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Search for high-energy tau-neutrino interactions

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Kinematic selection criteria are developed for separating tau-neutrino charged-current interactions from a large background of muon- and electron-neutrino interactions. The criteria are designed to detect the three-prong decay mode of the τ lepton and rely on the three-particle combination's transverse momentum being anticorrelated with the transverse momentum of the other visible particles and being correlated with the missing transverse momentum. The criteria are applied to a sample of events from an exposure of the Fermilab 15-ft bubble chamber to the quadrupole triplet neutrino beam. The average event energies for this beam are 90 GeV for neutrino and 60 GeV for antineutrino events. The 14 τ candidates selected agree with the calculated background of 14.3 ± 1.2. An upper limit on the probability of muon neutrinos oscillating into tau neutrinos of 0.053 is obtained.

I. INTRODUCTION

The discovery and the determination of the properties of the τ lepton[1] lead to the expectation of the existence of its neutral partner, the tau neutrino. In addition to confirming the existence of this fundamental particle by observing its charged-current (CC) interactions, one would like to compare the details of these interactions to those of electron and muon neutrinos. The source of tau neutrinos is also of great interest because of the possibility that they could come from oscillations of other types of neutrinos.

At present there is no compelling evidence of the interactions of tau neutrinos. Several experiments[2–5] in wide-band or narrow-band neutrino beams have set upper limits on oscillations of muon and electron neutrinos into tau neutrinos based on the absence of tau-neutrino interactions. Most of the experiments using visual detectors rely on the τ decay mode into an electron. An indication of tau-neutrino interactions would be an excess of events with primary electrons over what is expected from electron neutrinos in the beam. The best limit[2] obtained by this technique for the probability (averaged over the neutrino energy spectrum) of a muon neutrino oscillating to a τ neutrino is

$$P(\nu_\mu\to\nu_\tau)<0.02/0.6=0.03 \quad (90\% \text{ C.L.}) .$$

(Note that the upper limit on the ratio of ν_τ to ν_μ CC events must be divided by the ratio of the average cross sections to obtain an upper limit on the average oscillation probability. The larger τ-lepton mass results in a kinematic suppression of the ν_τ CC total cross section by a factor of 0.6 for the experiment[2] quoted here.) A different technique—looking for direct visual evidence of the τ-lepton decay in events produced in nuclear emulsions—gives an upper limit of[3]

$$P(\nu_\mu\to\nu_\tau)<0.0063 \quad (90\% \text{ C.L.}) .$$

Using the lower of these limits and the value of 0.77 (which is correct for the ν_μ energy spectrum in our experiment) for the ratio of the average ν_τ to ν_μ CC cross sections predicts an upper limit of 49 ν_τ CC events in a sample of 10 000 ν_μ CC events.

Another possible source of tau neutrinos is the decay of F mesons produced by interactions of 400-GeV protons in the target and by interactions of protons and mesons in the beam dump at the end of the decay region. Several detectors[6–10] have searched for interactions of tau neutrinos that could be produced by the decays of short-lived particles produced in beam dumps. One can estimate the contributions of these sources using the rates for prompt electron-neutrino CC events determined by beam-dump experiments at CERN. According to the review by Winter,[10] the different detectors all agree on a rate of 3.27 ± 0.30 events/(10^{18} protons)ton for prompt ν_e plus $\bar{\nu}_e$ CC events ($E_\nu > 20$ GeV) at a distance of 488 m from the beam dump. Scaling this rate (by the ratio of the squares of the distances) to distances from the 15-ft bubble chamber to the target (1400 m) and dump (1000 m), using a fiducial mass of 8.1 tons, and assuming half of the protons (2.55×10^{18} for the film used in this analysis) interact in the target and the other half in the dump results in an expectation of 16 ν_e plus $\bar{\nu}_e$ CC events from prompt sources in our experiment. To get an expected number of tau-neutrino events, one must multiply the number of electron-neutrino events by the ratio of tau-neutrino to electron-neutrino cross sections, the ratio of $F\bar{F}$ to $D\bar{D}$ production cross sections, and twice the ratio of the $F\rightarrow\tau\nu_\tau$ to $D\rightarrow e\nu_e$ branching fractions. (The subsequent decay of the τ-lepton results in two tau neutrinos for every $F\rightarrow\tau\nu_\tau$ decay.) The expected number of tau events is

$$(0.7)(0.2)(2)(0.3)16=1.3 ,$$

where we have used 0.2 for $\sigma_{F\bar{F}}/\sigma_{D\bar{D}}$ and 0.3 for $B(F\rightarrow\tau\nu_\tau)/B(D\rightarrow e\nu_e)$, as in Ref. 10. Therefore, the expected number of tau-neutrino events from prompt sources is undetectably small given the detection efficiency and backgrounds in our experiment. However, the expected event rate is very uncertain because there are no measurements of either the $F\bar{F}$ production cross section or the $F\rightarrow\tau\nu_\tau$ branching fraction.

