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A STUDY OF THE DECAY $\tau^- \to \pi^- \nu_\tau$*

C. A. Blocker,[¶] J. M. Dorfan, G. S. Abrams, M. S. Alam,[†]
A. Blondel,[§] A. M. Boyarski, M. Breidenbach, D. L. Burke,
W. C. Carithers, W. Chinowsky, M. W. Coles,[††] S. Cooper,[††]
W. E. Dieterle, J. B. Dillon, J. Dorenbosch,[‡] M. W. Eaton,
G. J. Feldman, M. E. B. Franklin, G. Gidal, G. Goldhaber,
G. Hanson, K. G. Hayes,[‡] T. Himel,[‡] D. G. Hitlin,[‡‡]
R. J. Hollebeek, W. R. Innes, J. A. Jaros, P. Jenni,[‡]
A. D. Johnson, J. A. Kadyk, A. J. Lankford, R. R. Larsen,
M. Levi,[¶] V. Lüth, R. E. Millikan, M. E. Nelson, C. Y. Pang,
J. F. Patrick, M. L. Perl, B. Richter, A. Roussarie,
D. L. Scharre, R. H. Schindler,[‡] R. F. Schwitters,[¶]
J. L. Siegrist, J. Strait, H. Taureg,[‡] M. Tonutti,[¶¶]
G. H. Trilling, E. N. Vella, R. A. Vidal, I. Videau,[§]
J. M. Weiss and H. Zaccone.[§§]

Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley, CA. 94720

and

Stanford Linear Accelerator Center
Stanford University, Stanford, CA. 94305

ABSTRACT

We present a high statistics measurement of the branching ratio for the decay $\tau^- \to \pi^- \nu_\tau$ using data obtained with the Mark II detector at the SLAC e^+e^- storage ring SPEAR. We have used events from the center-of-mass energy region 3.52 to 6.7 GeV to determine that $B(\tau^- \to \pi^- \nu_\tau) = 0.117 \pm 0.004 \pm 0.018$. From electron-muon events in the same data sample, we have determined that $B(\tau^- \to \pi^- \nu_\tau)/B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = 0.66 \pm 0.03 \pm 0.11$. We present measurements of the mass and spin of the τ and the mass of the τ neutrino based, for the first time, on a hadronic decay mode of the τ.

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All of the properties of the τ lepton that have been measured to date are consistent with the interpretation of the τ as a sequential lepton. If this hypothesis is correct, the decay $\tau^- \to \pi^- \nu_\tau$[1] proceeds via the standard hadronic weak axial vector current and $B(\tau^- \to \pi^- \nu_\tau)/B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$ can be explicitly calculated from known parameters.[2] A measurement of this ratio is an unambiguous test of the τ's coupling to the hadronic weak axial vector current.

We present here a measurement of the branching ratio $B(\tau^- \to \pi^- \nu_\tau)$ based on data taken with the Mark II detector at the e^+e^- storage ring SPEAR. The integrated luminosity of 21000 nb^{-1} at center-of-mass energies from 3.52 to 6.7 GeV corresponds to 58,600 produced $\tau^+\tau^-$ pairs. We also present measurements of the spin and mass of the τ and the mass of the τ neutrino based on the $\tau^- \to \pi^- \nu_\tau$ decay mode.

All aspects of the Mark II detector pertinent to this measurement have been fully discussed elsewhere.[3] We summarize here the characteristics relevant to this analysis. Charged particles are detected over 85% of the solid angle by the 16 layers of the central, cylindrical drift chambers. The momentum resolution for tracks constrained to the interaction vertex is $\frac{\delta p}{p} = \sqrt{(0.0145)^2 + (0.005p)^2}$ (p in GeV/c) where the first term is from multiple-scattering and the second term reflects the 200 micron spatial resolution. Outside the drift chambers are 48 time-of-flight (TOF) scintillation counters having a 300 picosecond timing resolution. Next comes the solenoidal magnet coil providing a uniform field of 4.1 kilogauss. Outside the coil are eight lead-liquid argon shower counters covering 65% of the solid angle. The energy resolution is $12\%/\sqrt{E(\text{GeV})}$, and the photon detection efficiency ranges from greater than 95% above 500 MeV down to 20% at 100 MeV. Outside the shower counters is the muon system consisting of layers of iron separated by layers of proportional tubes. One end of the detector is instrumented with a lead-proportional chamber endcap shower counter.

