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Search for the decay $\tau^- \to 4\pi^- 3\pi^+ (\pi^0)\nu_\tau$

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A search for the decay of the τ lepton to seven charged pions and one or zero π^0 mesons was performed using the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- collider. The analysis uses 232.2 fb^{-1} of data at center-of-mass energies on or near the $\Upsilon(4S)$ resonance. We observe 24 events with an expected background of 21.6 ± 1.3 events. Without evidence for a signal, we calculate an upper limit of $\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau) < 3.0 \times 10^{-7}$ at 90% confidence level. This is an improvement by nearly an order of magnitude over the previously established limit. In addition, we set upper limits for the exclusive decays $\tau^- \to 4\pi^- 3\pi^+ \nu_\tau$ and $\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau$.

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The decay of the τ lepton to seven charged particles[1] has not been observed to date. An upper limit of $\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau) < 2.4 \times 10^{-6}$ at 90% confidence level has been set by the CLEO Collaboration [1]. Theoretical calculations using an effective chiral Lagrangian to estimate the matrix elements show that the τ decay rate to seven charged particles is much smaller than the decay into five charged particles due to its smaller phase space. This leads to a theoretical branching fraction estimate of the order of 10^{-11}, which could be enhanced by up to an order of magnitude if this decay proceeds via resonances [2].

This analysis is based on data recorded by the *BABAR* detector at the PEP-II asymmetric-energy e^+e^-storage ring operated at the Stanford Linear Accelerator Center. The data sample consists of 232.2 fb^{-1} recorded at center-of-mass (CM) energies of 10.58 GeV and 10.54 GeV. With an expected cross section for τ pairs for these CM energies of $\sigma_{\tau\tau} = (0.89 \pm 0.02)$ nb [3], the number of produced τ pair events $N_{\tau\tau}$ is $(206.6 \pm 5.2) \times 10^6$.

The *BABAR* detector is described in detail in Ref. [4] and only a brief description is given here. Charged-particle momenta are measured with a 5-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5 T solenoidal magnetic field. A calorimeter (EMC) consisting of 6580 CsI(Tl) crystals is used to measure electromagnetic energy. A ring-imaging Cherenkov detector is used to identify charged hadrons, in combination with ionization energy loss measurements in the SVT and the DCH. Muons are identified by an instrumented magnetic-flux return (IFR). Particle four-momenta are reconstructed in the laboratory frame and then boosted to the e^+e^- center-of-mass frame using the measured beam energies.

We use Monte Carlo simulation techniques to estimate our signal efficiencies and background contamination from other τ pair events. The production of τ pairs is simulated with the KK generator [5], and nonsignal τ lepton decays are modeled with TAUOLA [6] according to measured rates [7]. Signal events were generated with uniform density throughout the available phase space. The simulation of the *BABAR* detector is based on GEANT 4 [8].

Events with eight charged tracks and a net charge of zero are selected. Tracks are required to have a distance of closest approach to the interaction point in the plane transverse to the beam axis ($\mathrm{DOCA_{XY}}$) of less than 1.5 cm, and a distance of closest approach along the beam direction of less than 10 cm. It is required that at least five of these eight tracks have a minimum transverse momentum (p_T) of 100 MeV/c, and 12 or more DCH hits. Photons are reconstructed from EMC clusters and are required to have a minimum energy of 70 MeV, more than three crystal hits, and a lateral energy profile consistent with that of a photon. The event is divided into hemispheres by a plane perpendicular to the thrust axis [9], where the thrust is calculated from all charged tracks and all photons in the event. The event thrust has to be larger than 0.9. We require all events to have one track in one hemisphere (the "tag-side" hemisphere) and seven tracks in the other hemisphere (the "signal side" hemisphere). The above requirements define the 1–7 topology.

Monte Carlo studies have shown that the background from τ-pair events stems from photon conversions in the detector material. To reduce this contribution and to exclude $e^+e^- \to q\bar{q}$ ($q = \{u, d, s, c, b\}$) decays containing kaons we apply particle identification on the signal side. We demand that at least six of the tracks are identified as pions with high probability. We apply looser identification criteria to the seventh track.

To further reduce photon conversions, we require all seven tracks on the signal side to have a minimum transverse momentum of 100 MeV/c and the ratio of $\mathrm{DOCA_{XY}/p_T}$ to be less than 0.7 $\mathrm{cm}/(\mathrm{GeV}/c)$.

