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Tau decays into three charged leptons and two neutrinos.

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Abstract

A search for $\tau \to ee^+e^-\nu_\tau\nu_e$ and $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ decays is performed using $3.60\,\mathrm{fb}^{-1}$ of data collected by the CLEO-II experiment at CESR. A first observation of the $\tau \to ee^+e^-\nu_\tau\nu_e$ process is presented. For this channel we obtained the branching fraction $B(\tau \to ee^+e^-\nu_\tau\nu_e) = (2.7^{+1.4}_{-1.3} \pm 0.4) \times 10^{-5}$. An upper limit is established for the second channel: $B(\tau \to \mu e^+e^-\nu_\tau\nu_\mu) < 3.1 \times 10^{-5}$ at 90% CL. Both measurements are consistent with the rates expected from Standard Model predictions.

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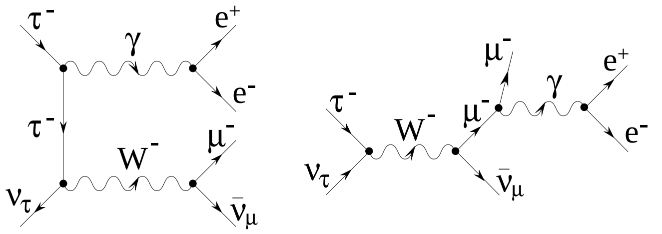
Tau decays into three charged leptons and two neutrinos are allowed processes in the Standard Model. They proceed via emission of a virtual photon with a subsequent internal conversion into a pair of electrons or muons. Two Feynman diagrams provide the dominant contribution to the decay rate. They are shown on the picture below for the $\tau^- \to \mu^- e^+ e^- \nu_\tau \bar{\nu}_\mu$ decay:



The contribution of a third diagram, with a virtual photon emitted from the W boson, is suppressed almost by two orders of magnitude due to the W boson propagator and has a negligible effect on the decay rate. For τ decays with two identical charged leptons in the final state, two additional exchange diagrams are involved. Branching fractions for these processes have recently been calculated by Dicus and Vega [1] and are listed in Table I. The branching fractions for tau decays with a virtual photon conversion into two muons in the final state, $\tau \to e\mu^+\mu^-\nu_\tau\nu_e$ and $\tau \to \mu\mu^+\mu^-\nu_\tau\nu_\mu$, are expected to be at the level of 10^{-7} and are too small to be measured with present τ decay data samples. On the other hand, the branching fractions for $\tau \to ee^+e^-\nu_\tau\nu_e$ and $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ are expected to be at the level of 10^{-5} which is comparable to the sensitivity reached in a recent search for neutrinoless tau decays into three charged particles [2]. In this study we concentrate on these electron modes.

The data used in this analysis were collected with the CLEO-II detector at the Cornell Electron Storage Ring (CESR). Our study uses information from a 67-layer tracking system which also provides specific ionization measurements, time-of-flight scintillation counters and a 7800-crystal CsI calorimeter. These elements are inside a 1.5 T superconducting solenoidal magnet whose iron yoke also serves as a hadron absorber for a muon identification system. A detailed description of the apparatus can be found in ref. [3]. Tau leptons are produced in pairs in e^+e^- collisions. About 60% of the events were obtained at the $\Upsilon(4S)$ resonance ($\sqrt{s} \simeq 10.59\,\mathrm{GeV}$) while the rest were obtained at energies approximately 60 MeV below the resonance. The data correspond to an integrated luminosity of about $3.60\,\mathrm{fb}^{-1}$ and the number of produced tau pairs, $N_{\tau\tau}$, is $(3.28 \pm 0.05) \times 10^6$.