Charged pions were identified as particles which (1) were not muons according to the muon system, (2) were not electrons according to the lead-liquid argon shower counters, (3) were not kaons according to the TOF system (relevant for momenta less than 1.3 GeV/c), and (4) were not protons according to the TOF system (relevant for momenta less than 2.1 GeV/c). The requirement that the particle be distinguishable from a muon rejects all particles with momenta below approximately 700 MeV/c, the range threshold for muon identification. The efficiency for identifying pions was measured with known pions from ψ and K_S^0 decays. The probability of misidentifying an electron as a pion was measured with known electrons from radiative Bhabha events and gamma conversions. For momenta above 700 MeV/c, the pion efficiency ranges from 82% to 90%, and the electron misidentification probability is less than 4%.

Events were selected if they had a charged pion and exactly one other, oppositely charged particle (X). The requirement of exactly two charged particles takes advantage of the low multiplicities typical of τ events and dramatically reduces contamination from hadronic events. To reduce background from events involving neutrals, particularly the decay $\tau^- \rightarrow \rho^- \nu_\tau \rightarrow \pi^- \pi^0 \nu_\tau$, we rejected any event having a photon with energy above 100 MeV. Photons less than 36 cm from a charged particle, measured at the liquid argon module, were ignored because of potential pattern recognition problems. To minimize beam-gas contamination, we required that the event vertex be within 10 cm, along the beam direction, of the beam crossing point. To reduce backgrounds from misidentified Bhabha and μ-pair events, we accepted only events with acoplanarity angle greater than 20°. The acoplanarity angle is $180^\circ - \Delta\phi$ where $\Delta\phi$ is the difference in azimuthal angles of the two charged particles.

There were 2150 $\pi^\pm X^\mp$ events satisfying the above criteria. Events in which both particles were identified as π's were counted twice. The estimated backgrounds are given in Table 1. The feed-down from events with more than two produced charged particles was measured with events satisfying the same criteria as the $\pi^\pm X^\mp$ events except that the two particles had the same charge. Assuming the probability of missing a particle was independent of the charge of the particle,[4] the feed-down to $\pi^\pm X^\mp$ events was twice[5] the number of $\pi^{\pm} X^{\pm}$ events. The beam gas background was calculated from the number of $\pi^{\pm} X^{\mp}$ events with a vertex between 15 and 25 cm, along the beam direction, from the interaction point. The other backgrounds were calculated from a Monte Carlo simulation program. The errors in these backgrounds are a combination of uncertainties in the models and uncertainties in the simulation of the detector by the Monte Carlo program. The net number of $\pi^{\pm} X^{\mp}$ events was $1138 \pm 46 \pm 174$[6] events.

The number of πX events after background subtraction ($N_{\pi X}$) is related to the branching ratio (B_π) for $\tau^- \to \pi^- \nu_\tau$ by

$$N_{\pi X} = 2\, B_\pi \sum_i \sigma^i_{\tau\tau} L^i \sum_j B_j\, \varepsilon^i_{\pi j} \qquad (1)$$

