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Search for Second-Class Currents in  $\tau^- \rightarrow \omega \pi^- \nu_\tau$ 

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We report an analysis of  $\tau^-$  decaying into  $\omega\pi^-\nu_\tau$  with  $\omega \rightarrow \pi^+\pi^-\pi^0$  using a data sample containing nearly  $320 \times 10^6 \tau$  pairs collected with the BABAR detector at the PEP-II B-Factory. We find no evidence

for second-class currents, and we set an upper limit of 0.69% at 90% confidence level for the fraction of second-class currents in this decay mode.

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Hadronic weak currents can be classified as either first- or second-class depending on the spin  $J$ , parity  $P$ , and  $G$ -parity  $G$  of the final hadronic system [1]. In the Standard Model, first-class currents (FCC) in  $\tau$  decays have  $J^{PG} = 0^{++}, 0^{--}, 1^{+-},$  or  $1^{-+}$ , and are expected to dominate. Second-class currents (SCC) have  $J^{PG} = 0^{+-}, 0^{-+}, 1^{++},$  or  $1^{--}$ , and are associated with a decay constant proportional to the mass difference between up and down quarks. Thus, they are expected to vanish in the limit of perfect isospin symmetry. A number of mechanisms have been suggested [2], including possible exchange of Higgs bosons, that could lead to an enhanced rate for second-class currents. Searches have taken place extensively in nuclear  $\beta$  decay experiments [3,4], with no confirmed observations. This Letter presents a search for SCC in  $\tau^- \rightarrow \omega \pi^- \nu_\tau$  decays with  $\omega \rightarrow \pi^+ \pi^- \pi^0$ , based on studying the angular distributions of final-state particles.

The decay  $\tau^- \rightarrow \omega \pi^- \nu_\tau$  [5] is expected to proceed predominantly through FCC mediated by the  $\rho$  resonance. This decay may also potentially proceed through SCC with  $J^{PG} = 0^{-+}$  or  $1^{++}$ . The latter may be mediated by  $b_1(1235)$  [6] with  $\tau^- \rightarrow b_1^- \nu_\tau \rightarrow \omega \pi^- \nu_\tau$ . The decay  $b_1^- \rightarrow \omega \pi^-$  occurs through  $S$ - and  $D$  waves [7], as compared to a  $P$  wave for FCC. Different alignments of  $\omega$  spin result in different angular distributions of the final-state particles. The expected distributions of  $\cos\theta_{\omega\pi}$ ,  $F(\cos\theta_{\omega\pi})$ , for all possible spin-parity states of the final-state particles are listed in Table I, where  $\theta_{\omega\pi}$  is the angle between the normal to the  $\omega$  decay plane and the direction of the remaining  $\pi$  in the  $\omega$  rest frame. The existing measurements of the angular distribution in  $\tau^- \rightarrow \omega \pi^- \nu_\tau$  are consistent with having only the  $P$ -wave contribution, and the present upper limit is 5.4% for the ratio of SCC to FCC contributions at 90% confidence level (CL) [8,9].

This analysis is based on data recorded by the *BABAR* detector [10] at the PEP-II asymmetric-energy  $e^+e^-$  storage rings operated at the SLAC National Accelerator Laboratory. The data sample consists of  $347.3 \text{ fb}^{-1}$  recorded at a center-of-mass energy of 10.58 GeV. With a cross section for  $\tau$  pairs of  $\sigma_{\tau\tau} = (0.919 \pm 0.003) \text{ nb}$  [11,12], this data sample contains nearly  $320 \times 10^6$  pairs of  $\tau$  decays.

The *BABAR* detector is described in detail in Ref. [10]. Charged-particle tracks are measured with a 5-layer double-sided silicon vertex tracker (SVT) together with a 40-layer drift chamber (DCH) inside a 1.5-T superconducting solenoid magnet. An electromagnetic calorimeter (EMC) consisting of 6580 CsI(Tl) crystals is used for identification of electrons and photons. Charged hadrons are identified by a ring-imaging Cherenkov detector in

combination with energy-loss measurements ( $dE/dx$ ) in the SVT and the DCH. An instrumented magnetic-flux return (IFR) provides muon identification.

