimeter. After the pre-selection the background from both generic τ decays and $q\bar{q}$ processes is significantly reduced. In particular, background from $B\bar{B}$ events and other QED backgrounds from Bhabha, two-photon and di-muon events are suppressed to negligible amounts.

To establish the decay of a τ to seven charged particles, the invariant mass of the 7-prong charged tracks is studied closely. Monte Carlo studies show that 98 % of the signal events have a mass between 1.3 and $1.8 \text{ GeV}/c^2$. The background from generic τ events is expected to lie around the τ -lepton mass, between 1.6 and $2.0 \text{ GeV}/c^2$. Hadronic events typically have a higher mass, which ultimately makes them easier to distinguish from the signal events, but are almost 100 times the amount of the τ background, which

makes them the dominant background in the signal region.

Contrary to $q\bar{q}$ processes, τ decays are accompanied by an undetected τ neutrino. This difference is successfully used to improve the separation between the signal and the background. If the τ neutrino is assumed to be massless and the τ -lepton direction is approximated by the vector momentum of the 7 charged tracks, the following variable can replace the invariant mass:

$$m_{\tau}^{*2} = 2(E_{beam} - E_{7h})(E_{7h} - P_{7h}) + m_{7h}^2 \quad (1)$$

where E_{beam} is the beam energy, E_{7h} , P_{7h} and m_{7h} are energy, momentum and the invariant mass of the seven charged tracks in the center-of-mass system. This variable is called the τ pseudo-mass [10]. Compared to the invariant mass, the pseudo-mass provides better signal-to-background separation due to the larger $q\bar{q}$ pseudo-mass. The pseudo-mass spectrum of signal events has a sharp cut-off at the τ mass. The signal region defined for the 7-prong invariant mass scale is the same for the pseudo-mass scale. The pseudo-mass of the 7-prong charged tracks will be used to establish the signal.

The seven charged tracks on the signal side are required to be pions. This requirement significantly reduces the background from generic τ decays with e^+e^- pairs from photon conversions passing the charged track criteria. It is also efficient against $c\bar{c}$ background with a significant amount of kaons produced on the signal side. Pion identification requires a particle to pass a number of likelihood selectors based on dE/dx information from the DCH and SVT, and information on Cherenkov angle and number of photons from the DIRC.

Photon conversions occur in the detector material. Typically a larger distance of closest approach (DOCA) to the beam spot is reconstructed for conversion tracks than for tracks coming from the e^+e^- collision point. In addition, the tracks from photon conversions typically have lower than average transverse momentum P_t . These two variables in combination improve the signal-to-background separation: $DOCA_{XY}/P_t$ is required to be less than $0.7 \frac{\text{cm}\cdot\text{c}}{\text{GeV}}$. These requirements effectively suppress

the background from τ migration.

The last criteria for discrimination against $q\bar{q}$ events is the tagging of the 1-prong side in the event, where hadronic processes are set apart from τ events by non-leptonic decays and higher photon multiplicity. If a particle on the 1-prong side is identified as an electron or a muon, up to 1 photon candidate is allowed to be in the same hemisphere. If a particle has failed both electron and muon identification criteria, which would mean the particle is a hadron, no photons are allowed on the 1-prong side, except when two photons compose a π^0 candidate with invariant mass $0.110 < M_{2\gamma} < 0.155 \text{ GeV}/c^2$, and the π^0 along with the hadron compose a ρ -meson candidate with $0.650 < M_{\rho} < 0.875 \text{ GeV}/c^2$. Information from the calorimeter and the drift chamber is used for the electron identification. Muon identification is based on information from the EMC and IFR. The 1-prong tags reduce the background from $q\bar{q}$ events by more than 80%. No photon multiplicity cut is applied on the signal 7-prong side to avoid an efficiency decrease in the $7\pi\pi^0$ channel.