where the first sum (index i) is over center-of-mass energies and the second sum (index j) is over decay modes of the τ. The quantity $\sigma^i_{\tau\tau}$ is the radiatively corrected τ-pair production cross section, L^i is the integrated luminosity, B_j is the branching ratio to decay mode j, and $\varepsilon^i_{\pi j}$ is the efficiency for detecting a πX event when one τ decays to $\pi\nu_\tau$ and the other τ decays via decay mode j. The branching ratios assumed are shown in Table II. Since the sum over decay modes includes the decay $\tau^- \to \pi^- \nu_\tau$, Equation (1) is a quadratic equation in B_π, which was easily solved once the $\varepsilon^i_{\pi j}$'s were determined by a Monte Carlo program. It was necessary to correct the efficiencies for loss of events due to the creation of spurious "photons" by the pattern recognition program from a combination of real deposited energy and electronic noise. This correction was measured in events with the same topology as the πX events (two charged particles and no real photons), namely μ-pairs ($e^+e^- \rightarrow \mu^+\mu^-$), Bhabha events ($e^+e^- \rightarrow e^+e^-$), and cosmic rays. After a 3% correction of the Bhabha events for real, radiative photons, all three types of events agreed within 1%, giving an average correction of 6%. The average efficiencies were $\varepsilon_{\pi\pi} = 0.154$ and $\sum_{j \neq \pi} B_j \varepsilon_{\pi j} = 0.0654$ yielding [6]

$$B(\tau^- \rightarrow \pi^- \nu_\tau) = 0.117 \pm 0.004 \pm 0.018. \qquad (2)$$

The systematic errors are 15% for the background subtraction, 6% for the luminosity measurement, 5% for initial state radiative corrections, 5% for electron-pion separation, 5% for muon-pion separation, 1% for the spurious photon correction, and 5% for uncertainties in the branching ratios in $\sum_{j \neq \pi} B_j \varepsilon^i_{\pi j}$. When these errors are propagated through Eq. (1), the net systematic error on $B(\tau^- \rightarrow \pi^- \nu_\tau)$ is 15%.

To reduce some of the systematic errors, such as the luminosity, in the ratio $B(\tau^- \rightarrow \pi^- \nu_\tau)/B(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau)$, we have measured the τ leptonic branching ratio from the same data sample used for the $\tau^- \rightarrow \pi^- \nu_\tau$ analysis. We selected events having an electron identified by the liquid argon system, an oppositely charged muon identified by the muon system, and no other particles. There were 294 $e^\pm \mu^\mp$ events of which 5 ± 3 were estimated to come from charm production,

30 ± 7 from other τ decays, and 2 ± 1 from multiprong hadronic production. This gives a net signal of $257\pm17\pm8$ $e^{\pm}\mu^{\mp}$ events. The average efficiency for detecting $e\mu$ events was 0.071, giving

$$B(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\, B(\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau) = 0.030\pm0.002\pm0.004. \quad (3)$$

The systematic error comes from the following added in quadrature: 6% for the luminosity, 5% for radiative corrections to the τ-pair production cross section, 3% for the efficiency calculation, 5% for electron identification, 5% for muon identification, 3% for the background subtraction, and 1% for the spurious photon correction. Assuming that $B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)/B(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$ is equal to the theoretical[2] value of 0.973, we have

$$\begin{aligned} B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) &= 0.176\pm0.006\pm0.010 \\ B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) &= 0.171\pm0.006\pm0.010 \end{aligned} \quad . \quad (4)$$

This is in excellent agreement with the world average[7] of $B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 0.170\pm0.011$ and $B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) = 0.179\pm0.015$.

Combining Equations (2) and (4) gives

$$B(\tau^- \to \pi^-\nu_\tau)/B(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = 0.66\pm0.03\pm0.11.$$

This is in good agreement with the theoretical[2] prediction of 0.58 and with previous measurements[8] by Mark I (0.53 ± 0.23), PLUTO (0.51 ± 0.17), and DELCO (0.46 ± 0.18).

In order to demonstrate that these πX events are consistent with τ production and subsequent decay, we have performed several additional measurements on the data. A subset of these events having an identified lepton opposite the π were studied. The lepton could either be an electron identified by the liquid argon system or a muon identified by the muon system. The lepton energy spectra for the $e\pi$ and $\mu\pi$ events, Fig. 1, are in good agreement with the hard spectra expected from τ decays. Semi-leptonic decays of charmed particles give considerably softer decays.