Monte Carlo simulation is used to estimate the signal efficiencies and background contamination. KK2F [12] is used to generate  $\tau$  pairs with the decays of the  $\tau$  leptons modeled by TAUOLA [13]. Continuum  $q\bar{q}$  events are simulated using JETSET [14]. Final-state radiative effects are generated for all decays using PHOTOS [15]. The detector response is simulated with GEANT4 [16], and the Monte Carlo events are reconstructed in the same manner as data.

Since  $\tau$  pairs are produced back to back in the  $e^+e^-$  center-of-mass frame, each event is divided into two hemispheres according to the thrust axis [17], calculated using all reconstructed charged particles. Candidate events in this analysis are required to have a “1–3 topology,” where one track is in one hemisphere (tag hemisphere) and three tracks are in the other hemisphere (signal hemisphere). Events with four well-reconstructed tracks and zero net charge are selected for further analysis. The polar angles of all four tracks and the neutral clusters used in  $\pi^0$  reconstruction are required to be within the calorimeter acceptance range. Events are rejected if the invariant mass of any pair of oppositely charged tracks, assuming electron mass hypotheses, is less than  $90 \text{ MeV}/c^2$ , as these tracks are likely to be from photon conversions in the detector material.

The charged particle found in the tag hemisphere must be either an electron or a muon candidate. Electrons are identified using the ratio of calorimeter energy to track momentum ( $E/p$ ), the shape of the shower in the calorimeter, and  $dE/dx$ . Muons are identified by signals in the IFR and small energy deposits in the calorimeter consistent with expectation for a minimum-ionizing particle. Charged particles found in the signal hemisphere must be identified as pion candidates. The  $\pi^0$  candidates are reconstructed from two separate EMC clusters with energies above 100 MeV that are not associated with charged tracks; these  $\pi^0$  candidates are required to have invariant masses be-

TABLE I. Expected angular distributions,  $F(\cos\theta_{\omega\pi})$ , for possible spin-parity states in the decay  $\tau^- \rightarrow \omega \pi^- \nu_\tau$ .  $L$  is the orbital angular momentum.

$J^P$	$L$	$F(\cos\theta_{\omega\pi})$
$1^-$	1	$(1 - \cos^2\theta_{\omega\pi})$
$0^-$	1	$\cos^2\theta_{\omega\pi}$
$1^+$	0	1
$1^+$	2	$(1 + 3\cos^2\theta_{\omega\pi})$

tween 100 and 160 MeV/c<sup>2</sup>. Events are required to have a single  $\pi^0$  in the signal hemisphere. The  $\tau$  candidates are reconstructed in the signal hemisphere using the three tracks and the  $\pi^0$  candidate. The invariant mass of the  $\tau$  candidate,  $m(\pi^-\pi^-\pi^+\pi^0)$ , is required to be less than the mass of the  $\tau$  lepton. The Monte Carlo simulation predicts that 14% of the events remaining after the event selection process are  $\tau$ -pair events that do not contain a  $\tau^- \rightarrow \pi^-\pi^-\pi^+\pi^0\nu_\tau$  decay, and 1.3% are  $e^+e^- \rightarrow q\bar{q}$  events.

Each selected event has two  $\pi^+\pi^-\pi^0$  combinations. The  $\omega$  signal region is defined for masses  $m(\pi^+\pi^-\pi^0)$  between 760 MeV/c<sup>2</sup> and 800 MeV/c<sup>2</sup> with mass regions of width 60 MeV/c<sup>2</sup> on each side of the peak used as sideband regions for background studies, as shown in Fig. 1. For each  $\omega$  candidate, the angle  $\theta_{\omega\pi}$  is calculated. The distribution of  $\cos\theta_{\omega\pi}$  is used for the SCC measurement.