In this paper we explain in detail a technique for isolating tau-neutrino CC interactions in which the τ lepton decays into three charged hadrons. (This technique, with slightly different cuts, was also used in an experiment in a narrow-band $\bar{\nu}_\mu$ beam[5].) The technique differs from that proposed by Poppe[11] in that it uses more detailed kinematic cuts to separate tau events from neutral-current (NC) events. We apply this technique to events produced in a wide-band neutrino beam and rely on the results of our electron scan to reject electron-neutrino CC events and on the external muon identifier (EMI) in conjunction with the internal picket fence (IPF) to identify muons and thus reject muon-neutrino CC events. The method should work even better for beam-dump experiments, where the ratio of tau neutrinos to muon and electron neutrinos should be much larger.

In Sec. II, we discuss experimental details for the data sample used in this analysis. The tau selection criteria, along with expected backgrounds and tau detection efficiencies, are given in Sec. III. Finally, Sec. IV gives the results of this analysis.

II. EXPERIMENTAL DETAILS

The data used in this analysis come from a 326 000-picture exposure of the Fermilab 15-ft bubble chamber to the quadrupole triplet neutrino beam. The complete exposure corresponds to 3.4×10^{18} protons on target. An important feature of the quadrupole triplet beam is that lower energy neutrinos are suppressed. In fact, the average observed event energies for ν_μ and $\bar{\nu}_\mu$ CC events are 90 and 60 GeV, respectively. The bubble-chamber liquid was a neon (47% atomic)—hydrogen mixture with a density, radiation length, and absorption length of 0.56 g/cm^3, 53 cm, and 193 cm, respectively. More details of the experimental conditions, scanning, muon identification, electron identification, and other cuts are given in previous publications on dimuons[12] and dilepton events.[13] For the present analysis, we use the same fiducial volume as that used for the latter.

The two-plane EMI and prototype IPF available for this experiment are described in detail elsewhere.[14,15] For this experiment, the IPF consisted of 16 picket chambers each with an active area of 0.1 m by 1.0 m and constructed electrically as though it were a drift chamber with all the sense wires ganged together. The pickets were placed inside the bubble-chamber vacuum tank between the 1-in.-thick steel chamber body and the superconducting coil. The active area of the pickets comprised 30% of the area spanned by them. Previous analyses of CC events from this experiment have required muons to be identified in both planes of the EMI and have not used the IPF. For the present analysis, it is important to identify muons with higher efficiency and to keep hadron misidentification small. Therefore, we use time coincidences between the IPF and the EMI to allow us to identify muons using only a single EMI plane.

In order to have high electronic efficiencies for the EMI and IPF, we use only data from the latter $\frac{3}{4}$ of the experiment. The numbers of ν_μ and $\bar{\nu}_\mu$ CC events with the muon identified (two-plane muon) in both EMI planes for this part of the experiment are 6780 and 1100, respectively. The average EMI electronic efficiency is 0.93 for each plane. The EMI geometric acceptances for μ^- tracks to hit both planes, only the first plane, and neither plane are 0.87, 0.10, and 0.03, respectively for muon momenta above 4 GeV/c. The corresponding μ^+ acceptances are 0.92, 0.06, and 0.02, respectively. For μ^- of momenta below 4 GeV/c, these acceptances are 0.04, 0.18, and 0.78, respectively; the corresponding μ^+ acceptances are 0.10, 0.29, and 0.61. The overall efficiency of the IPF is determined from the fraction of events with two-plane muons that also have at least one hit in the IPF that is in time with the EMI. This fraction is 0.70. The IPF efficiency increases with the visible hadronic energy and the number of primary tracks that leave the bubble chamber without interacting. For example, the IPF efficiency for events with hadronic energy above 10 GeV is 0.85 and that for events with at least two leaving primary tracks each with momentum above 4 GeV/c is 0.87.

To reject muon-neutrino CC events from the samples of NC and τ candidates, we identify muons using single-plane as well as two-plane criteria. For tracks hitting both EMI planes, either time-coincident matches of confidence levels above 10^{-4} in both planes or a match of confidence level above 0.1 in either plane that is in-time with a hit in the IPF is required to identify the track as a muon. For tracks hitting the first but not the second EMI plane, only a match of confidence level above 0.01 was required if the track's momentum exceeded 4 GeV/c. For tracks of momenta below 4 GeV/c, the EMI match was required to be in time with the IPF. These criteria correctly identify the muon in 85% of all ν_μ CC events and 89% of all $\bar{\nu}_\mu$ CC events. (These fractions of identified muons are higher than those in previous analyses[12,13] primarily due to the use of single-plane in addition to two-plane criteria for muon identification.) The other leaving tracks in events with two-plane muons can be used to determine how often hadrons will be misidentified as muons using these criteria. The result is that 0.11 of all events (NC as well as CC) will have a hadron misidentified as a muon.