There were 372 (231) e-π (μ-π) events of which 168 ± 29 (77 ± 15) were calculated to be background (primarily from other τ decays, as with the πX events). The average efficiency for detecting $e\pi$ ($\mu\pi$) events from τ decays was 0.0955 (0.0542) which gives

$$B_e B_\pi = 0.018 \pm 0.002 \pm 0.004 \qquad (5)$$

$$B_\mu B_\pi = 0.024 \pm 0.002 \pm 0.006. \qquad (6)$$

Dividing (5) by (6) gives $B_\mu / B_e = 1.33 \pm 0.18 \pm 0.36$ in agreement with the theoretical expectation[2] of 0.973. Setting B_μ / B_e equal to 0.973 and using Equation (4) gives

$$B_\pi = 0.119 \pm 0.009 \pm 0.020 \qquad (7)$$

$$B_\pi / B_e = 0.68 \pm 0.07 \pm 0.10. \qquad (8)$$

There is good agreement with the results obtained from the πX events.

In Fig. 2 we plot the product of $B(\tau^- \to \pi^- \nu_\tau)$ and the τ production cross section (calculated from Eq. (1), assuming $B_\pi = 0.117$ in the sum over j) as a function of the center-of-mass energy. We have fit the production cross section to the hypothesis that the τ is a point-like particle[9] with spin 0, ½, or 1. The free parameters in the fit were m_τ, $B(\tau^- \to \pi^- \nu_\tau)$, and, for the spin 1 case, two additional parameters described in Ref. 9. Since the branching fraction is a parameter in the fit, it serves as the normalization, and hence the fit constitutes a test of the shape of the production cross section. The spin 0 and spin 1 hypotheses are eliminated at the 95% confidence level (χ^2/DOF = 27/8 and 48/6). On the other hand, the data are well fit by the spin ½ hypothesis (χ^2/DOF = 8/8). The fit to the spin ½ hypothesis yields $m_\tau = 1.803 \pm 0.016$ GeV/c^2, in agreement with measurements[10] by DELCO ($1.782^{+0.002}_{-0.007}$), DESY-Heidelberg ($1.787^{+0.010}_{-0.018}$), and DASP (1.807 ± 0.020).

The pion energy spectrum, after bin-by-bin background subtractions and efficiency corrections, is shown in Fig. 3 for different center-of-mass energies. Since $\tau^- \to \pi^- \nu_\tau$ is a two-body decay, the expected pion energy spectrum is flat for monoenergetic τ's produced at a fixed center-of-mass energy. All spectra are flat and do not peak at high energies as expected for Bhabha and μ-pair events or at low energies as is typical of hadronic and two-photon events.

The end point of the pion energy spectrum is determined by the pion, τ, and τ neutrino masses. We have fit the pion spectrum to obtain an upper limit for m_{ν_τ}. Since this fit is sensitive to systematic variations in efficiencies and background subtraction for data from different center-of-mass energies, we used only data from the largest block of fixed energy running (5.2 GeV) in the fit. In Fig. 4, we plot the upper limit on m_{ν_τ} as a function of the assumed τ mass. For $m_\tau = 1.782$ GeV/c^2, the result is $m^2_{\nu_\tau} = 0.010 \pm 0.025$ GeV^2/c^4, which gives a two-standard deviation upper limit on the τ neutrino mass of 0.25 GeV/c^2. The DELCO group has obtained a similar limit[11] from the electron spectrum from $\tau^- \to e^- \bar{\nu}_e \nu_\tau$.

In summary, we have measured $B(\tau^- \to \pi^- \nu_\tau)$ to be $0.117 \pm 0.004 \pm 0.018$. From the same data, we have measured $B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \cdot B(\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau)$ to be $0.030 \pm 0.002 \pm 0.004$. Assuming the ratio of the electronic and muonic decay rates of the τ to be the theoretically expected value, these results were combined to give $B(\tau^- \to \pi^- \nu_\tau)/B(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = 0.66 \pm 0.03 \pm 0.11$. This is in good agreement with previous experiments[8] and with the theoretical prediction[2] of 0.58. The τ production cross section favors a spin ½ assignment for the τ and disfavors spin 0 and spin 1. From the τ production cross section, we measure m_τ to be 1.803 ± 0.016 GeV/c^2, in agreement with previous experiments.[10] From the energy spectrum of the pion in these decays, we have placed a two-standard deviation upper limit of 250 MeV/c^2 on the mass of the τ neutrino. These measurements support the sequential lepton model of the τ and indicate that the hadronic weak axial vector current couples to the τ with the expected relative strength.