Further suppression of $e^+e^- \to q\bar{q}$ events is achieved by requiring the tag side to satisfy one of the following criteria: 1) a tightly identified electron or muon with no more than one additional photon on the tag side; 2) a tight lepton veto and no additional photon; or 3) a reconstructed ρ meson with an invariant mass of $0.650 < \mathrm{m}_\rho < 0.875\ \mathrm{GeV}/c^2$, derived from the combination of the 1-prong track with a reconstructed π^0 candidate. The π^0 candidates are formed by combining two photons and requiring an invariant mass between 0.113 and 0.155 GeV/c^2.

*Deceased.

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

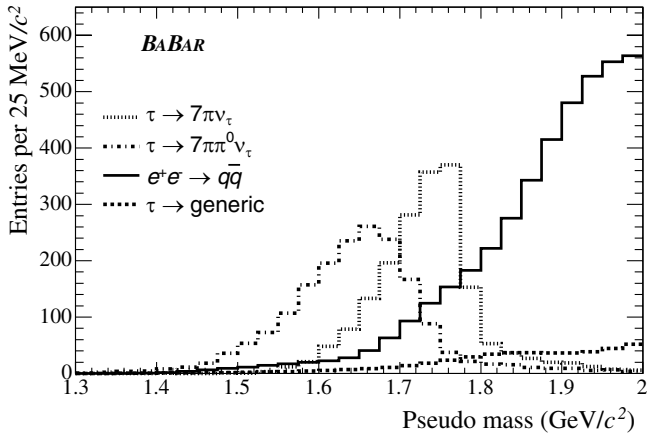

FIG. 1. Pseudo mass distributions of the seven charged tracks after the 1–7 topology selection for signal (dashed-dotted: $\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau$; dotted: $\tau^- \to 4\pi^- 3\pi^+ \nu_\tau$), generic τ (including 5-prong decays) (dashed), and $e^+e^- \to q\bar{q}$ Monte Carlo events (solid). Entries are normalized to the data luminosity. To display the two signal modes we assumed a branching fraction of 2×10^{-5}.

After applying these requirements we calculate the pseudo mass (m) of the τ lepton [10]:

$$m^2 = 2(E_{\rm beam} - E_{7\pi})(E_{7\pi} - P_{7\pi}) + m_{7\pi}^2. \qquad (1)$$

The pseudo mass is an approximation of the invariant mass of the tau, where the neutrino's flight direction is approximated by the combined momentum vector $P_{7\pi}$ of the seven charged tracks, and its energy is taken to be the difference between the beam energy $E_{\rm beam}$ in the center-of-mass system and the combined energy $E_{7\pi}$ of the charged tracks. The pseudo mass allows for a better discrimination between signal events and background from $e^+e^- \to q\bar{q}$ events than $m_{7\pi}$. The final event count is performed in the signal region $1.3 < m < 1.8$ GeV$/c^2$. Figure 1 illustrates the pseudo mass spectra of simulated signal and background contributions after the topology selection.

For this analysis, a comparison of Monte Carlo simulation and data has shown that $e^+e^- \to q\bar{q}$ background contributions cannot reliably be extracted from simulation due to difficulties in modeling the fragmentation processes. The shape of the pseudo mass distribution appears to be correctly modeled, but the overall normalization is not. Therefore, we estimate this background directly from data, using a method described below. On the other hand, the simulation of τ pair events yields a reliable estimate of their expected background contribution, verified by loosening requirements that suppress the tau background. A breakdown of the signal efficiencies and individual τ background contributions are listed in Table I for each selection step. In this table the generic τ sample does not contain 5π and $5\pi\pi^0$ decays, which are listed separately since they comprise the only background from τ decays after the final selection.

TABLE I. Cumulative signal efficiencies in % and τ background contributions as number of events scaled to the data luminosity after the various selection criteria. ID denotes Identification, Conv. Conversion, and Gen. Generic.

	Efficiency [%]		Number of events		
	$7\pi\nu_\tau$	$7\pi\pi^0\nu_\tau$	Gen. τ	$5\pi\nu_\tau$	$5\pi\pi^0\nu_\tau$
1–7 Topology	23.6 ± 1.4	22.1 ± 1.4	767	198	187
Particle ID	20.7 ± 1.3	19.6 ± 1.3	108	64	75
Conv. veto	15.8 ± 1.0	14.9 ± 1.0	0	4.7	9.2
1-Prong tag	10.2 ± 0.7	9.6 ± 0.7	0	1.7	4.2
Signal region	9.4 ± 0.6	9.3 ± 0.6	0	0.4	0.8

The efficiencies for events in the signal region for $\tau^- \to 4\pi^- 3\pi^+ \nu_\tau$ and $\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau$ are $(9.4 \pm 0.1 \pm 0.6)\%$ and $(9.3 \pm 0.1 \pm 0.6)\%$. The first errors are statistical and the second systematic.