In order to find events with muons, we originally measured all noninteracting tracks leaving the bubble chamber within 60° of the neutrino-beam direction. Since then we have systematically made complete measurements of all events containing a two-plane muon and of all events with an identified primary electron. In about 15% of the film from the latter $\frac{3}{4}$ of the experiment, we have made complete measurements on a sample of NC candidates. An event in the NC sample must have at least two primary tracks and visible energy above about 5 GeV but must not have either a leaving track identified as a muon (by the above criteria) or an identified single primary electron (from the electron scan). Most tau-neutrino CC events would also satisfy the criteria used to select the NC sample. In the remaining 85% of the film, we have made complete measurements on only a special sample of τ candidates. To be in this special sample, an event must satisfy all the criteria for the NC sample and, in addition, have at least two leaving tracks of momenta above 4 GeV/c and invariant mass below 1.8 GeV. These additional criteria allow us to select (from the leaving track measurements) a relatively small number of events for complete measurements and still have some sensitivity for real tau-neutrino events. (Tau-neutrino CC events where the τ lepton decays into three charged hadrons would satisfy these criteria if any two of the hadrons had momenta above 4 GeV/c and left the bubble chamber without interacting.)

III. TAU SELECTION CRITERIA

The τ-lepton branching ratio into three charged hadrons (plus neutrals) obtained from a fit to all measurements by the Particle Data Group[16] is 0.17. This value is dominated by recent measurements[17,18] at high-energy e^+e^- colliders, which are about half the values measured at lower energy machines. Because we rely on the three-prong decay mode, our τ detection efficiency is directly proportional to this branching ratio.

Tau-neutrino events having a three-prong hadronic decay will have no primary muons or electrons. The three charged particles from the τ decay will have net charge ± 1, invariant mass less than the τ mass, and usually a substantial fraction of the event's total energy. The transverse momentum (relative to the incident-neutrino direction) of the three-particle combination will often be large and in the opposite direction to the transverse momentum $\vec{p}^{\,t}_x$ of all the other visible particles because the three particles come from the τ decay. Also, the missing transverse momentum may be dominated by the ν_τ from the τ decay so the transverse momentum vector $\vec{p}^{\,t}_3$ of the three-particle combination will tend to be correlated with the missing-transverse-momentum direction $\hat{p}^{\,t}_{\rm miss}$ in events with large missing transverse momentum. These characteristics provide a powerful discrimination against muon-neutrino NC events. In NC events the transverse momentum of the hadron system is in the opposite direction to that of the outgoing neutrino, which dominates the missing transverse momentum. Therefore, a combination of three high-energy hadrons will usually have its transverse momentum opposite to the missing transverse momentum and in the same direction as the transverse momentum of the other visible particles.

The main discrimination against muon-neutrino CC events is the use of the EMI to identify muons. For CC events without EMI-identified muons, there are kinematic cuts (criteria 6 and 7 below) that reduce this potential background. These kinematic cuts are necessary because the missing transverse momentum in CC events is due to undetected hadrons and is therefore correlated with the hadron system.

The main focus of the kinematic criteria described below is the reduction of backgrounds, especially those from NC events, that fake tau-neutrino events. The values for the kinematic cuts are chosen to reduce backgrounds as much as possible but still leave some sensitivity for real tau-neutrino events. In particular, one of the main goals is to reduce backgrounds from NC events to a level of a few events because kinematic cuts are the only way to separate NC events from tau-neutrino events where the τ lepton decays into hadrons.

The criteria used to select candidates for tau-neutrino interactions are the following.

(1) Events must have no identified primary muons or electrons.

(2) There must be at least one combination of three charged particles (identified protons excluded) with net charge ± 1 and invariant mass (assuming all three particles are pions) less than 1.8 GeV.

(3) The combination of three particles must have total momentum p_3 that exceeds 20% of the total visible momentum and p_3 must be greater than 20 GeV/c.

(4) For events with missing transverse momentum exceeding that of the three-particle combination, the projection of the combination's transverse momentum $\vec{p}^{\,t}_3$ onto the missing transverse momentum direction $\hat{p}^{\,t}_{\rm miss}$ must be above 1.0 GeV/c (i.e., $\vec{p}^{\,t}_3 \cdot \hat{p}^{\,t}_{\rm miss} > 1.0$ GeV/c). Note that a necessary condition is $p^t_3 > 1.0$ GeV/c.

(5) For events with $p^t_{\rm miss} < p^t_3$, the projection of the combination's transverse momentum $\vec{p}^{\,t}_3$ onto the direction of the transverse momentum $\hat{p}^{\,t}_x$ of all other visible

particles must be less than -1.5 GeV/c (i.e., $\vec{p}\,^t_3 \cdot \hat{p}\,^t_x < -1.5$ GeV/c). A necessary condition for this criterion to be satisfied is $p^t_3 > 1.5$ GeV/c.

(6) The magnitude of the combination's transverse momentum p^t_3 must exceed by at least 0.5 GeV/c the transverse momentum of any possible muon not included in the three-particle combination (a possible muon is any track that leaves the chamber without interacting).