There are three background sources to be considered in this analysis: combinatoric background,  $q\bar{q}$  events, and nonsignal  $\tau$  decays. The combinatoric background is expected, and confirmed by the simulation, to have a distribution of  $\cos\theta_{\omega\pi}$  which is independent of  $m(\pi^+\pi^-\pi^0)$ . This allows the sideband regions to be used to subtract this background. The number of combinatoric events lying within the signal region is obtained by fitting the  $m(\pi^+\pi^-\pi^0)$  spectrum with a relativistic Breit-Wigner convolved with a resolution function for the  $\omega$  resonance and a polynomial for the combinatoric background. The polynomial is integrated over the signal region to find the number of continuum events in the signal region.

After subtracting the combinatoric background, approximately 0.3% of the remaining events in the signal region are expected to be of  $q\bar{q}$  origin, while 4.6% are expected to be from nonsignal  $\tau$  decays. The background from  $e^+e^- \rightarrow q\bar{q}$  events that contain  $\omega \rightarrow \pi^+\pi^-\pi^0$  de-

cays is studied using events with  $m(\pi^-\pi^-\pi^+\pi^0)$  well above the  $\tau$  mass ( $>2.1$  GeV/c<sup>2</sup>). In this region, where all events are considered to be of  $q\bar{q}$  origin, a comparison of the numbers of  $\omega$  mesons in simulation and data is used to scale the simulated  $q\bar{q}$  background before subtracting from data.

The dominant nonsignal  $\tau$  background, comprising 99% of the remaining background, is  $\tau^- \rightarrow \omega\pi^-\pi^0\nu_\tau$ , where the additional  $\pi^0$  has not been reconstructed. The decay  $\tau^- \rightarrow \omega\pi^-\pi^0\nu_\tau$  has not been well measured and is incorrectly modeled in the Monte Carlo simulation. To correct for the differences between data and Monte Carlo simulations, events with an additional  $\pi^0$  candidate in the signal hemisphere are selected, using the same cuts discussed above. Using these events, the Monte Carlo branching fraction of  $\tau^- \rightarrow \omega\pi^-\pi^0\nu_\tau$  is corrected by comparing the numbers of fitted  $\omega$  candidates in data and Monte Carlo simulations. The fit function used for this is a relativistic Breit-Wigner convolved with a resolution function plus a polynomial background. The branching fraction obtained using this correction technique is found to be consistent with existing measurements [7]. To correct the angular distribution of  $\tau^- \rightarrow \omega\pi^-\pi^0\nu_\tau$ , backgrounds, consisting of combinatorics,  $q\bar{q}$  events, and  $\tau^- \rightarrow \omega\pi^-\nu_\tau$  decays (assuming the angular distribution corresponding to the dominant FCC contribution), are subtracted from the  $\omega\pi^-\pi^0$  data sample, and the remaining  $\cos\theta_{\omega\pi}$  distribution is used to correct the  $\tau^- \rightarrow \omega\pi^-\pi^0\nu_\tau$  distribution in the Monte Carlo simulation.

After subtracting backgrounds and applying  $\cos\theta_{\omega\pi}$ -dependent efficiency corrections, a binned fit to the remaining  $\cos\theta_{\omega\pi}$  distribution is carried out using

$$F(\cos\theta_{\omega\pi}) = N \left[ \frac{1}{2} \epsilon + \frac{3}{4} (1 - \epsilon)(1 - \cos^2\theta_{\omega\pi}) \right], \quad (1)$$

where  $N$  is a normalization factor and the parameter  $\epsilon$  is the fraction of  $\tau^- \rightarrow \omega\pi^-\nu_\tau$  decays that proceed through SCC. In Eq. (1), only the  $L = 0$  term is used to describe the SCC contribution since this function gives the most conservative estimate of  $\epsilon$  (i.e., the largest upper limit).