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Present addresses:

¶ Harvard University, Cambridge, MA 02138
† Vanderbilt University, Nashville, TN 37235
†† DESY, Hamburg, Fed. Rep. of Germany
‡ EP Division, CERN, Geneva, Switzerland
‡‡ California Institute of Technology, Pasadena, CA. 91125
¶¶ Universität Bonn, Fed. Rep. of Germany
§ LPNHE, École Polytechnique, Palaiseau, France
§§ CEN-Saclay, France

References

1. Throughout this paper, all particle reactions also imply the charge conjugate reaction. For example, $\tau^- \to \pi^- \nu_\tau$ stands for itself and for $\tau^+ \to \pi^+ \bar{\nu}_\tau$.

2. H. B. Thacker and J. J. Sakurai, Phys. Lett. 36B, 103 (1971) and Y. S. Tsai, Phys. Rev. D4, 2821 (1971).

3. G. S. Abrams et al., Phys. Rev. Lett. 43, 477 (1979).
T. M. Himel, Ph. D. Thesis, SLAC-Report No. 223 (1979).
J. L. Siegrist, Ph. D. Thesis, SLAC-Report No. 225 (1979).
R. H. Schindler, Ph. D. Thesis, SLAC-Report No. 219 (1979).
C. A. Blocker, Ph. D. Thesis, LBL-Report 10801 (1980).

4. This is not true of two-photon production where the scattered e^+e^- are usually not detected. These events were accounted for separately.

5. For four-charged particles with a total charge of zero, there are four ways of pairing them so that they have opposite charges and two ways such that they have the same charge.

6. The first error of all quantities is statistical, and the second is systematic.

7. Particle Data Book, Rev. of Mod. Phys. 52 (1980).

8. G. J. Feldman, talk given at the International Conference on Neutrino Physics-Neutrino 1978, Purdue University, April 28 - May 2, 1978 and SLAC-PUB-2138 (1978).
G. Alexander et al., Phys. Lett. 78B, 162 (1978).
W. Bacino et al., Phys. Rev. Lett. 42, 6 (1979).

9. Y. S. Tsai, Phys. Rev. D12, 3533 (1975). Tsai originally used data from DELCO on $\tau^- \to e^- \bar{\nu}_e \nu_\tau$ to eliminate the spin 0 and spin 1 hypotheses for the τ. Y. S. Tsai, SLAC-PUB-2105 (1978) and Y. S. Tsai, Proceedings of the 1980 Guangzhou Conference on Theoretical Physics, Vol. 2, 1346 (1980). The DELCO analysis of the same data is in W. Bacino et al., Phys. Rev. Lett. 41, 13 (1978).

10. R. Brandelik et al., Phys. Lett. 73B, 109 (1978).
W. Bacino et al., Phys. Rev. Lett. 41, 13 (1978).
W. Bartel et al., Phys. Lett. 77B, 331 (1978).

11. W. Bacino et al., Phys. Rev. Lett. 42, 749 (1979).

Table I

Source	Number
Multiprong Events	80 ± 9
Beam-gas	14 ± 4
Other τ decays (primarily $\tau^- \rightarrow \rho^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$)	590 ± 170
Charm production	49 ± 24
Non-charm hadronic production	97 ± 19
$e^+e^- \rightarrow e^+e^-\gamma$	63 ± 13
$e^+e^- \rightarrow \mu^+\mu^-\gamma$	5 ± 1
2-Photon production	114 ± 15
Total	1012 ± 174

Estimated backgrounds to πX events. Except for multiprong events, all backgrounds refer to events with exactly two produced charged particles.