(7) None of the three particles of the combination can be a possible muon carrying a large fraction of the combination's total momentum and transverse momentum. Specifically, no possible muon can have both more than 70% of the total momentum and more than 85% of the transverse momentum of the combination.

Criteria 1 and 2 have a small effect (from hadrons misidentified as muons and experimental resolution in three-particle mass) on real tau events, but get rid of about 85% of muon-neutrino and 75% of electron-neutrino CC events. Criterion 3 is necessary to further reduce backgrounds from hadron combinations in NC and CC events.

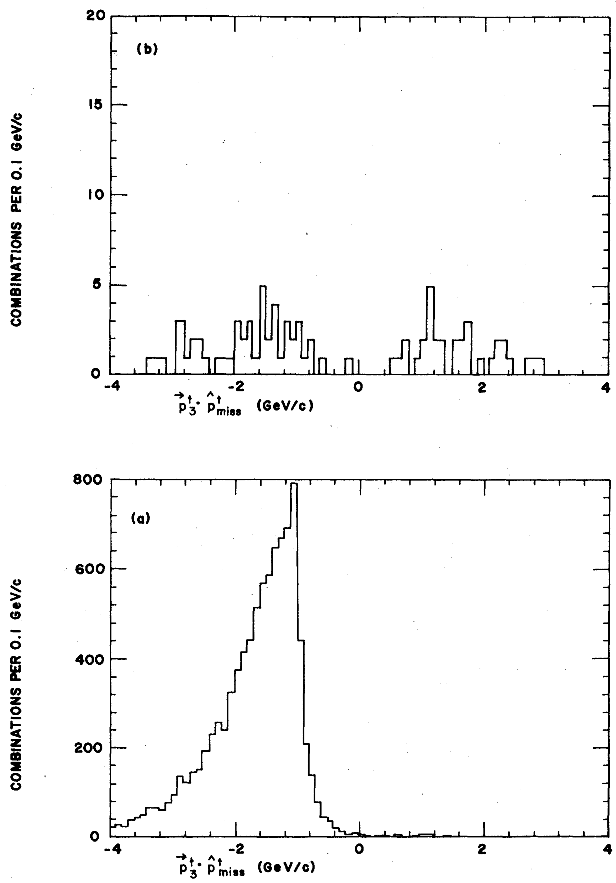

FIG. 1. (a) Plot of the transverse-momentum projection $\vec{p}\,^t_3 \cdot \hat{p}\,^t_{\rm miss}$ for simulated NC events with $p^t_{\rm miss} \geq p^t_3$. The three-particle combination must satisfy selection criteria 1–3. There may be more than one combination per event. (b) Plot of analogous transverse-momentum projection for 86 tau-neutrino Monte Carlo events with $p^t_{\rm miss} \geq p^t_3$. The vector $\vec{p}\,^t_3$ is the transverse momentum of the three charged particles from the τ-lepton decay.

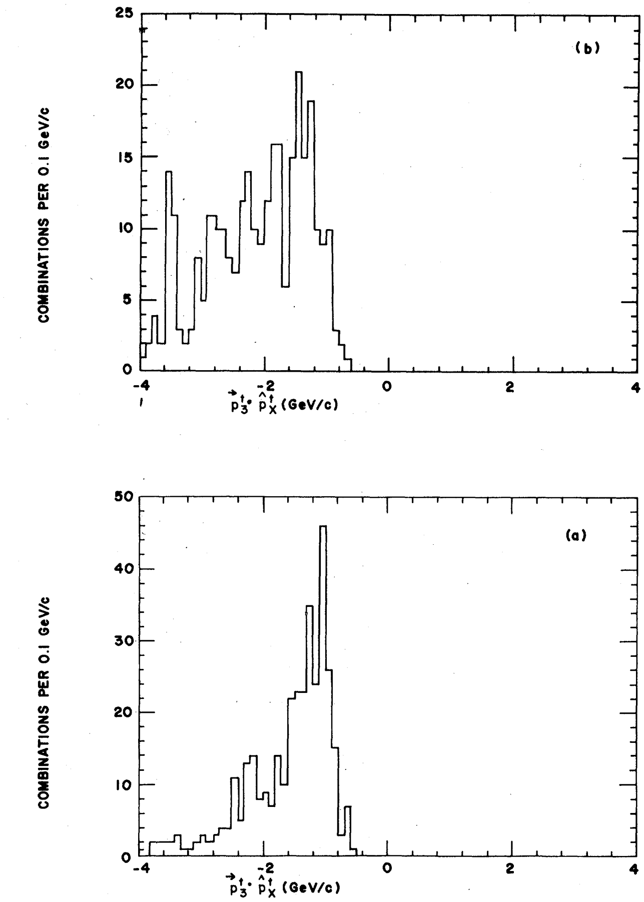

FIG. 2. (a) Plot of the transverse-momentum projection $\vec{p}\,^t_3 \cdot \hat{p}\,^t_x$ for simulated NC events with missing transverse momentum $p^t_{\rm miss} < p^t_3$. The vector $\hat{p}\,^t_x$ gives the direction of the transverse momentum of all visible particles except those in the three-particle combination. (b) Plot of the analogous transverse-momentum projection for 335 tau-neutrino Monte Carlo events with $p^t_{\rm miss} < p^t_3$.