Since an event generator is needed in order to estimate the detector acceptance and the efficiency of data selection, we performed our own calculation of the relevant matrix elements using the symbolic manipulation program FORM [4]. Using our Monte Carlo program we have generated $100,000$ $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ and $60,000$ $\tau \to ee^+e^-\nu_\tau\nu_e$ decays. No τ polarization effects or higher order radiative corrections were taken into account in simulating these decay modes. The KORALB/TAUOLA program package [5] was used to simulate the tau-pair production and the decay of the other tau in the event. Detector signals were simulated by the standard CLEO-II simulation program [6]. To check our Monte Carlo generator, we used it to calculate the branching fraction for the known five lepton decay of the muon, $\mu \to eee\nu_\mu\nu_e$. The result, listed in Table I, is consistent with the calculation of Dicus and Vega and also with an earlier estimate $B(\mu \to eee\nu_\mu\nu_e) = (3.54 \pm 0.09) \times 10^{-5}$ by

Bardin *et al.* [7]. It also agrees well with the experimental measurement $B(\mu \to eee\nu_\mu\nu_e) = (3.4 \pm 0.4) \times 10^{-5}$ by the SINDRUM collaboration [8]. For tau decays our branching fraction estimates are 6-7% higher than those calculated by Dicus and Vega.

The momenta distributions of electrons from $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ and $\tau \to ee^+e^-\nu_\tau\nu_e$ decay modes are shown in Fig. 1. These plots reveal an intrinsic difficulty of detecting such τ decays: for both channels the electron spectrum is peaked at very low momenta where there is a high probability for electron absorption in the beam pipe or for a mismeasurement of its trajectory and a misidentification.

From our branching fraction calculation we expect about 137 $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ and 292 $\tau \to ee^+e^-\nu_\tau\nu_e$ decays in our data sample. To extract these decays we search for events where one τ decays into a single charged particle (1-prong decay) and the other τ decays into three charged particles (3-prong decay). The 3-prong decay is the signal candidate and the 1-prong decay is an allowed τ decay with one charged particle, zero or more photons and at least one neutrino in the final state. For each candidate event we require four well-reconstructed charged particle tracks with zero total charge. At CLEO-II center-of-mass energies, each tau lepton has sufficient boost to render its daughter particles well-separated from those of the other tau, so we select candidate events in a 1-vs-3 topology. The event topology is determined by defining a plane perpendicular to each momentum vector and counting tracks on either side of the plane. Events with no track separated by more than 90 degrees from all other tracks are rejected. In ambiguous cases, where more than one such track exists, the event topology is selected by choosing the solution with the maximum angle between the 1-prong track momentum vector and the sum of momenta on the 3-prong side. We also require no photons with energy larger than $E > 60$ MeV in the 3-prong hemisphere.

Substantial background suppression comes from lepton identification on the 3-prong side. In the $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ channel we require a muon candidate with momentum less than 2.2 GeV/c to pass through at least 3 hadronic absorption lengths of iron and through at least 5 absorption lengths if its momentum is greater than 2.2 GeV/c. For such muon candidates, the energy deposited in the CsI calorimeter, E_c, must be compatible with that expected for a minimum ionizing particle: 0.1 GeV $< E_c <$ 0.5 GeV. We also require that the charge of the muon candidate is opposite to that of the 1-prong track. For electron identification, we rely mostly on specific ionization measurements in the drift chamber. We require that the electron candidate specific ionization differs from the expected value by less than 3 standard deviations. If there is a time-of-flight measurement we require that it is compatible with the electron hypothesis within 3 standard deviations, and if the electron candidate reaches the CsI calorimeter we require that the ratio of the energy deposited in the calorimeter to the electron momentum, p_e, is less than 1.1. This last requirement helps reject events where there is a photon on the 3-prong side which goes undetected because its calorimeter energy deposit overlaps with an energy deposit from one of the electron candidates. In addition, the electron candidates with transverse momentum larger than 0.3 GeV/c and within the high resolution region of the calorimeter (*i.e.,* the angle between the track and the beam axis is greater than 45^o) are required to have $E_c/p_e > 0.8$. For the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel at least one electron candidate (not necessarily in the high resolution region) is required to satisfy this latter condition. In order to suppress a strong $e^+e^- \to e^+e^-e^+e^-$ background we also require that in this channel the 1-prong particle is not consistent with being an electron. It must either pass through three absorption lengths of a muon filter or it must be within the high resolution region of the calorimeter, have transverse momentum larger than 0.3 GeV/c and have the ratio of the calorimeter energy to the track's momentum less than 0.7.