3. BACKGROUND ESTIMATE IN THE SIGNAL REGION

During the course of this analysis it turned out that the quantitative agreement between data and Monte Carlo was less than satisfactory. In particular, the $q\bar{q}$ Monte Carlo does not adequately represent the data. Extensive studies on various topologies from 1-3 to 1-8 were performed to estimate the level of disagreement. It was concluded, that the data – Monte-Carlo disagreement is negligible for low track multiplicity topologies such as 1-1 or 1-3 dominated with τ events, tolerable for 1-5 topologies, where the content of $q\bar{q}$ and τ events is roughly the same, and significant for topologies like 1-7 and 1-8, where $q\bar{q}$ processes completely dominate.

Contrary to simulation of complex hadronization and fragmentation processes that constitute the $q\bar{q}$ background, generic τ Monte Carlo provides a reasonable data representation and is used for a τ background estimate in the signal region. According to Monte Carlo simulation only $0.6 \pm$

0.4 τ -pair events are expected to remain in the signal region after all cuts. The only τ decay mode which contributes to this background is the $\tau^- \rightarrow 3\pi^- 2\pi^+ \pi^0 \nu_\tau$ mode.

In order to determine the $q\bar{q}$ background level in the signal region we turn to data. Figure 1(a) shows the pseudo-mass distribution for 1-7 topology data events after the pre-selection with the generic τ -pair background subtracted. The region below 2 GeV/c² was blinded throughout the development of this analysis. Superimposed is a Gaussian fit to the pseudo-mass spectrum between 2.0 and 2.5 GeV/c² and its extrapolation below 2.0 GeV/c² to the signal region. The integral

$$N_{bkg} = N_{HM} \frac{\int_{1.3}^{1.8} e^{-(m-\mu)^2/2\sigma^2} dm}{\int_{2.0}^{2.5} e^{-(m-\mu)^2/2\sigma^2} dm} \quad (2)$$

where N_{HM} is the number of events with the 7-prong pseudo-mass between 2.0 and 2.5 GeV/c², gives an estimate of the number of background events in the signal region.

The variables used in the cut-based event selection are not correlated with the pseudo-mass, therefore the fit parameters only marginally vary with the tighter cuts. Since the final selection cuts on the 1-prong hemisphere reduce the data sample considerably, as shown in Figure 1(b), we fix the parameters of the Gaussian, central value and width, to their preselection values.

Since there is no obvious reason for the whole $q\bar{q}$ pseudo-mass spectrum to behave like a Gaussian, we do not attempt to fit the whole spectrum, but only the part that is of interest to the analysis. We checked that a Gaussian gives a good representation of the data by studying the spectrum using 1-7 Monte Carlo and 1-8 data samples. As a result of the extrapolation, the estimated number of $q\bar{q}$ background events in the signal region is 11.3 ± 2.2 events. The errors are extracted from the fit parameters, namely the mean and the sigma. In this case they are highly correlated, a two dimensional Gaussian p.d.f. [11] is used in a toy Monte Carlo study to generate the values of the mean and sigma according to their uncertainties expressed in the covariance matrix.