In CC events, one can distinguish two types of fake tau candidates—one where the muon is included as one of the three tracks and the other where the muon is excluded. There are many more three-particle combinations of mass below 1.8 GeV and with transverse momentum above 1.0 GeV/c where the muon is excluded, but requiring $P_3 > 20$ GeV/c eliminates 72% of them. For such combinations including the muon, the 20-GeV/c requirement eliminates only 44%.

Criteria 4 and 5 are very effective in reducing backgrounds from NC events. Figures 1(a) and 2(a) show the transverse-momentum projections $\vec{p}\,^t_3 \cdot \hat{p}\,^t_{\rm miss}$ (for events with $p^t_{\rm miss} \geq p^t_3$) and $\vec{p}\,^t_3 \cdot \hat{p}\,^t_x$ (for events with $p^t_{\rm miss} < p^t_3$), respectively, for three-particle combinations in simulated NC events satisfying criteria 1–3 and with $p^t_3 > 1.0$ GeV/c. For these plots and for background calculations, we simulate NC events by taking CC events and treating the muon as undetected. Because we have only systematically measured CC events with a muon of momentum above 4 GeV/c, Monte Carlo events are used to estimate backgrounds for the case where $p_\mu < 4$ GeV/c. Figures 1(b) and 2(b) are the analogous momentum projections for 421 Monte Carlo tau-neutrino interactions. Note that most tau-neutrino interactions with three-prong τ decays have $p^t_{\text{miss}} < p^t_3$. The Monte Carlo program we use[19] simulates measurements of primary tracks, K^0 and Λ decays, and γ conversions and generates output in the same format as real data. This output is then processed by the same analysis program that is used on real data.

Criteria 6 and 7 reduce backgrounds from CC events in which the muon is not identified by the EMI. Criterion 6 removes 94% of candidates where the muon is not included; criterion 7 removes 72% of combinations where the muon is included. These fractions of CC events removed by criteria 6 and 7 and the data in Figs. 3(a) and 4(a) come from measured CC events. Figure 3(a) is a plot of the muon's transverse momentum p^t_μ versus the maximum transverse momentum of fake τ combinations satisfying criteria 1—5 and not including the muon. Only events below the line satisfy criterion 6. Figure 3(b) is the analogous plot for tau-neutrino Monte Carlo events except that the vertical axis in this plot is the maximum transverse

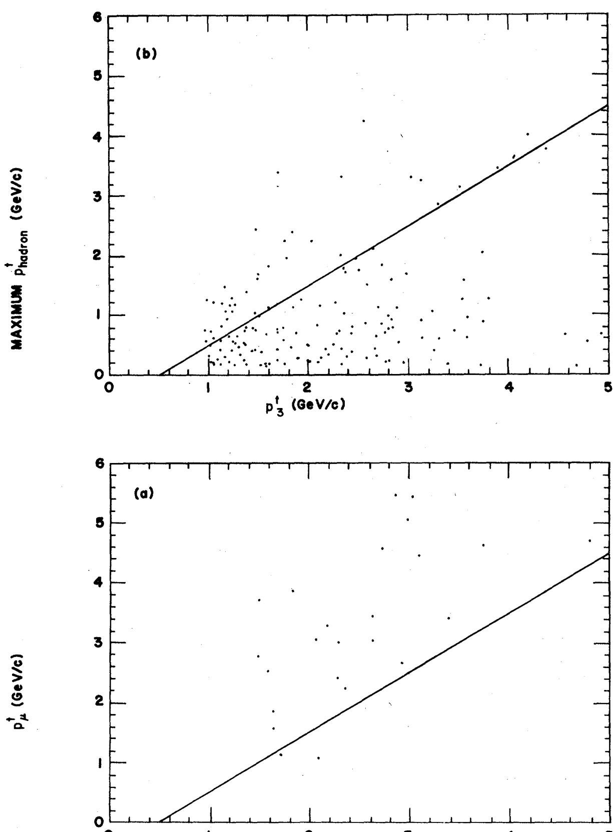

FIG. 3. (a) Scatter plot of the muon transverse (relative to the incoming neutrino direction) momentum p^t_μ versus the maximum transverse momentum of fake τ combinations satisfying selection criteria 1—5 and not including the muon. (b) Analogous plot for tau-neutrino Monte Carlo events. Only events with a noninteracting charged hadron that does not come from the τ-lepton decay contribute to this plot.