Table II

Decay Mode	Branching Ratio
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$	0.176
$\mu^- \bar{\nu}_\mu \nu_\tau$	0.171
$\rho^- \nu_\tau$	0.216
$\pi^- \pi^o \pi^o \nu_\tau$	0.05
$\pi^- \pi^o \pi^o \pi^o \nu_\tau$	0.02
$K^- \nu_\tau$	0.007
$K^{*-} \nu_\tau$	0.015

Branching ratios used for efficiency calculations.

Figure Captions

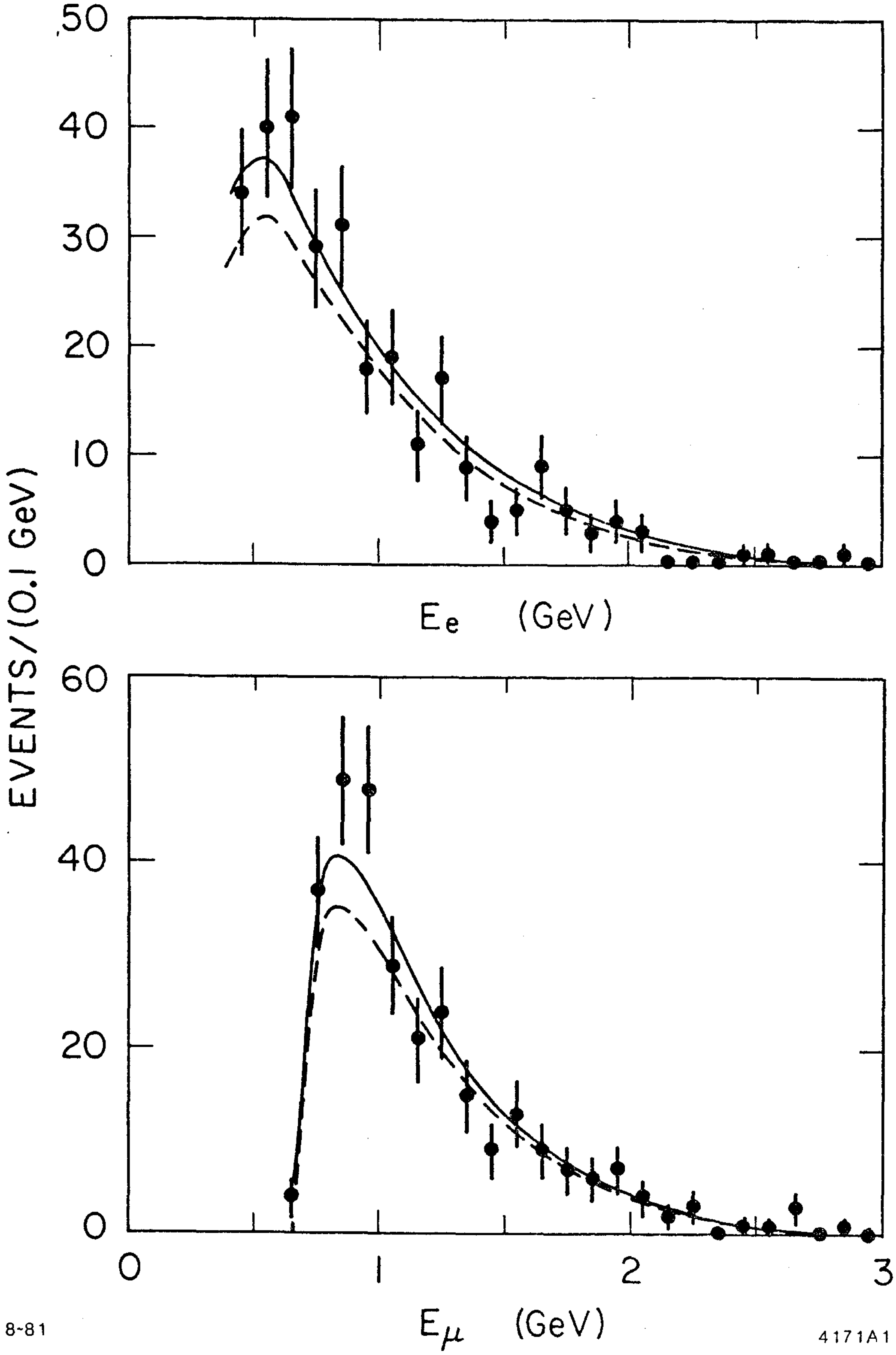
1\. a) Electron energy spectrum for e-π events. Dashed curve is the Monte Carlo expectation for signal events. Solid curve is the Monte Carlo expectation for signal plus background.