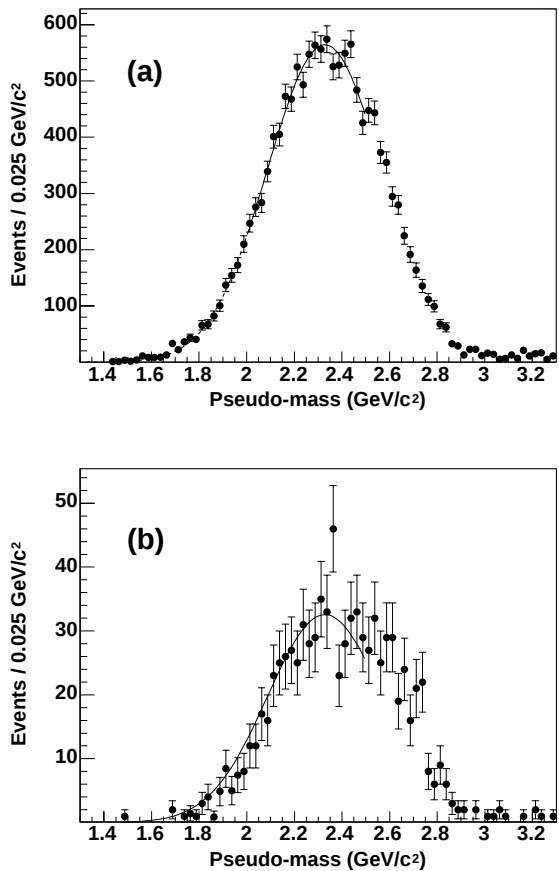


Figure 1. **(a)**: Gaussian fit (solid curve) of the 7-prong pseudo-mass spectrum of the data events from 2.0 to 2.5 GeV/c² after the pre-selection and its extrapolation (dashed curve) below 2.0 GeV/c² to the signal region; **(b)**: Gaussian function with mean and sigma from (a), superimposed on the pseudo-mass spectrum of the data events after the final 1-prong selection.

These fit parameters are then used to estimate the number of background events N_{bkg} in the signal region. The uncertainties are extracted from the N_{bkg} distribution by calculating $\pm 1\sigma$ from the mean value. Another contribution to the uncertainty of the background number comes from the Poisson error of the fitted number of events in the pseudo-mass spectrum. Both uncertainties are added in quadrature.

To validate the extrapolation method used for the background estimate we studied 1-8 topology data events, which are clear hadronic background with negligible contribution from τ events. The background estimate from the Gaussian fit and extrapolation is compared to the number of events observed in the signal region at different selection levels. Similar to the case of the 1-7 topology, the variations of the fit parameters are small throughout the cuts. The study showed good agreement between the estimated and observed number of events at all selection levels.

As a cross-check, the same study was performed on 1-7 topology Monte Carlo events. Although not valid for a reliable quantitative estimate, Monte Carlo simulation of $q\bar{q}$ background reflects the Gaussian-like shape of the 7-prong pseudo-mass spectrum reasonably well. Similar to the case of the 1-8 topology data, the estimated and observed number of $q\bar{q}$ background events agree well within their statistical errors.

Combining the generic τ and $q\bar{q}$ background estimates, the total number of background events expected in the signal region in 124.3 fb^{-1} of data is 11.9 ± 2.2 .

4. RESULTS AND SYSTEMATIC UNCERTAINTIES

After unblinding the 7-prong pseudo-mass region below $2.0 \text{ GeV}/c^2$ (see Figure 2), 7 events were observed in the signal region in 124.3 fb^{-1} of data, at the signal detection efficiency of 8.05% for $\tau^- \rightarrow 4\pi^- 3\pi^+ \nu_\tau$ and 8.04% for $\tau^- \rightarrow 4\pi^- 3\pi^+ \pi^0 \nu_\tau$ modes. No evidence for the τ decay to seven charged pions was found.

Several sources contribute to the systematic uncertainties. Track reconstruction with 5.2% and particle identification with 2.7% errors are

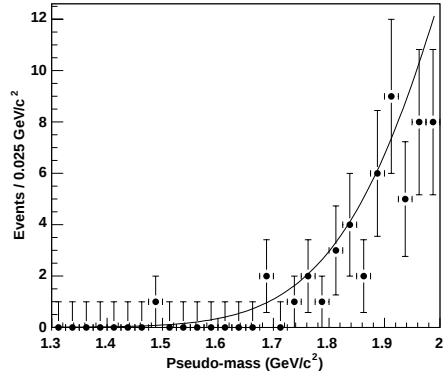


Figure 2. Data events with 7-prong pseudo-mass below $2.0 \text{ GeV}/c^2$ after the selection cuts. The curve represents the Gaussian function superimposed on the pseudo-mass spectrum for the background estimate.

the two major sources for signal efficiency systematic uncertainty. Uncertainties from limited signal Monte Carlo statistics (2.6%), data luminosity and $\tau^+ \tau^-$ cross-section (2.3%) and 1-prong generic τ branching ratio (0.5%) are also included. The uncertainties are added in quadrature, resulting in 6.8% total systematic uncertainty of the signal efficiency.

