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Measurement of the $\tau^- \to K^- \pi^0 \nu_\tau$ branching fraction

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A measurement of the $\tau^- \to K^- \pi^0 \nu_\tau$ branching fraction has been made using 230.2 fb^{-1} of data recorded by the *BABAR* detector at the PEP-II e^+e^- collider, located at the Stanford Linear Accelerator Center (SLAC), at a center-of-mass energy $\sqrt{s}$ close to 10.58 GeV. We measure $\mathcal{B}(\tau^- \to K^- \pi^0 \nu_\tau) = (0.416 \pm 0.003(\mathrm{stat}) \pm 0.018(\mathrm{syst}))\%$.

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The τ is the only lepton with a sufficiently large mass to decay to hadrons. Tau decays to hadronic final states proceed via W exchange and thus the decay rates to the final states containing a strange quark are suppressed by the factor $(|V_{us}|/|V_{ud}|)^2$ relative to the nonstrange final states, where $|V_{ud}|$ and $|V_{us}|$ are the moduli of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2] elements. For a given value of m_s [3], $|V_{us}|$ can be determined up to unprecedented precision [4,5] from the inclusive sum of the branching fractions of τ decays to hadronic final states with net strangeness equal to unity. This determination of $|V_{us}|$ can be performed even without detailed knowledge of the hadronic mass spectrum arising due to incompleteness in our understanding of some of the intermediate resonance contributions.

In this paper we present a measurement of the $\tau^- \to K^- \pi^0 \nu_\tau$ branching fraction.[1] In recent years, measurements of the branching fractions for τ decays to strange hadronic final states have been made using CLEO [6], ALEPH [7], and OPAL [8] data, but have often been limited by the size of the available data samples. The high luminosity provided by the PEP-II asymmetric-energy e^+e^- storage rings [9] at the Stanford Linear Accelerator Center (SLAC) coupled with the large cross section for $\tau^+\tau^-$-pair production has given us a very large sample for studying such decays in the *BABAR* detector.

The *BABAR* detector is described in detail elsewhere [10]. Charged particles are detected and their momenta measured with a five-layer double-sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a 1.5 T superconducting solenoidal magnet. A ring-imaging Cherenkov detector (DIRC) provides additional separation power for identification of charged particles for momenta greater than 1 GeV/c, and thus complements dE/dx measurements in the DCH, useful for the identification of charged particles below 1 GeV/c. Energies of photons and electrons are measured by a CsI(Tl) crystal electromagnetic calorimeter (EMC), and the instrumented magnetic flux return (IFR) is used to identify muons.

The analysis described in this paper is based on a data sample corresponding to an integrated luminosity of 208.7 fb^{-1} collected at a center-of-mass energy $\sqrt{s}$ of 10.58 GeV and 21.5 fb^{-1} at $\sqrt{s} = 10.54$ GeV. With a cross section for $\tau^+\tau^-$ pair production averaged over $\sqrt{s}$ of $\sigma_{\tau\tau} = (0.919 \pm 0.003)$ nb [11], this total data sample of 230.2 fb^{-1} contains 211.6×10^6 $\tau^+\tau^-$ pairs.

Studies of Monte Carlo (MC) simulated events are carried out for signal and various background samples; τ pairs are generated with `KK2f` [12] and their decays simulated with `TAUOLA` [13]. Signal τ decays are modeled using form factors from the Breit-Wigner line shape of $K^*(892)$ decays [14], which nearly saturates the $\tau^- \to K^- \pi^0 \nu_\tau$ final state [6–8]. The other τ decays into any of the possible final states, according to the measured branching fractions [14]. To estimate non-tau backgrounds, samples of $\Upsilon(4S) \to B\bar{B}$, $e^+e^- \to q\bar{q}$ ($q = u$, d, s, c), and $e^+e^- \to \mu^+\mu^-(\gamma)$ are generated with `EvtGen` [15], `Jetset7.4` [16], and `KK2f` [12] MC programs, respectively. The available MC samples are weighted according to their respective size and cross sections in order to match the data integrated luminosity [14].

Each event is divided into hemispheres in the center-of-mass (CM) frame using the plane perpendicular to the thrust axis, which is the direction that maximizes the sum of the longitudinal components of the momenta of reconstructed particles, both neutral and charged. Only events with one charged track in each hemisphere, and with both tracks consistent with originating from the interaction point (1-1 topology) are selected. The net charge of the event is required to be zero.