The main sources of background left after the lepton identification are: low multiplicity $e^+e^- \to q\bar{q}$ events, 2-photon processes, radiative μ-pairs and the radiative leptonic decays $\tau \to l\nu_\tau\nu_l\gamma$ (l stands for e or μ) with subsequent $\gamma \to e^+e^-$ conversion in the detector material, τ decays into three hadrons and a neutrino where all hadrons are misidentified as leptons, and finally τ decays into $\rho\nu_\tau$ with subsequent $\rho \to \pi\pi^0$, $\pi^0 \to e^+e^-\gamma$ decays, where the γ escapes detection and the π is misidentified as a lepton.

In order to suppress a non-tau background, we require undetected neutrinos be present by selecting events with large missing energy, $\mathrm{E_{miss}} > 1.5$ GeV, and a large value of total transverse momentum of the charged particles with respect to the beam direction, $p_t >$ 150 MeV/c. $\tau \to 3h\nu_\tau$ decays contribute to the background in our analysis due to a rather large branching fraction, about 8.4% [9], and a few percent probability for pions to fake leptons. The probability for a pion to pass our muon identification criteria is about 3-4%. The probability for low energy pions to fake electrons is even larger because we rely on specific ionization for particle identification and in the momentum range 150-200 MeV/c pion and electrons have about the same ionization losses. In order to reduce the $\tau \to 3h\nu_\tau$ background, we consider the probability for all our electron candidates to be pions. This probability is estimated from the specific ionization measurement. We define the quantities:

$$\kappa_2 = \frac{\mathrm{P}_{e^+}\mathrm{P}_{e^-}}{\mathrm{P}_{e^+}\mathrm{P}_{e^-} + \mathrm{P}_{\pi^+}P_{\pi^-}}, \ \kappa_3 = \frac{\mathrm{P}_e\mathrm{P}_{e^+}\mathrm{P}_{e^-}}{\mathrm{P}_e\mathrm{P}_{e^+}\mathrm{P}_{e^-} + \mathrm{P}_\pi\mathrm{P}_{\pi^+}P_{\pi^-}}$$

for the $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ and $\tau \to ee^+e^-\nu_\tau\nu_e$ channels respectively, where $\mathrm{P}_e = (2\pi)^{-1/2}\exp(-\sigma_e^2/2)$ and $\mathrm{P}_\pi = (2\pi)^{-1/2}\exp(-\sigma_\pi^2/2)$. Here, σ_e and σ_π are the numbers of standard deviations of measured specific ionization from that expected for an electron and a pion. These quantities characterize the purity of the sample from a contamination with events with pions faking electrons. We require κ_2 and κ_3 to be greater than 0.97.

We check for photon conversions in our data sample by reconstructing a possible conversion point. At such point, the e^+ and e^- tracks should be parallel in the transverse plane perpendicular to the beam axis. We require that the distance from this point to the beam is less than 2 cm. This suppresses photon conversions because the closest distance where the photons can convert in the detector material is 3.5 cm from the beam axis (beam pipe radius). In the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel this requirement must be satisfied for both e^+e^- combinations.

In the $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ and $\tau \to ee^+e^-\nu_\tau\nu_e$ processes the invariant mass of the three charged leptons tends to be small. After the boost to the lab system their tracks are almost parallel. This feature provides the possibility of differentiating these decays from the $\tau \to \rho\nu_\tau, \rho \to \pi\pi^0$, $\pi^0 \to e^+e^-\gamma$ process where the γ escapes detection and the π is misidentified as a lepton. The distribution of the sum of the cosines of the angles ϑ_{ij} between the 3-prong tracks is shown in Fig. 2 for the data, signal Monte Carlo and a sample of generic tau Monte Carlo. We compare the distributions for the signal and generic tau Monte Carlo events and require $\sum_{i<j}\cos\vartheta_{ij} > 2.93$ for both channels.