The same uncertainties apply to the τ background estimate, but they are negligible compared to statistical uncertainty of 58%, coming from the limited τ Monte Carlo statistics (3 events out of 621 fb^{-1}), and 15% error from the $\tau^- \rightarrow 3\pi^- 2\pi^+ \pi^0 \nu_\tau$ branching ratio. The total uncertainty of the τ background estimate is 60%.

The nature of the $q\bar{q}$ background estimate error was already discussed, the uncertainty comes from the fit parameters (18%), namely mean and sigma, and the number of events fitted (4%). The studies of the systematic uncertainty due to the choice of the fit range show a 3% error. As a result, the total uncertainty of $q\bar{q}$ background estimate is 19%. The results discussed in this section are summarized in Table 1.

Table 1

Results: expected background and observed data events, signal efficiency and the decay BR upper limit.

$N_{\tau\tau}$	$(110.5 \pm 2.5) \times 10^6$
Expected $\tau^+\tau^-$ background	0.6 ± 0.4
Expected $q\bar{q}$ background	11.3 ± 2.2
Expected total background	11.9 ± 2.2
Observed events	7
$\tau^- \rightarrow 4\pi^- 3\pi^+ \nu_\tau$ efficiency %	8.05 ± 0.55
$\tau^- \rightarrow 4\pi^- 3\pi^+ \pi^0 \nu_\tau$ efficiency %	8.04 ± 0.55
$BR(\tau^- \rightarrow 4\pi^- 3\pi^+ (\pi^0) \nu_\tau)$ (90 % CL)	$< 2.7 \times 10^{-7}$

The branching ratio upper limit of the $\tau^- \rightarrow 4\pi^- 3\pi^+ (\pi^0) \nu_\tau$ decay is calculated based on the following likelihood function, which convolutes a Poisson distribution with two Gaussian resolution functions for the background and the efficiency:

$$\mathcal{L}(n, \hat{b}, \hat{f}; B, b, f) = \frac{\mu^n e^{-\mu}}{n!} \frac{1}{2\pi\sigma_b\sigma_f} \times e^{-\frac{1}{2}\left(\frac{\hat{b}-b}{\sigma_b}\right)^2 - \frac{1}{2}\left(\frac{\hat{f}-f}{\sigma_f}\right)^2} \quad (3)$$

where B denotes the branching fraction of $\tau^- \rightarrow 4\pi^- 3\pi^+ (\pi^0) \nu_\tau$, $f = 2N_{\tau\tau}\epsilon$, b is the expected total background, $\mu = \langle n \rangle = fB + b$, n is the number of observed events, and $\hat{b}$ ($\hat{f}$) is sampled from a normal distribution $N(b, \sigma_b)$ ($N(f, \sigma_f)$). The signal efficiency ϵ is set at $(8.04 \pm 0.55)\%$ as the smallest of the two decay modes. The number of τ pair events $N_{\tau\tau}$ is $(110.5 \pm 2.5) \times 10^6$. The errors on the number of τ pair events from luminosity and cross section, and efficiency are incorporated in σ_f . A Bayesian upper limit was derived using a uniform prior in the branching ratio, the background, and the signal efficiency. As a result, the following preliminary upper limit on the branching ratio of the 7-prong τ decays is obtained at 90% confidence level:

$$BR(\tau^- \rightarrow 4\pi^- 3\pi^+ (\pi^0) \nu_\tau) < 2.7 \times 10^{-7} \quad (4)$$

This limit is approximately 10 times better than the current upper limit.

In conclusion, we have searched for the decay $\tau^- \rightarrow 4\pi^- 3\pi^+ (\pi^0) \nu_\tau$ using 124.3 fb^{-1} of data collected at the BABAR detector. We found no evidence for the decay, and set a much more stringent upper limit on the decay branching ratio.

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