To help validate the analysis method, the procedures were applied to Monte Carlo samples generated to include small fractions (1% and 2%) of the second-class current process  $\tau^- \rightarrow b_1(1235)^-\nu_\tau \rightarrow \omega\pi^-\nu_\tau$ , as well as to a sample containing no SCC contribution. In each case, the fits to the simulated detector-level, background-subtracted angular distributions returned values consistent with the input fractions of SCC.

The largest contributions to systematic uncertainties on  $\epsilon$  are scaling and modeling the Monte Carlo background. The correction applied to the branching fraction of  $\tau^- \rightarrow \omega\pi^-\pi^0\nu_\tau$  has an error associated with it, determined by the available statistics. This correction factor is adjusted by  $\pm 1\sigma$  to obtain the uncertainty in  $\epsilon$  while the errors associated with correcting the angular distribution are folded

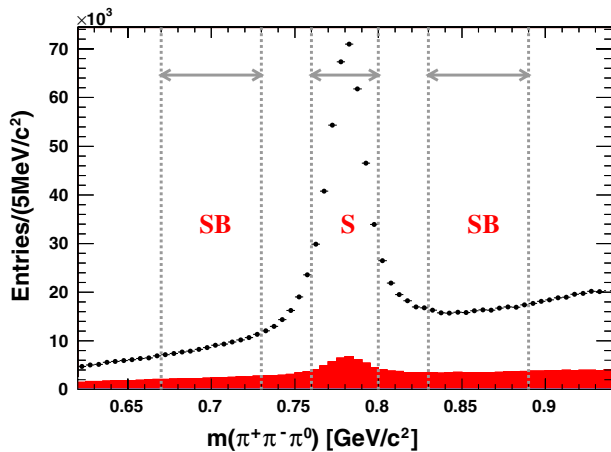


FIG. 1 (color online).  $\omega$  candidate mass spectra for selected events in data and background expected from simulation (shaded histogram). The background histogram does not include the nonresonant  $\tau^- \rightarrow \pi^-\pi^-\pi^+\pi^0\nu_\tau$  decays. The signal (S) and sideband (SB) regions are indicated in the figure.

TABLE II. Summary of systematic uncertainties on  $\epsilon$ .

Source	Uncertainty ( $\sigma_\epsilon$ )
$\mathcal{B}(\tau^- \rightarrow \omega \pi^- \pi^0 \nu_\tau)$	$\pm 0.07\%$
nonsimulated $\tau$ decays	$+0.00\%$ $-0.55\%$
$q\bar{q}$ scaling	$\pm 0.01\%$
Total	$+0.08\%$ $-0.55\%$

into the statistical uncertainty. In addition, there are  $\tau$  decays that may be present in the final event sample but which are not included in the simulation. The largest of these are expected to be  $\tau^- \rightarrow \omega K^- \nu_\tau$ ,  $\tau^- \rightarrow \omega \pi^- \pi^0 \pi^0 \nu_\tau$ , and  $\tau^- \rightarrow \omega \pi^- \pi^- \pi^+ \nu_\tau$  decays which, when combined, can add up to 0.2% of the final event sample. Since the effect that these decays have on the angular distribution is unknown, the extreme cases are taken to obtain the uncertainty. These cases correspond to the decays having either entirely  $1 - \cos^2\theta_{\omega\pi}$  or entirely  $\cos^2\theta_{\omega\pi}$  distributions. The scaling of  $q\bar{q}$  events can also affect the measurement of  $\epsilon$ , and the uncertainty is obtained by adjusting the scaling factor by  $\pm 1\sigma$ . These systematic uncertainties are summarized in Table II.