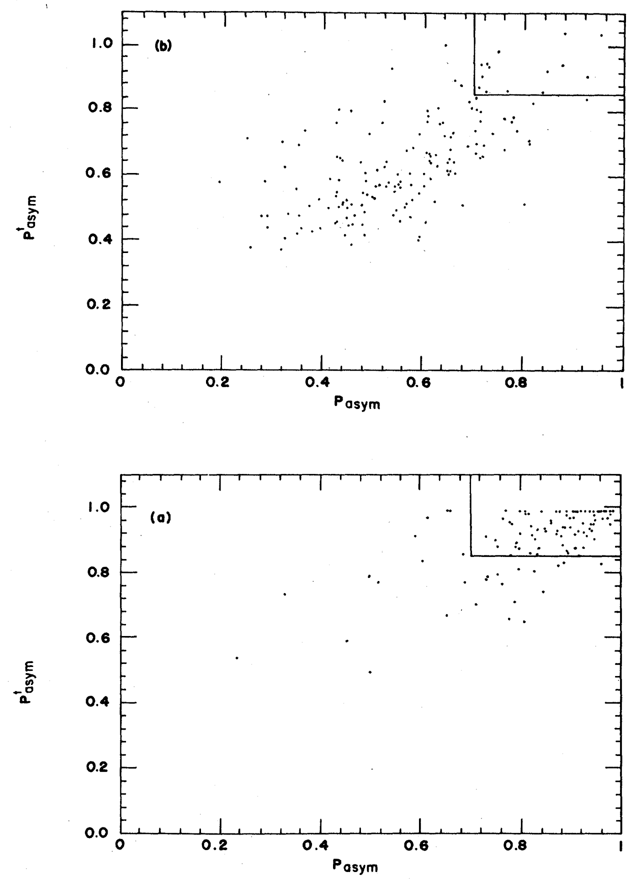

FIG. 4. (a) Scatter plot of the transverse-momentum asymmetry p^t_{asym} $(=p^t_\mu/p^t_3)$ versus the total-momentum asymmetry p_{asym} $(=p_\mu/p_3)$ for fake τ combinations satisfying criteria 1—5 and including the muon. (b) Analogous plot for tau-neutrino Monte Carlo events. The asymmetry parameters for these events are calculated using the total momentum and transverse momentum of the maximum-transverse-momentum noninteracting hadron (if any) from the τ-lepton decay and dividing by the appropriate quantities from the three-particle combination.

momentum of noninteracting charged hadrons (if any) that are not from the τ lepton decay. Figure 4(a) is a plot of the transverse-momentum asymmetry $(p^t_{\text{asym}} = p^t_\mu/p^t_3)$ versus the total-momentum asymmetry $(p_{\text{asym}} = p_\mu/p_3)$ for fake τ combinations satisfying criteria 1—5 and including the muon. Events in the upper right are eliminated by criterion 7. Figure 4(b) is the analogous plot for tau-neutrino Monte Carlo events.

The NC backgrounds are obtained by multiplying the probability that a NC event will fake a tau candidate (obtained from simulating NC events by ignoring the muon in CC events and thereby equating the outgoing neutrino momentum to the muon momentum) by the expected total number of NC events. Because of the slight difference in the NC and CC y distributions and the fact that very-low-y NC events cannot produce fake τ candidates, the probabilities obtained from simulated NC events are slight overestimates for ν-induced and underestimates for $\bar{\nu}$-induced NC events. Also, the absence of single charm production in real NC events means that simulated NC events may overestimate the true background. (Because of the hard charm fragmentation function, the three charged particles from a charged D meson decay will often have high momentum and thus the event may satisfy the tau selection criteria if the muon is not identified.) The probabilities for faking a tau candidate are 25/8532 and 3/541 for ν-induced NC events with outgoing neutrino momentum above and below 4 GeV/c, respectively.

The CC backgrounds for events with muon momentum above 4 GeV/c are obtained by multiplying the probability that a CC event will fake a tau candidate (determined to be 173/6785 by treating the muon as a hadron in 6785 measured ν-induced CC events) by the appropriate EMI acceptance and EMI and IPF inefficiencies. The probability that a ν-induced CC event with muon momentum below 4 GeV/c will fake a tau candidate is determined from 541 Monte Carlo events to be 5/541. The probabilities for faking tau candidates for $\bar{\nu}$-induced events are determined in an analogous manner and are in general smaller than those for ν-induced events. The CC backgrounds due to EMI dead time are obtained using the probabilities above and an estimated dead-time fraction of 0.012. This dead time results from an electronic gate used to reduce noise in the EMI.

The fraction of fake tau candidates with at least one τ^- combination is 0.40 for NC events, but is 0.60 for CC events. The reason for the difference in these factors is that most of the fake tau combinations in ν_μ CC events *include* the muon so such combinations automatically have at least one negatively charged particle. The resulting backgrounds are given for various classes of NC and CC events in Table I. (The backgrounds in this table exclude contributions from electron neutrino events. These neglected contributions are only about 3% of those from muon neutrino events.) The probabilities for faking a tau candidate given above do not include the requirement, used for the special τ candidate sample, that at least two of the three tracks be leaving tracks of momenta above 4 GeV/c. This additional requirement multiplies the NC and CC with $P_\mu < 4$ GeV/c backgrounds by a factor of 0.24 and the other CC backgrounds by a factor of 0.31.