To suppress light quark (u, d, s) hadronic events, while retaining the relatively large fraction ($\approx$35%) of τ leptons that decay leptonically, we require that one hemisphere contains a track that is identified either as an electron (e-tag) or as a muon (μ-tag). The charged track in the opposite hemisphere is then required to be within the geometrical acceptance of the DIRC and to be identified as a kaon, and inconsistent with an electron. In order to reject events where the kaon has decayed or interacted before reaching the DIRC, a two-dimensional requirement on the Cherenkov angle (θ_C) versus the laboratory momentum of the candidate kaon (p_{lab}) is used: θ_C (rad) $\leq 0.48 + 0.31 * p_{\mathrm{lab}}$ (GeV/c).

Event shape variables are used to discriminate against remaining $B\bar{B}$ and $q\bar{q}$ backgrounds. The thrust magnitude is required to be greater than 0.9, and the ratio of the 2nd to the 0th Fox-Wolfram moments [17] is required to be greater than 0.5. Also, to account for the substantial energy carried away by neutrinos in τ pair events, the total missing momentum in the laboratory frame is required to be greater than 0.5 GeV/c. This discriminates against Bhabha scattering and μ-pair events, as well as $q\bar{q}$ production.

[1]Throughout this paper, the charge conjugate decays are implied.

Moreover, we remove events in which a K_S^0 decay to two charged pions is identified.

We further require that the event contains only one π^0. Only π^0 mesons that have been reconstructed from two separate EMC clusters with an energy above 50 MeV, not associated with charged tracks, are considered in the analysis. Candidate π^0 mesons are required to have an invariant mass in the range $100 < m_{\gamma\gamma} < 160$ MeV$/c^2$ and an energy above 200 MeV in the CM frame. The mass of the selected photon pair is constrained to the nominal π^0 mass [14] to improve the purity of the selected $\pi^0 s$. The angle between the charged kaon and π^0 momenta in the CM frame is required to be less than 1.0 rad.

After all the above requirements, there remain 44 348 e-tagged events, and 33 764 μ-tagged events.

The MC simulated events are adjusted to improve their accuracy in modeling data events, according to several dedicated studies on specific control samples. Charged tracks are weighted to compensate for the different particle identification (PID) efficiencies between data and MC. On average, the MC efficiency is reduced by 15% and 3% for muons and kaons, respectively. The electron identification is properly simulated and therefore no MC efficiency correction is applied. A correction to the π^0 MC efficiency has been obtained from detailed studies based on $\tau^- \rightarrow \rho^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \nu_\tau$ events. As a result of this study, the π^0 MC efficiency is reduced by 2%.

We estimate the $\tau^- \rightarrow K^- \pi^0 \nu_\tau$ selection efficiencies to be 1.31%, 0.96%, and 2.27% for the e-tag, μ-tag, and combined samples, respectively, using the signal MC sample with all requirements and corrections applied. The efficiency as a function of the $K^- \pi^0$ mass is consistent with being constant.

Figure 1 shows the invariant mass spectra of the selected $K^- \pi^0$ candidates and simulated backgrounds for the combined sample after all the analysis requirements. The contribution from light quarks, $c\bar{c}$ and $\mu^+ \mu^- (\gamma)$ backgrounds is much smaller than the τ-pair backgrounds. The contribution from $B\bar{B}$ backgrounds is negligible. The $K^*(892)^-$ resonance is seen prominently above the simulated background. Decays to higher K^* resonances are expected near 1.4 GeV$/c^2$ [18–20], such as the $K^*(1410)^-$ [21] and $K_0^*(1430)^-$ [21], but their branching fractions are not well measured yet. These decays are not included in our simulation of τ-pair events, but appear to be present in the data near 1.4 GeV$/c^2$. Below 0.7 GeV$/c^2$, the background is dominated by $K^- \pi^0 \pi^0$ and $K^- K^0 \pi^0$ events, for which the branching fractions are only known with relative uncertainties $\approx 40\%$ and $\approx 15\%$, respectively. These uncertainties are taken into account in the estimation of the systematic uncertainty due to modeling of the τ backgrounds.

The branching fraction $\mathcal{B}(\tau^- \rightarrow K^- \pi^0 \nu_\tau)$ is calculated as $\mathcal{B} = [N_{\rm sel} - N_{\rm bkg}]/2\varepsilon_{\rm sig} N_{\tau\tau}$, where $N_{\tau\tau} = \mathcal{L}\ \sigma_{\tau\tau} = 2.116 \times 10^8$ is the number of produced $\tau^+\tau^-$ pairs; $\varepsilon_{\rm sig}$ is the estimated signal selection efficiency; $N_{\rm sel}$ is the number of events selected in data; and $N_{\rm bkg}$ is the estimated number of background events obtained from MC simulations. For the combined e-tagged and μ-tagged sample, $N_{\rm sel} = 78\,112 \pm 280$ events and the estimated background is $N_{\rm bkg} = 38\,247 \pm 159$ events. The branching fraction $\mathcal{B}(\tau^- \rightarrow K^- \pi^0 \nu_\tau)$ is found to be $(0.416 \pm 0.003(\text{stat}))\%$, where the statistical uncertainty comes from the uncertainty in the number of signal events, $N_{\rm sel} - N_{\rm bkg}$. Several cross checks were performed by determining the branching fraction as a function of tag type, π^0 momentum, kaon charge, and run period; all were found to give consistent results.

