

A NEW LIMIT ON THE MASS OF THE TAU NEUTRINO.

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**ABSTRACT.** A high statistics sample of tau-lepton decays into  $\pi^+\pi^-\pi^\pm\nu_\tau$ , has been collected using the ARGUS detector, operating at around 10 GeV centre of mass energies in the DORIS II  $e^+e^-$  storage ring at DESY. From the endpoint of the tau neutrino energy spectrum, we derive a preliminary upper limit for the mass of the tau neutrino of  $70 \text{ MeV}/c^2$  at the 95% confidence level.

Previous upper limits for the mass of the tau neutrino have been established from the energy spectrum of the electron <sup>1)</sup> in three body decays of  $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ , and from the end point of the pion energy spectrum <sup>2)</sup> in the decay  $\tau^- \rightarrow \pi^- \nu_\tau$ . ( The convention that charge conjugate states are implied is used in all of the following. ) The tau leptons were produced in  $e^+e^-$  collisions at the SPEAR storage ring, with centre-of-mass energies around  $3.5 \text{ GeV}/c^2$ . The mass sensitivity in the electron case is limited, since this is a three body decay. The endpoint of the pion spectrum is, in principle, a direct measure of the mass, but a substantial background from radiative Bhabhas and hadronic events had to be subtracted from the raw spectrum in the actual measurement.

More recent limits have been determined from tau decays, observed at PEP, into the  $\pi^+\pi^-\pi^-\pi^0\nu_\tau$  <sup>3)</sup> and  $K^+K^-\pi^-\nu_\tau$  <sup>4)</sup> channels. There, a different technique was used. The high mass region of the hadronic mass spectrum, sensitive to neutrino mass, was studied to obtain an improved measurement. The increased sensitivity is due to the fact that the mass spectrum for such channels peaks near the tau mass, where the effects of a finite neutrino mass are large. The data samples were, in fact, relatively small. In passing, it should be noted that such limits have some dependence on whether the three or four-body mass spectrum is phase space, or resonant. The present best limit so obtained is the mass of the tau neutrino is less than  $143 \text{ MeV}/c^2$  at the 95% confidence level <sup>3)</sup>.

Here, a new experimental limit for the tau neutrino mass from the ARGUS collaboration <sup>5)</sup> is reported, based on a study of a sample of about 1500 decays in the channel,  $\tau^- \rightarrow \pi^+\pi^-\pi^-\nu_\tau$ . The tau leptons were produced in  $e^+e^-$  annihilation at centre-of-mass energies around  $10 \text{ GeV}/c^2$ . The data were collected using the ARGUS detector, located in one of the two interaction regions at the DORIS II  $e^+e^-$  storage ring at DESY. In obtaining this new limit, we have returned to the method of studying the high-energy endpoint of the hadronic energy spectrum, or equivalently, the low energy part of the tau neutrino energy spectrum. The improvement in the limit is due to high statistics, good resolution with small systematic absolute scale error ( $\pm 0.15\%$ ), and low backgrounds from Bhabha or hadronic events. The first is a result of the higher cross section at DORIS energies in comparison to PEP/PETRA. The second and third reflect the improvement in detector technology since the early SPEAR measurements, and the fact that the topologies for tau and multi-hadron events are more cleanly distinguishable at DORIS energies.

A short description of the ARGUS detector and trigger requirements can be found in reference 6. The event sample used in the analysis represents a total luminosity of  $61.4 \text{ pb}^{-1}$ , of which,  $7.3 \text{ pb}^{-1}$ ,  $36.2 \text{ pb}^{-1}$ ,  $8.8 \text{ pb}^{-1}$  and  $9.0 \text{ pb}^{-1}$  were collected on the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(4S)$  and nearby continuum, respectively. Events were selected which would satisfy the

topology of tau-pair production, where one tau ( $\tau^+$ ) decays into a single charged track, and the second ( $\tau^-$ ) into 3 charged tracks. The decay into a single isolated charged track acts as a tag, which, if the further requirement is made that no neutral energy be seen in the detector, represents  $46.6 \pm 1.9\%$  <sup>7)</sup> of all tau decay channels.

The acceptance of the single charged track tagging has been increased by including the contribution from the decay channel  $\tau^+ \rightarrow \rho^+ \nu^+$ , where  $\rho^+ \rightarrow \pi^+ \pi^0$ , accounting for a further  $22.1 \pm 2.4\%$  <sup>7)</sup> of tau decays. The  $\pi^0$  is reconstructed from shower counter measurements: either from two observed neutral clusters, which reconstruct to within  $\pm 20$  MeV/c<sup>2</sup> of the  $\pi^0$  mass, or from a single shower cluster of energy greater than 1 GeV, at which energy the two photons from the  $\pi^0$  decay often coalesce into a single shower. A  $\rho^+$  was defined by the reasonably unrestrictive requirement that the invariant mass of the tagging track and the  $\pi^0$  lies between  $0.57$  GeV/c<sup>2</sup> and  $1.07$  GeV/c<sup>2</sup>.