The signal efficiency, ϵ, after application of all the selection requirements and accounting for τ pair tagging, is estimated from the Monte Carlo to be $2.8 \pm 0.1\%$ for the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel and $2.2 \pm 0.1\%$ for the $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ channel (statistical errors only). The very soft electron momentum spectrum is the main reason for such low efficiencies. With these estimates, our Standard Model calculations predict 8.1 $\tau \to ee^+e^-\nu_\tau\nu_e$ and 3.0 $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ remaining events on average. In the data, five events satisfy all selection criteria in the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel and one event in the $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ channel. Distributions of several kinematic variables for both the signal Monte Carlo and the selected data events are shown in Fig. 3 for the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel. They indicate that the five remaining events in this channel are kinematically consistent with tau decays into three electrons and two neutrinos.

The remaining background from other tau decays is estimated by applying the above selection criteria to a sample of generic tau Monte Carlo events, not containing the signal channels, corresponding to $10.2\,\mathrm{fb}^{-1}$ (about 2.8 times larger than the data). In the $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ channel one event passed all our requirements. No generic tau Monte Carlo events were accepted in the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel, and in this channel we estimate the background contribution from other tau decays to be less than 0.4 events at 68% confidence level (CL). No events satisfied our selection criteria from a sample of $6.1 \cdot 10^6$ $e^+e^- \to B\bar{B}$ and $1.4 \cdot 10^7$ continuum ($e^+e^- \to q\bar{q}$, $q = u, d, s$ and c) Monte Carlo events in either of the two channels. We conclude that $B\bar{B}$ and continuum backgrounds are negligible. We expect no $e^+e^- \to e^+e^-e^+e^-$ background in the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel after requiring the 1-prong track not to be an electron. We checked this conclusion by looking at specific ionization measurements of the 1-prong tracks. These measurements favor the pion hypothesis over the electron one in all five remaining events. In addition, three of those events have a pair of photons in the 1-prong hemisphere with invariant mass compatible with that of a π^0.

The main systematic errors in this study arise from uncertainties in our knowledge of the lepton identification efficiency and slow track reconstruction efficiency. Combined together, they are estimated to give an overall systematic error of 15%. We assume that the background rate in the $\tau \to ee^+e^-\nu_\tau\nu_e$ channel is not larger than 0.4 events and calculate the branching fraction as

$$B(\tau \to ee^+e^-\nu_\tau\nu_e) = (2.7^{+1.4}_{-1.3} \pm 0.4) \times 10^{-5},$$

where the first errors show 68% confidence level bounds taking into account statistical fluctuations and possible background contamination. The obtained result is consistent with our theoretical expectation of 4.46×10^{-5} at 18% confidence level.

Though one event is observed in the $\tau \to \mu e^+e^-\nu_\tau\nu_\mu$ channel and its kinematical parameters are compatible with those of expected signal, we are not able to make a reliable estimate of the corresponding branching fraction. We calculate instead an upper limit on this branching fraction as $3.89/(2\,\epsilon N_{\tau\tau})$ at 90% CL and we do not attempt to subtract the background. As previously, we assign a systematic error of 15% to this result and increase the branching fraction limit by this amount. The resulting upper limit is

$$B(\tau \to \mu e^+e^-\nu_\tau\nu_\mu) < 3.1 \times 10^{-5} \quad \text{at 90\% CL.}$$

The obtained limit is consistent with our theoretical calculation $B(\tau \to \mu e^+e^-\nu_\tau\nu_\mu) = 2.09 \times 10^{-5}$.

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TABLES

TABLE I. τ and μ branching fractions calculated in different studies. Errors given here are due to inaccuracies in numerical integration only.

Channel	Dicus & Vega	Our calculation
$\tau \to eee\nu_\tau\nu_e$	$(4.15 \pm 0.06) \times 10^{-5}$	$(4.457 \pm 0.006) \times 10^{-5}$
$\tau \to \mu ee\nu_\tau\nu_\mu$	$(1.97 \pm 0.02) \times 10^{-5}$	$(2.089 \pm 0.003) \times 10^{-5}$
$\tau \to e\mu\mu\nu_\tau\nu_e$	$(1.257 \pm 0.003) \times 10^{-7}$	$(1.347 \pm 0.002) \times 10^{-7}$
$\tau \to \mu\mu\mu\nu_\tau\nu_\mu$	$(1.190 \pm 0.002) \times 10^{-7}$	$(1.276 \pm 0.004) \times 10^{-7}$
$\mu \to eee\nu_\mu\nu_e$	$(3.60 \pm 0.02) \times 10^{-5}$	$(3.605 \pm 0.005) \times 10^{-5}$