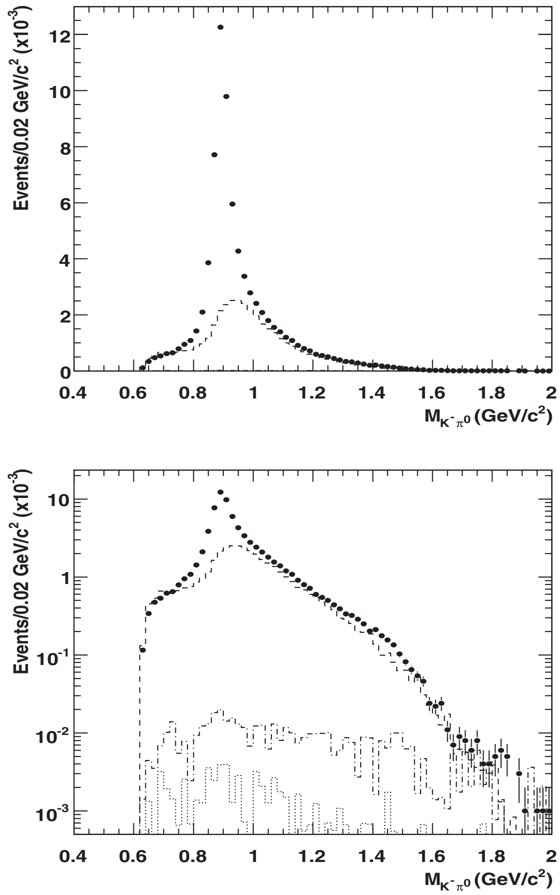

FIG. 1. Distribution of the reconstructed $K^- \pi^0$ mass for the combined sample in linear (top) and logarithmic (bottom) scale. The dots are the data, while the histograms are background MC events with selection and efficiency corrections: τ background (dashed line), $q\bar{q}$ (dash-dotted line), $\mu^+\mu^-$ (dotted line).

A summary of the systematic uncertainties is given in Table I. The uncertainty in the charged track reconstruction efficiency is estimated to be 0.31% per track, based on studies of data control samples of τ-pair events decaying to one charged particle on one side and three charged particles on the other side. The systematic uncertainty associated with the efficiency of detecting a π^0 is 3.26%. The stated uncertainty in the charged particle identification

TABLE I. Relative systematic uncertainties in the $\tau^- \to K^- \pi^0 \nu_\tau$ analysis.

Systematic	e-tag	μ-tag	Combined
	(%)	(%)	(%)
Tracking efficiency	0.62	0.62	0.62
π^0 efficiency	3.26	3.26	3.26
Particle identification	2.09	2.34	2.17
$\tau\tau$ cross section ($\sigma_{\tau\tau}$)	0.31	0.31	0.31
Luminosity ($\mathcal{L}$)	0.94	0.94	0.94
Signal modeling and MC statistics	0.38	0.52	0.35
τ backgrounds	1.35	1.35	1.35
TOTAL	4.28	4.42	4.32

efficiency represents the combined uncertainty for the two charged tracks, (e, K) or (μ, K). This uncertainty includes a contribution due to the misidentification of charged pions as kaons. The uncertainty associated with the $\tau^+\tau^-$ pair production cross section is 0.31% [11] and the luminosity determination uncertainty is 0.94%. The effects of approximations in the MC signal modeling and of the finite MC statistics on the overall efficiency are negligible, but have been included in the estimation of the systematic uncertainty. The branching fractions for several τ decay modes that contribute to the background, particularly Cabibbo-suppressed decays, are not well known. The resulting uncertainty due to the τ-pair background estimate on the $\tau^- \to K^- \pi^0 \nu_\tau$ branching fraction is 1.35%. Backgrounds from other sources are very small and their impact of the signal extraction is negligible.

The total systematic uncertainty is the quadratic sum of the individual sources described above, and is 4.32% for the combined sample.

In summary, using 211.6×10^6 $\tau^+\tau^-$ pairs recorded by the *BABAR* detector, we obtain the following result:

$$\mathcal{B}(\tau^- \to K^- \pi^0 \nu_\tau) = (0.416 \pm 0.003(\text{stat}) \pm 0.018(\text{syst}))\%.$$

This measurement of the branching fraction is the most precise to date and is consistent with the existing world average, $\mathcal{B}(\tau^- \to K^- \pi^0 \nu_\tau) = (0.454 \pm 0.030)\%$ [14].

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