Subsets of the generic Monte Carlo dataset are used in the background studies and in the determination of the efficiencies. Therefore, to estimate the sensitivity of the analysis without the effect of statistical correlations in the Monte Carlo samples, an ensemble of simulated experiments is used. In this study, angular distributions are generated for the signal and sideband regions to simulate the statistics available in the data and various Monte Carlo samples used in the analysis, with  $\epsilon = 0$  in the signal Monte Carlo simulation. After subtracting background samples, the angular distribution is corrected for efficiency and fitted using Eq. (1). The statistical uncertainty on  $\epsilon$  obtained from the fit is 0.63%, which combined with the systematic uncertainties leads to an estimated uncertainty of  $\sigma_\epsilon = {}^{+0.64}_{-0.84}\%$ .

The angular distribution of the final-state particles in data is obtained by subtracting estimated backgrounds as described above. The remaining distribution is corrected for efficiency and fitted using Eq. (1) as shown in Fig. 2. The fit has  $\chi^2/(\text{degrees of freedom}) = 15.4/18$ , and the fitted value of  $\epsilon$  in the data is  $[-0.55 \pm 0.58(\text{stat}) {}^{+0.08}_{-0.55}(\text{syst})]\%$ , which is consistent with no SCC contribution to  $\tau^- \rightarrow \omega \pi^- \nu_\tau$  decays.

The upper limit on  $\epsilon$  is obtained using a Bayesian approach [18] with a prior that is flat for  $\epsilon > 0$  and zero for  $\epsilon < 0$ . The probability distribution for the value of the SCC contribution is a Gaussian with mean  $\epsilon = -0.55\%$  and errors  $\sigma_\epsilon = {}^{+0.64}_{-0.84}\%$ , taken from the simulation studies; however, since negative values of  $\epsilon$  are nonphysical, only the positive portion of this probability distribution is used in the limit calculation. The limits obtained from this

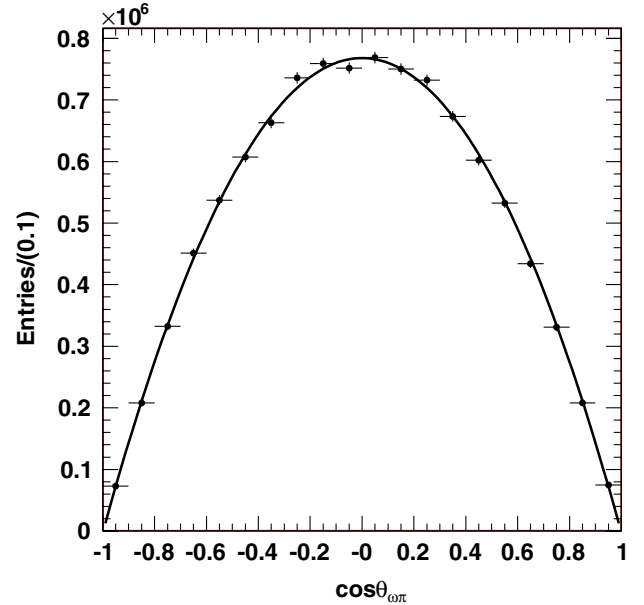


FIG. 2 (color online). The  $\cos\theta_{\omega\pi}$  distribution for the data. The curve is the result of the fit described in the text.

method are  $\epsilon < 0.68\%$  at 90% CL and  $\epsilon < 0.84\%$  at 95% CL.

In summary, a search for second-class currents in the decay  $\tau^- \rightarrow \omega \pi^- \nu_\tau$  has been conducted with the *BABAR* detector. No evidence for second-class currents is observed, and a 90% confidence level Bayesian upper limit for the fraction of the second-class current in  $\tau^- \rightarrow \omega \pi^- \nu_\tau$  decays is set at 0.68%. For comparison with the previous result from CLEO, this is equivalent to a ratio of second-class (nonvector) to first-class (vector) currents of 0.69%. This limit is an order of magnitude lower than the limit set by the CLEO collaboration [9].

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