The systematic errors on the signal efficiencies include contributions from uncertainties in the reconstruction of charged tracks (5.2%), the uncertainty associated with the particle identification on the signal and tag side (2.7%), the luminosity measurement and the τ pair cross-section determination (2.3%), and the uncertainty on the generic 1-prong τ decay branching ratios (0.5%). Since the efficiencies of the two decay channels to the 7-prong τ decays are in good agreement, we average them and obtain an overall efficiency for the decay $\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau$ of $(9.4 \pm 0.6)\%$ which includes the statistical and systematic contributions described above.

To determine the number of $e^+e^- \to q\bar{q}$ events in the signal region, we use the following procedure: we histogram the pseudo mass distribution of all data events that satisfy the topology requirement and are in the pseudo mass sideband $1.8 < m < 2.6$ GeV$/c^2$. The contribution of the τ background, determined from the simulation, is subtracted from this histogram, and the resulting distribution is fit with a Gaussian function. We then fix the mean and the width of this Gaussian, and use it to fit the τ-background-subtracted distributions of sideband events for all subsequent cuts, floating only the normalizations.

TABLE II. Predicted and observed number of events in the signal region of $1.3 < m < 1.8$ GeV$/c^2$. The τ background yield is obtained from the simulation, and its error reflects finite Monte Carlo statistics. The $e^+e^- \to q\bar{q}$ yield is determined by fitting the data in the pseudo mass sideband, and its error results from data statistics. BG denotes background.

	τ BG	$e^+e^- \to q\bar{q}$ BG	Observed
1–7 Topology	128 ± 13	574 ± 21	695
Particle ID	28 ± 6	241 ± 10	244
Conv. veto	2.4 ± 1.3	119 ± 5	104
1-Prong tag	1.3 ± 1.0	20.3 ± 0.7	24