Events were required to satisfy the following specific conditions, maximizing the acceptance for the desired tau-pair decay topology, while minimizing backgrounds:

- (1) exactly four charged tracks, with charge sum zero,
- (2) momentum sum,  $P_s = \sum_{i=1}^4 |p_i|$ , greater than  $2.7$  GeV/c, to eliminate two-photon events, and less than  $0.92\sqrt{s}$ , to eliminate exclusive resonance decays,
- (3) a hemisphere cut,  $\cos\theta_{1i} \leq 0$ , where  $\theta_{1i}$  is the angle between the tagging track 1 and tracks  $i = 2, 4$ , and  $\cos\theta_{ij} > 0$ , where  $i = 2, 4$  and  $j = 3, 4$ , for the tracks on the three-prong side of the event,
- (4) for the tagging track, a polar angle cut,  $|\cos\theta_1| \leq 0.75$ , to ensure good momentum resolution and that trigger conditions are satisfied,
- (5) tracks on the three-prong side of the event satisfy the pion hypothesis based on dE/dx and time-of-flight measurements made by the detector,
- (6) sufficiently large opening angles between the three charged pions, with  $\cos\theta_{\pi^+\pi^-} < 0.992$ , to reject Bhabha and radiative  $\mu^+\mu^-$  events with converted photons,
- (7) besides the 1 or 2 clusters required to reconstruct a  $\pi^0$  if the  $\rho$ -channel tag is used, no additional energy in the shower counters exceeding 50 MeV and unassigned to one of the charged tracks, thereby suppressing feedthrough from tau decays into  $\pi^+\pi^-\pi^-\pi^0\nu^+$ ,
- (8) for the case of a  $\rho$  channel tag, momentum of the  $\rho$  greater than  $0.9$  GeV/c, and the angle between the  $\pi^0$  and  $\pi^-$  from the  $\rho$  of less than  $90^\circ$ , again suppressing contributions from four-pion tau decays,

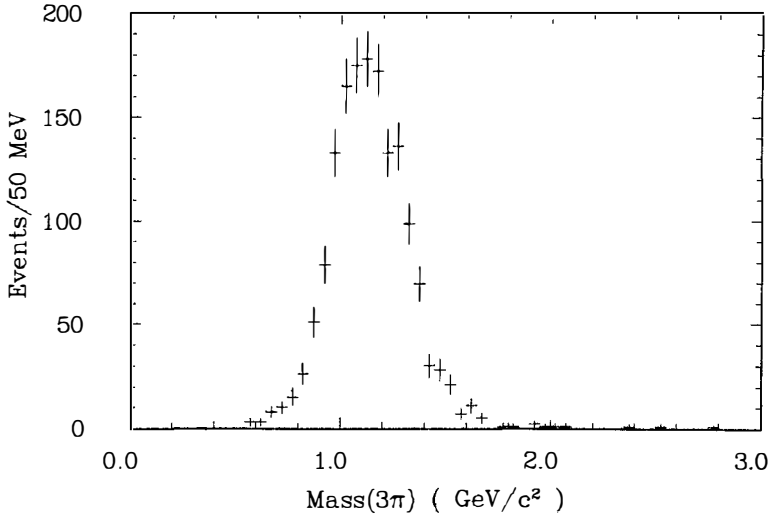


Figure 1. Invariant mass of three charged pions from the decay  $\tau^- \rightarrow \pi^+\pi^-\pi^-\nu_\tau$ , without acceptance corrections.

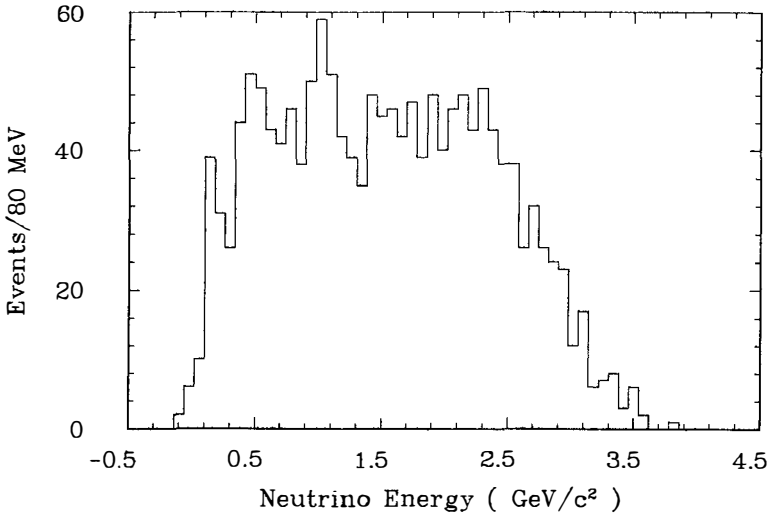


Figure 2. Tau neutrino energy spectrum determined from the energy of the three pion system in the decay  $\tau^- \rightarrow \pi^+\pi^-\pi^-\nu_\tau$ , without acceptance corrections.