The average detection efficiency of real tau events depends on the tau-neutrino energy spectrum. We generate ν_τ CC events using the ν_μ energy spectrum and the Monte Carlo program[19] used to generate ν_μ CC events with two important modifications. One is that the values of the x and y scaling variables are required to be in the allowed kinematic region for the chosen neutrino energy. (The kinematic region is smaller than that for muon neutrinos due to the larger mass of the τ lepton.) The other is that the τ-lepton decay is generated assuming three charged pions plus a neutrino and using four-body phase space. The ν_τ and ν_μ energy spectra will be the same if there are oscillations between only these neutrino types and a large mass difference between them. We assume the energy

TABLE I. Backgrounds for tau candidates for seven classes of events. The NC-event backgrounds are obtained using CC events and treating the muon as undetected. The CC-event backgrounds come from treating the muon as a hadron. The entries in the two columns are the numbers of events expected to have at least one three-particle combination (having either charge or negative charge, respectively) that satisfies the selection criteria.

		Either charge	τ^- only
(1) NC ($P_\nu > 4$ GeV/c	ν	8.31±1.66	3.33±1.05
for outgoing neutrino)	$\bar{\nu}$	0.30±0.30	0.30±0.30
(2) NC ($P_\nu < 4$ GeV/c)	ν	0.97±0.56	0.39±0.26
	$\bar{\nu}$	0.05±0.03	0.05±0.03
(3) CC ($P_\mu > 4$ GeV/c,	ν	10.16±0.77	6.09±0.46
μ hits both planes)	$\bar{\nu}$	1.81±0.29	1.00±0.22
(4) CC ($P_\mu > 4$ GeV/c,	ν	2.04±0.16	1.23±0.09
μ hits only first plane)	$\bar{\nu}$	0.16±0.03	0.09±0.02
(5) CC ($P_\mu > 4$ GeV/c	ν	6.92±0.53	4.15±0.32
μ misses both planes)	$\bar{\nu}$	0.60±0.10	0.33±0.07
(6) CC ($P_\mu < 4$ GeV/c)	ν	4.34±1.94	2.60±1.16
	$\bar{\nu}$	0.17±0.07	0.09±0.04
(7) CC (1.2% EMI dead time)	ν	2.81±0.21	1.68±0.13
	$\bar{\nu}$	0.37±0.06	0.20±0.04
Subtotals	ν NC	9.28±1.77	3.72±1.09
	CC	26.27±2.43	15.75±1.46
	$\bar{\nu}$ NC	0.35±0.30	0.35±0.30
	CC	3.11±0.43	1.71±0.31
Total		39.0 ±3.0	21.5 ±1.9
Total (at least two leaving tracks with momenta above 4 GeV/c)		9.9 ±1.3	5.5 ±0.7

spectra are the same to obtain the average tau detection efficiency and the limit on the average oscillation probability. For a small mass difference, the ν_τ energy spectrum will be softer than the ν_μ spectrum and thus the average tau detection efficiency will be smaller than that given below. The fraction of all three-prong τ^- decays that pass all the selection criteria is 0.25. About half of the decays are lost due to the 20 GeV/c minimum momentum requirement. Most of the remainder of the loss is due to the requirements on the three-particle transverse momentum specified by selection criteria 4 and 5. The fraction of events with a three-prong τ^- decay that pass the selection criteria is 0.31. This fraction is higher than the fraction of three-prong τ^- decays correctly selected because some other three-particle combination (usually including at least one track from the τ^- decay) sometimes satisfies the criteria.

To obtain an overall τ detection efficiency, we use the fraction of events with three-prong τ^- decays that are selected. For the special τ sample, the three-prong τ^- event detection efficiency must be multiplied by the fraction of detected three-prong τ decays with at least two leaving tracks of momenta above 4 GeV/c (0.30) to get the overall τ detection efficiency. This fraction must be multiplied by the fraction of events with more than 20 GeV of visible hadron energy that do *not* have a hadron misidentified as a muon. The fraction of all NC events with no hadron misidentified as a muon is 0.89, but this fraction decreases to 0.83 for visible hadronic energy above 20 GeV and to 0.67 for the special τ sample with at least two leaving tracks of momenta above 4 GeV/c. Multiplying also by the three-prong branching ratio (0.17) gives

$$\epsilon_\tau=(0.17)(0.31)(0.83)=0.044 \quad (\text{NC}-\text{candidate sample})$$

and

$$\epsilon'_\tau=(0.17)(0.31)(0.67)(0.30)=0.011 \quad (\text{special } \tau \text{ sample}) .$$

The effective detection efficiency for the combined sample is given by

$$\bar{\epsilon}_\tau=(0.15)(0.044)+(0.85)(0.011)=0.016 .$$

Note that this is the appropriate detection efficiency for ν_τ CC events where the ν_τ is produced by an oscillation of the ν_μ beam. Tau neutrinos originating from prompt sources should have a softer energy spectrum and therefore a lower detection efficiency.