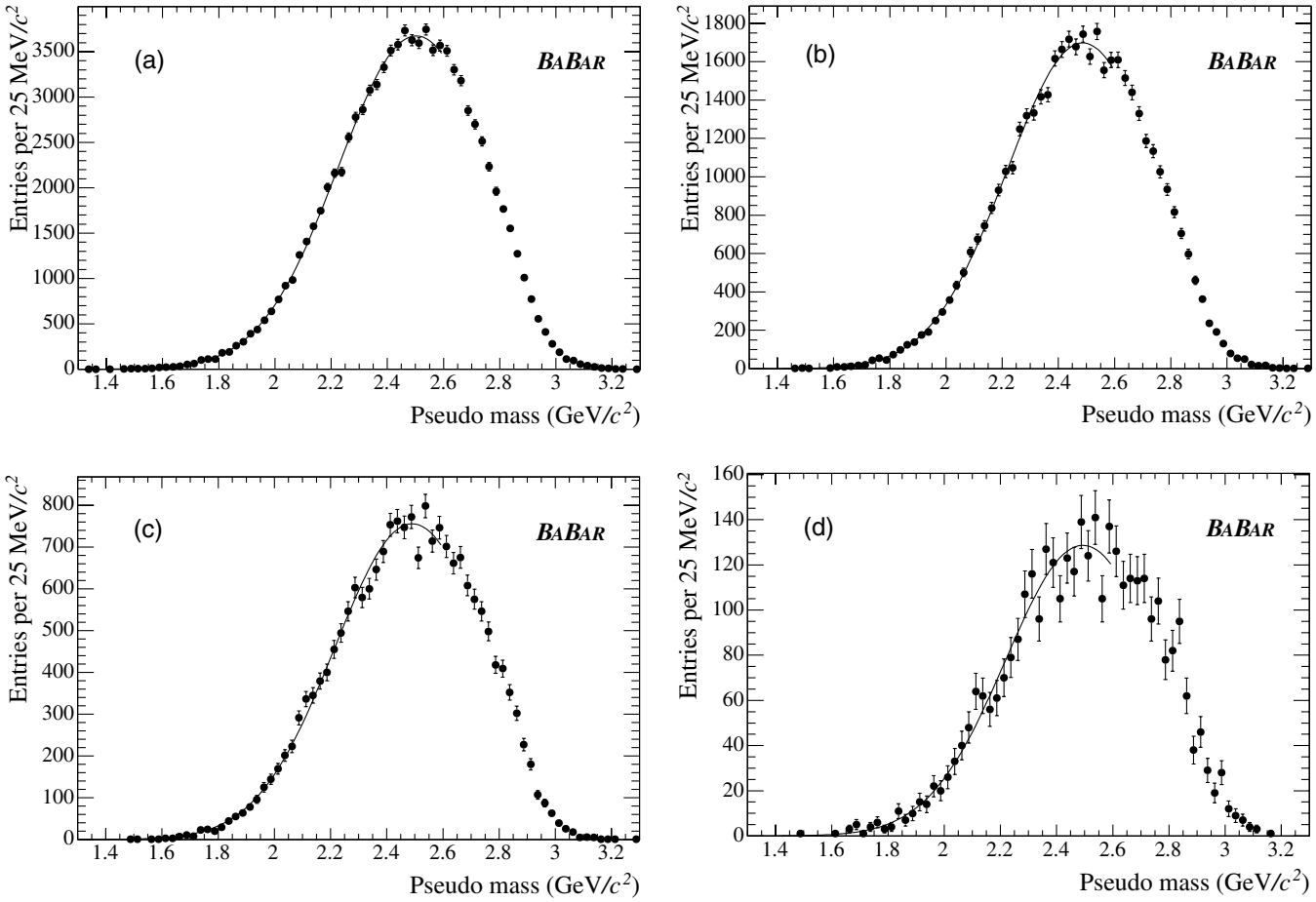

FIG. 2. Pseudo mass distributions for 1–7 topology data. (a) after 1–7 topology selection; (b) after particle identification; (c) after conversion veto; (d) after 1-prong tag.

Integrating the area of the resulting Gaussian functions in the signal region $1.3 < m < 1.8$ GeV$/c^2$ yields an estimate of the $e^+e^- \to q\bar{q}$ background contributions.

Table II lists the number of expected τ and $e^+e^- \to q\bar{q}$ background events in the signal region after the four selection steps. In Fig. 2(a)–2(d) we show the tau-background-subtracted pseudo mass data distribution after the four selection steps. Although entries below 1.8 GeV$/c^2$ are shown here, these events were hidden during the development of our analysis to avoid experimenter bias. Overlaid in the individual figures are the fit results to the pseudo mass spectra in the range of 1.8 to 2.6 GeV$/c^2$.

After the final selection we observe 24 events in the data [see Fig. 3(a)] with a total number of predicted background from τ and $e^+e^- \to q\bar{q}$ events of 21.6 ± 1.2. The statistical error of the $e^+e^- \to q\bar{q}$ background estimate is derived from the statistical uncertainties of the parameters in the Gaussian fit.

To validate the $e^+e^- \to q\bar{q}$ background estimation we use 1-8 topology data[2], which has negligible expected signal contributions. We fit the pseudo mass distribution between 1.8 and 2.6 GeV$/c^2$, integrate the fit function in the pseudo mass region 1.3 to 1.8 GeV$/c^2$, and compare this with the number of events found in data (see Table III, columns two and four). In addition, we repeat the fit with mean and sigma floating ("free" fit) in each individual distribution to compare the expected numbers of events (Table III, column three). As a final cross check, fits with the Gaussian mean and width floating were performed for the 1-7 topology data, and the results are included in Table III, column five. We note the very good agreement of the fits with fixed or floating Gaussian parameters.

The systematic error on the number of expected background events is ± 0.4 events, derived from variations of the fit range and shape of the extrapolation function. The total number of expected background events is 21.6 ± 1.3.

We calculate the branching fraction of the $\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau$ decay based on the following likelihood function, which convolves a Poisson distribution with two Gaussian resolution functions, accounting for the uncertainties in the background and in the efficiency:

[2]The event selection of the 1–7 topology was modified accordingly, to accommodate eight tracks on the signal side.