FIGURES

FIG. 1. Simulated momenta distributions for electrons from tau decays into three charged leptons and two neutrinos: a) electrons and positrons from $\tau \rightarrow \mu e^{+} e^{-} \nu_{\tau} \nu_{\mu}$, two entries per event, b) electrons from $\tau^{-} \rightarrow e^{-} e^{+} e^{-} \nu_{\tau} \bar{\nu}_{e}$, two entries per event, c) positrons from $\tau^{-} \rightarrow e^{-} e^{+} e^{-} \nu_{\tau} \bar{\nu}_{e}$. Note the difference in scales in b). The number of electrons, N_e, is normalized to unity in each plot.

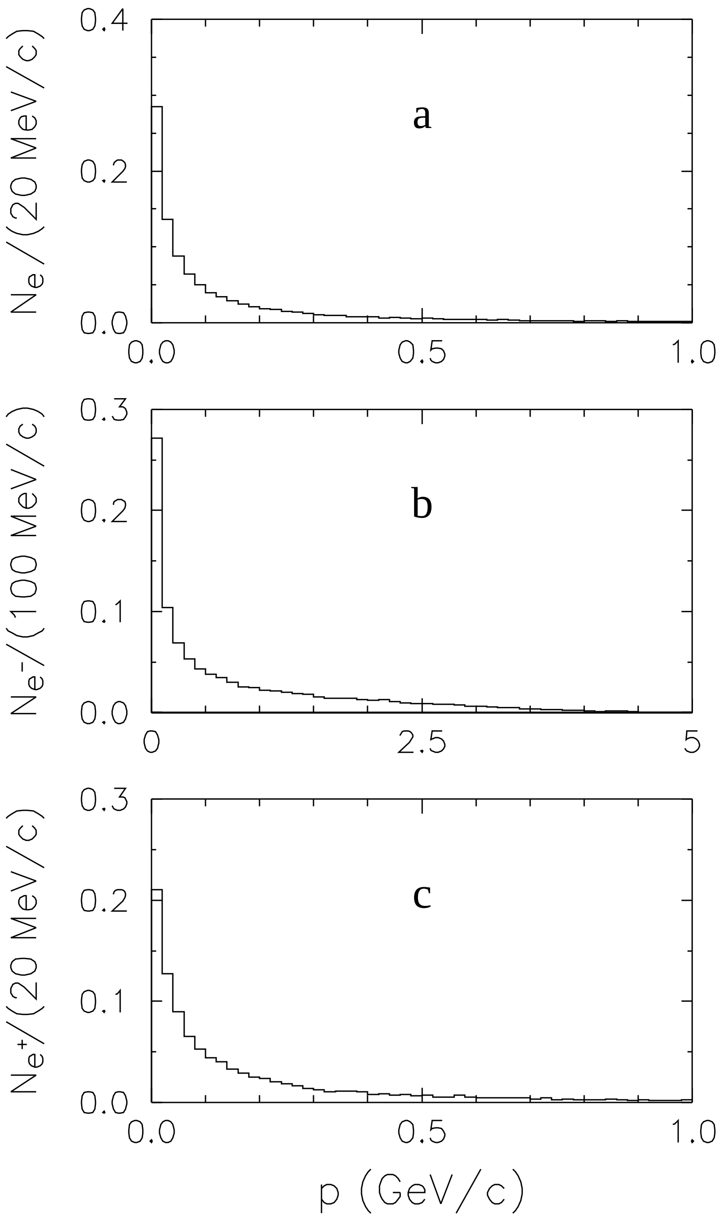

FIG. 2. Sum of cosines of the angles ϑ_{ij} between the 3-prong side tracks for the data (asterisks) signal Monte Carlo (solid line) and generic tau Monte Carlo sample (dashed line) for the two channels studied. The signal Monte Carlo histograms are normalized to Standard Model theoretical predictions. The generic tau Monte Carlo histograms are normalized to the data luminosity. In our analysis we require $\sum_{i<j} \cos\vartheta_{ij} > 2.93$ for both channels.