- (9) shower counter energy for the tagging charged prong less than 3.5 GeV, in order to suppress background from Bhabha events.

The last requirement causes some loss of acceptance for the case where the tagging track is an electron. However, Bhabha events would populate the low-energy region of the neutrino energy spectrum, and thus are potentially troublesome in a study sensitive to this portion of the spectrum.

A total of 1566 events satisfy these selection criteria, and are predominantly three-prong decays of the tau lepton. The amount of background from hadronic, radiative Bhabha and muon-pair events is estimated, from the number of events beyond a three-pion mass of 1.8 GeV/c<sup>2</sup>, to be less than 1%. Contributions from misidentification of tau decays into  $\pi^+\pi^-\pi^-\pi^0\nu_\tau$  and  $K^+K^-\pi^-\nu_\tau$  are estimated to be less than 4%, populating mostly the region of low three pion invariant mass. The invariant mass spectrum for the events, uncorrected for acceptance, is shown in figure 1, with the pion mass assumed for each of the three hadrons. The spectrum is dominated by a broad resonance, which has been shown to have the properties of the  $A_1$ <sup>8,9</sup>. This interpretation is certainly consistent with our observation that the three-body final state is more than 90% composed of the two-body subsystem  $\rho^0\pi^-$ , although a definitive result awaits the completion of a full Dalitz plot analysis. However, knowledge of the resonant behaviour of this three-body tau decay channel is not an important factor in obtaining the tau neutrino mass limit.

Rather than studying the three-pion energy spectrum directly in obtaining the mass limit, we convert this to a spectrum for the tau neutrino energy, by using:

$$E_\nu = E_\tau - \sum_{i=2}^4 E_i \quad (1)$$

where  $E_\tau$  is the beam energy, and the energies,  $E_i$ , of the three decay hadrons are calculated from their measured momenta, again using pion mass assignments. The resulting spectrum is shown in figure 4.

For a given three-pion invariant mass, assuming an isotropic decay of the tau, events uniformly populate the region between:

$$E_\nu^{\text{min}} = \gamma E^* (1 - \beta) \quad (2)$$

and

$$E_\nu^{\text{max}} = \gamma E^* (1 + \beta) \quad (3)$$

where  $\gamma = E_\tau/m_\tau$  and  $\beta = p_\tau/E_\tau$ , and  $E^*$  is the energy of the tau neutrino in the tau centre-of-mass. If the tau neutrino has a finite mass, then the energy spectrum is shifted higher

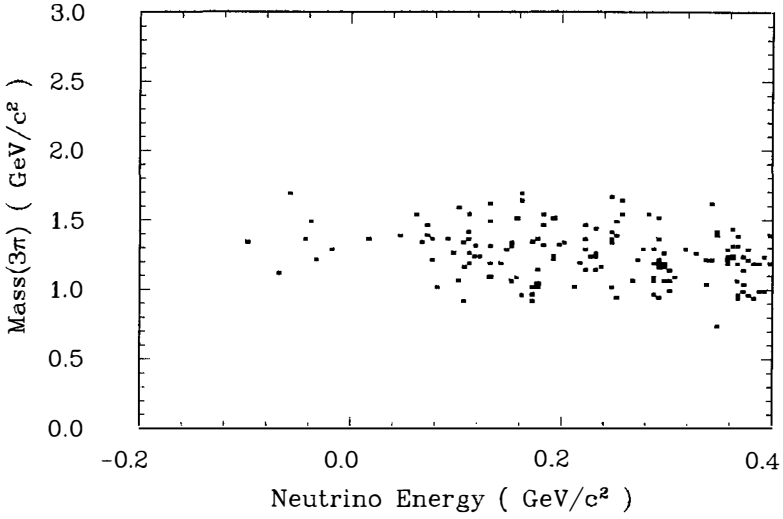


Figure 3. Plot of the low-energy end of the neutrino energy spectrum versus invariant three pion mass. The size of the squares is proportional to the number of entries in a given bin.