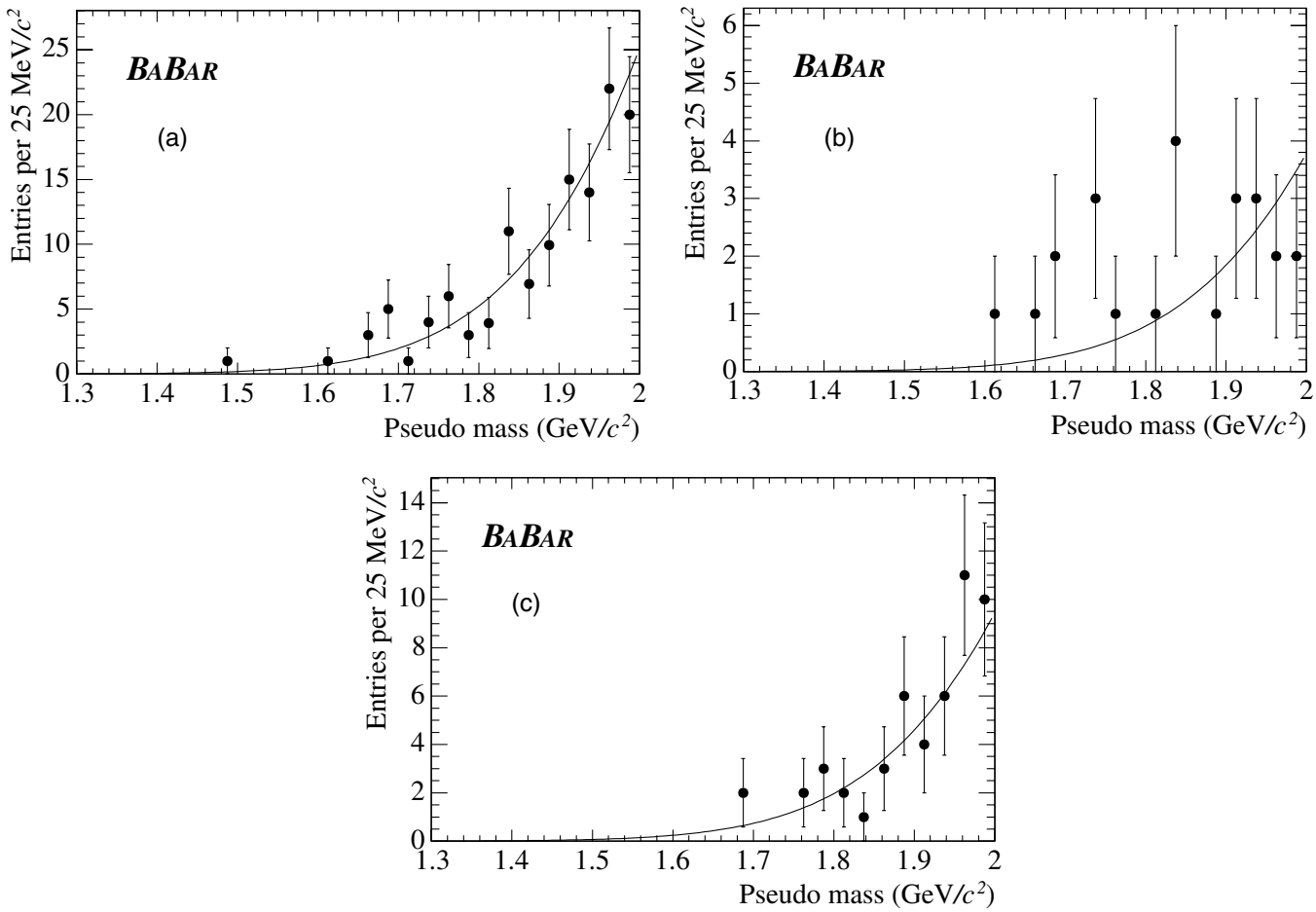

FIG. 3. Details of the data pseudo mass spectra. (a) $\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau$, (b) $\tau^- \to 4\pi^- 3\pi^+\nu_\tau$, (c) $\tau^- \to 4\pi^- 3\pi^+\pi^0\nu_\tau$ event candidates.

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

where $\mathcal{B}$ denotes the branching fraction of $\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau$, $f = 2N_{\tau\tau}\epsilon$, ϵ is the signal efficiency, $\mu = \langle n \rangle = \hat{f}\mathcal{B} + \hat{b}$, with n the number of observed events, and b and σ_b are the expected background and its error. σ_f incorporates the errors on the signal efficiency and the number of τ pair events.