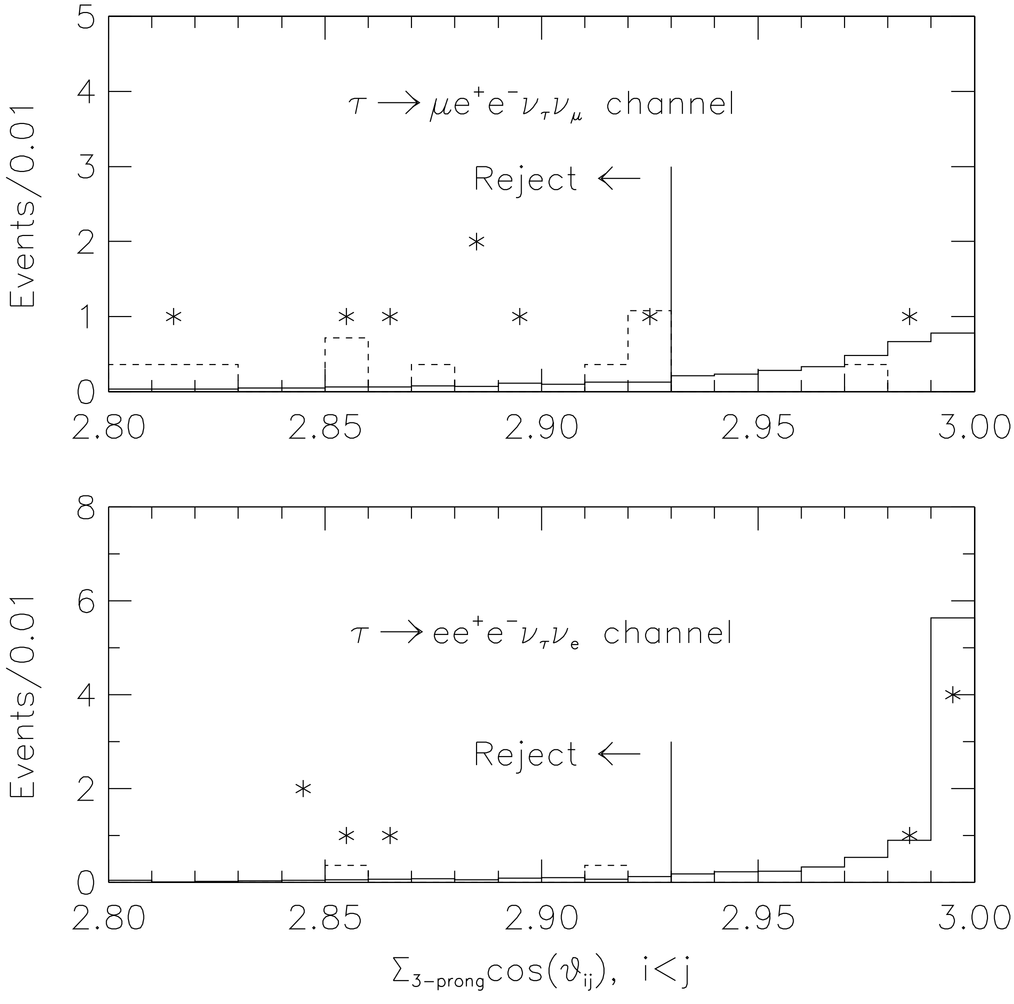

FIG. 3. Comparison of the kinematical distributions for the $\tau \to ee^+e^-\nu_\tau\nu_e$ Monte Carlo (solid line) and data (shaded histogram) events passing all our selection requirements: a) the e^+e^- invariant mass averaged over two possible combinations, $M_{e^+e^-}$, b) the 3-prong invariant mass, $M_{\text{3-prong}}$, and c) the momentum of the 3-prong electron with the charge opposite to that of the parent tau, p_{opp}. The normalization of the plots is arbitrary.