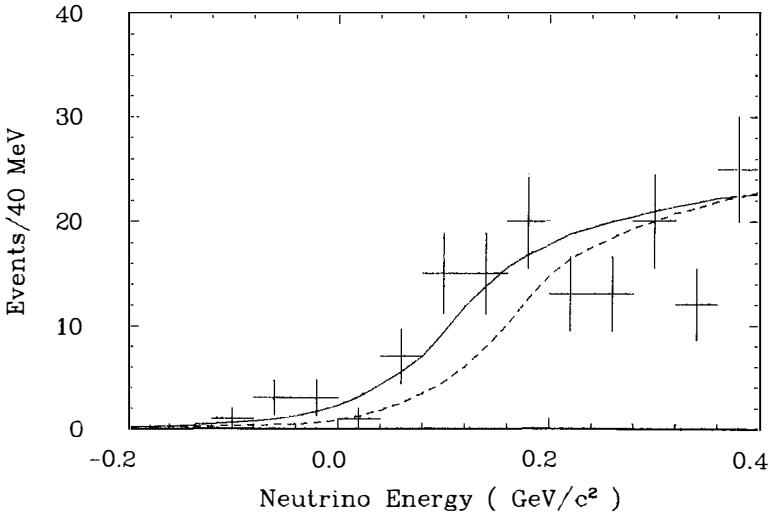


Figure 4. Mass sensitive region of the tau neutrino energy spectrum, with superimposed Monte Carlo expectations for  $m(\nu_\tau)=0$  (solid line) and  $140 \text{ MeV}/c^2$  (dashed line), normalized to the number of events in the complete spectrum.

by:

$$E_{\nu}^{\text{min}}(m_{\nu} \neq 0) = E_{\nu}^{\text{min}}(m_{\nu} = 0) + \frac{\gamma m_{\nu}^2}{2 E^*} \quad (4)$$

The lower limit,  $E_{\nu}^{\text{min}}$ , is a slow function of the three-pion invariant mass, so that, for  $m_{\nu} = 0$ , the entire mass spectrum has some contribution to the region below  $E_{\nu} = 300 \text{ MeV}/c^2$ . The relative importance of the higher mass portion of the spectrum of course is greater, since the density of events there as a function of  $E_{\nu}$  is greater. However, the mass sensitive region is dominated by the high statistics portion of the three-pion mass spectrum, as can readily be seen in figure 3.

In order to compute the limit on the tau neutrino mass, we have used a Monte Carlo to predict the shape of the spectrum in the mass sensitive region. The calculation is based on the observed mass spectrum for masses less than  $m_{\tau}$ , assumes isotropic decays of the tau lepton,  $\tau^{-} \rightarrow (3\pi)^{-}\nu_{\tau}$ , in the tau rest frame, and includes the effects of momentum resolution, the machine energy spread, radiative corrections<sup>10)</sup> and detector acceptance. The momentum resolution, which is the most important factor in determining the obtainable limit, is confirmed by two experimentally accessible measurements: muon-pair events at high momenta<sup>11)</sup>, where  $\sigma(p_{\text{T}})/p_{\text{T}} = 0.012 p_{\text{T}} \text{ GeV}/c$ , and by the width of the T peak in the missing mass spectrum of  $\Upsilon' \rightarrow \pi^{+}\pi^{-}\text{X}$  events<sup>6)</sup> at lower momenta, where the average  $\sigma(p_{\text{T}})/p_{\text{T}}$  is 0.009.

The low-energy endpoint of the neutrino energy spectrum is shown in figure 3, together with the calculated spectrum assuming  $m_{\nu} = 0$  and  $m_{\nu} = 140 \text{ MeV}/c^2$ . The shift, proportional to  $m_{\nu}^2/E^*$ , of the calculated spectrum toward higher energies is clearly illustrated. The maximum likelihood technique has been used in the mass sensitive region from  $-100 \text{ MeV}/c^2$  to  $+300 \text{ MeV}/c^2$  to obtain a limit on the tau neutrino mass. There are 90 events in the fit region.

The sensitivity of the obtained limit to sources of systematic error has been studied by varying both the upper limit of the three-pion-mass included and the limits of the interval of neutrino energy used, by changing the momentum resolution by 20%, and by varying the level of hadronic background by a factor of four. The mass limit was found to vary relatively little under such changes; the result is statistics dominated. If account is taken of all such sources of systematic error, including the amount of hadronic background and reasonable uncertainties in the momentum resolution, we obtain an upper limit on the tau neutrino mass of  $70 \text{ MeV}/c^2$ , at the 95% confidence level.

In summary, we have obtained a new limit for the mass of the tau neutrino. This limit is based on a study of the neutrino energy spectrum, obtained from a high statistics sample of tau decays into the channel,  $\pi^{+}\pi^{-}\pi^{\pm}\nu_{\tau}$ . The method used, namely a measurement of the

endpoint position of this spectrum, is quite analogous to earlier measurements in the  $\pi^\pm\nu_\tau$  channel by MARK II <sup>2)</sup>. High statistics, small hadronic backgrounds and good control of systematics have resulted in an improvement by a factor of two over the previous best limit <sup>3)</sup>.

## REFERENCES

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