IV. RESULTS AND CONCLUSIONS

The criteria for the special τ-candidate sample (no identified muons or single primary electrons, but at least two leaving tracks of momenta above 4 GeV/c and invariant mass less than 1.8 GeV), applied to our leaving track measurements, selected 1024 events. In about 85% of the film, only candidates satisfying these criteria have been completely measured. In the other 15% of the film, all NC candidates (about 1000 events) with at least two tracks and visible energy above about 5 GeV have been measured. Fourteen events have τ combinations satisfying all the criteria. Five of the 14 candidates come from the 15% of the film in which all selected NC candidates were measured. All but one (event 15 210 796) of these five candidates have at least two of the three tracks of the τ combinations that are leaving tracks with momenta above 4 GeV/c. Five of the 14 events have only τ^+ combinations, six events have only τ^- combinations, and three events have combinations of both charges. Table II contains some of the relevant kinematic quantities for the 14 candidates.

TABLE II. Kinematic quantities for 14 events that satisfy the τ selection criteria. For events in which more than one three-particle combination of the same charge satisfy the selection criteria, only the combination with the largest momentum (p_3) appears in the table. The quantities in the last two columns are defined as in Fig. 4(b). All three tracks of the τ combination in event 15 210 796 interact in the bubble chamber.

Event	τ charge	E_{vis} (GeV)	p^t_{miss} (GeV/c)	$M_{\pi\pi\pi}$ (GeV)	p_3 (GeV/c)	p_{asym}	p^t_{asym}
15 100 492	+	55	0.25	1.24	29	0.68	0.85
15 160 170	−	51	0.51	1.44	37	0.46	0.56
15 210 796	+	38	0.65	0.90	29		
15 280 646	−	104	0.78	1.51	53	0.53	0.58
15 401 056	−	52	0.82	1.70	32	0.49	0.73
15 621 110	−	68	0.13	1.61	43	0.85	0.82
15 651 490	−	75	0.74	1.62	30	0.38	0.75
	+			1.50	28	0.42	0.70
15 730 413	+	137	1.08	1.02	34	0.49	0.52
	−			1.58	31	0.52	0.60
15 950 517	−	38	0.79	1.75	29	0.35	0.57
16 100 935	−	140	0.22	1.61	105	0.88	0.82
16 131 137	+	67	0.78	1.13	26	0.76	0.82
16 160 324	+	46	0.10	1.08	35	0.81	0.84
16 270 392	+	169	0.89	1.78	123	0.74	0.79
16 450 162	−	193	1.99	1.44	91	0.76	0.60
	+			1.56	88	0.79	0.64

The 14 τ candidates have all been examined under high magnification by a physicist to look for visual evidence that the three particles forming the τ combination came from the decay of a short-lived particle. (Decays of short-lived, probably charmed, particles have been seen[13,20] beyond 5 mm from the primary vertex in CC events in this experiment.) No convincing evidence of a visible decay was seen. For tau-neutrino events with the same energy spectrum as the muon neutrino events in our experiment, about 20% of the produced τ leptons would decay beyond 5 mm from the primary vertex.

The expected backgrounds are obtained by adding 15% of the next-to-last row in Table I to 85% of the last row. The resulting backgrounds are 14.3 ± 1.2 for combinations of either charge and 7.9 ± 0.7 for τ^- combinations. Therefore the observed 14 events with combinations of either charge and 9 events with τ^- combinations agree with the expected backgrounds. Calculating the 90%-confidence-level upper limit corresponding to the 9 observed τ^- candidates and including the uncertainty in the expected background gives an upper limit of 6.4 events from sources other than calculated backgrounds. Dividing by the effective τ detection efficiency (0.016), the ratio of the average ν_τ to the average ν_μ cross section (0.77), and the total number of ν_μ CC events (9830) gives for the probability of a ν_μ oscillation into ν_τ

$$P(\nu_\mu \rightarrow \nu_\tau) < 0.053 \quad (90\%\ \text{C.L.})\ .$$

This limit is less restrictive than those determined by experiments looking for the electron decay mode[2] and for visible τ decays,[3] but is based on a method with completely different systematics.

In conclusion, we have developed kinematic criteria that correctly select 25% of all three-prong τ^- decays (assuming the ν_τ energy spectrum is the same as the ν_μ spectrum in our experiment) and that substantially reduce backgrounds from muon neutrino NC and unidentified CC events. Note especially (see Table I) that the background from NC events is only about $\frac{1}{3}$ that from CC events. The kinematic criteria are much more effective in rejecting NC than CC events; improved muon identification is the most effective means to reduce the CC background. These criteria select candidates consistent with the expected backgrounds in our data. This technique should be valuable for detecting tau-neutrino interactions in beam-dump experiments where the ratio of the tau-neutrino flux to the muon- and electron-neutrino fluxes is expected to be considerably higher than in conventional neutrino beams.

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