The likelihood function is maximized with respect to the branching fraction $\mathcal{B}$, $\hat{f}$ and $\hat{b}$, and the following numerical value for the branching fraction is obtained by MINUIT [11]:

$$\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau) = (0.7^{+1.4}_{-1.3}) \times 10^{-7}.$$

Since we have no evidence for a signal we compute a Bayesian upper limit using a uniform prior in the branching fraction, the background, and the efficiency. This is done by integrating out $\hat{f}$ and $\hat{b}$ in the likelihood function and plotting $\mathcal{L}$ as function of $\mathcal{B}$. In this way we normalize the distribution to unity and get as the result of this analysis an upper limit at the point where the integral reaches 0.9:

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

With the same approach, setting the number of observed events $N_{\rm obs}$ to the expected number of background events of $N_{\rm exp} = 21.6$, we calculate the sensitivity of the analysis to be $\mathcal{B}^{N_{\rm obs}\equiv N_{\rm exp}}(\tau^- \to 4\pi^- 3\pi^+(\pi^0)\nu_\tau) < 2.5 \times 10^{-7}$ at 90% CL.

In addition to this inclusive result, we set limits on the branching fractions of the exclusive decay modes $\tau^- \to 4\pi^- 3\pi^+\nu_\tau$ and $\tau^- \to 4\pi^- 3\pi^+\pi^0\nu_\tau$. To select $\tau^- \to 4\pi^- 3\pi^+\nu_\tau$ candidates in the inclusive sample, we require

TABLE III. Observed and predicted number of $e^+e^- \to q\bar{q}$ background events in the 1-8 and 1-7 topology data for the different selection criteria.

	1–8 (fixed)	1–8 (free)	1–8 obs.	1–7 (free)
Topology	19.0 ± 2.7	19.0 ± 2.7	23	574 ± 21
Particle ID	12.2 ± 1.6	11.2 ± 2.0	10	222 ± 19
Conv. veto	2.7 ± 0.3	2.6 ± 1.4	1	126 ± 18
1-Pr. tag	0.5 ± 0.1	0.3 ± 0.5	0	20.2 ± 7.7

the number of photons on the signal side to be zero. This yields a signal efficiency for $\tau^- \to 4\pi^- 3\pi^+ \nu_\tau$ decays of $(5.5 \pm 0.3)\%$ while reducing the expected generic τ decay and $e^+e^- \to q\bar{q}$ background to 3.9 ± 0.8 events. The decays $\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau$ are treated as background in this case and have a reconstruction efficiency of $(0.8 \pm 0.1)\%$. Reversing this selection by demanding at least one reconstructed π^0 on the signal side yields a signal efficiency for the $\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau$ decay of $(3.6 \pm 0.3)\%$ and an expected generic τ decay and $e^+e^- \to q\bar{q}$ background of 8.2 ± 0.5 events. In this case, the reconstruction efficiency for $\tau^- \to 4\pi^- 3\pi^+ \nu_\tau$ is $(0.3 \pm 0.0)\%$. The systematic uncertainties of the $\tau^- \to 4\pi^- 3\pi^+ \nu_\tau$ mode are identical to the inclusive measurement already discussed above. For the $\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau$ mode, an additional uncertainty of 5.0% on the efficiency of the π^0 reconstruction is taken into account.

The likelihood function (2) was modified to accommodate one exclusive mode acting as background for the other. We observe eight events in the $\tau^- \to 4\pi^- 3\pi^+ \nu_\tau$ signal region and seven events in $\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau$. We calculate the following numerical values for the branching fractions:

$$\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+ \nu_\tau) = (2.0^{+1.5}_{-1.2}) \times 10^{-7},$$
$$\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau) = (-1.0 \pm 1.8) \times 10^{-7}.$$

Without evidence for a signal we compute Bayesian upper limits using uniform priors in the branching fractions, the backgrounds, and the efficiencies, of

$$\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+ \nu_\tau) < 4.3 \times 10^{-7} (\text{at } 90\% \text{ CL}),$$
$$\mathcal{B}(\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau) < 2.5 \times 10^{-7} (\text{at } 90\% \text{ CL}).$$

With the same approach, setting the number of observed events $N_{\rm obs}$ to the expected number of background events, we calculate the sensitivities $\mathcal{B}^{N_{\rm obs} \equiv N_{\rm exp}}(\tau^- \to 4\pi^- 3\pi^+ \nu_\tau) < 2.2 \times 10^{-7}$ and $\mathcal{B}^{N_{\rm obs} \equiv N_{\rm exp}}(\tau^- \to 4\pi^- 3\pi^+ \pi^0 \nu_\tau) < 4.2 \times 10^{-7}$. Figs. 3(b) and 3(c) show details of the data pseudo mass spectra with an overlay of the expected background distributions.

This analysis improves the existing experimental limits by an order of magnitude for the inclusive mode, but is still several orders of magnitude larger than the theoretical prediction. The exclusive decays are reported for the first time and are consistent with the inclusive result.

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