b) Muon energy spectrum for μ-π events.

2\. τ-pair production cross section measured from the $\tau^- \rightarrow \pi^- \nu_\tau$ decay mode. The curves are fits for different spin assignments for the τ. The errors include an estimated 15% point-to-point systematic uncertainty from background subtractions.

3\. Pion energy spectrum for π-X events with bin-by-bin background subtraction and efficiency corrections. The curves are the expected spectra for $m_\tau = 1.782$ GeV/c^2, $m_\nu = 0$, and $B_\pi = 0.117$.

4\. Upper limit (95% confidence level) on the mass of the τ neutrino as a function of the mass of the τ.



50
40
30
20
10
0
E_e (GeV)
EVENTS/(0.1 GeV)
60
40
20
0
0
1
2
3
E_μ (GeV)
8-81
4171A1

Fig. 1

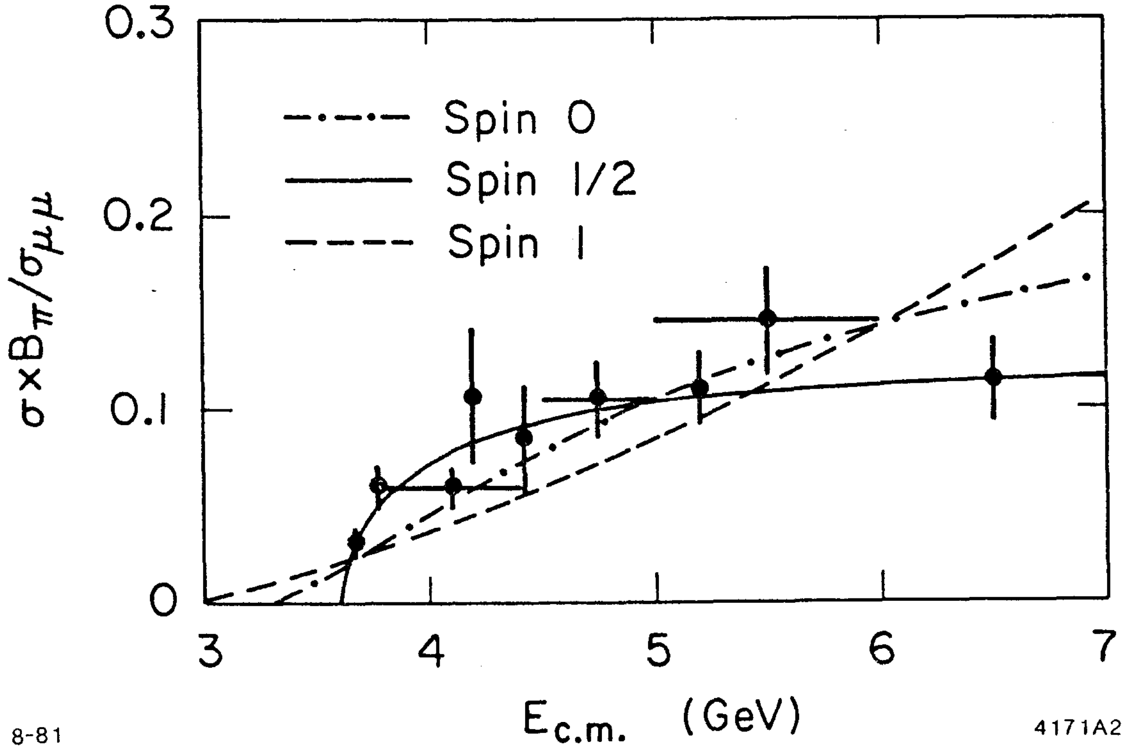
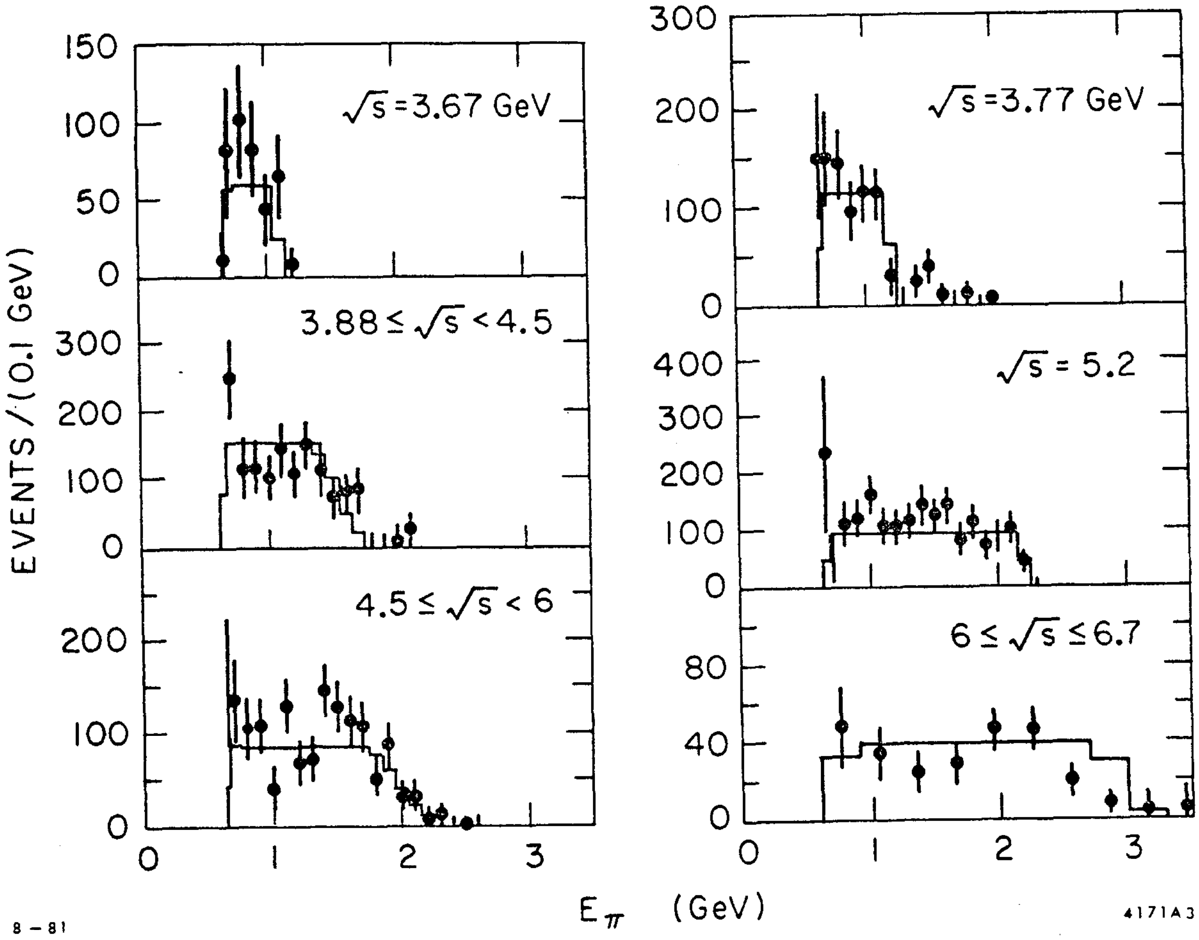
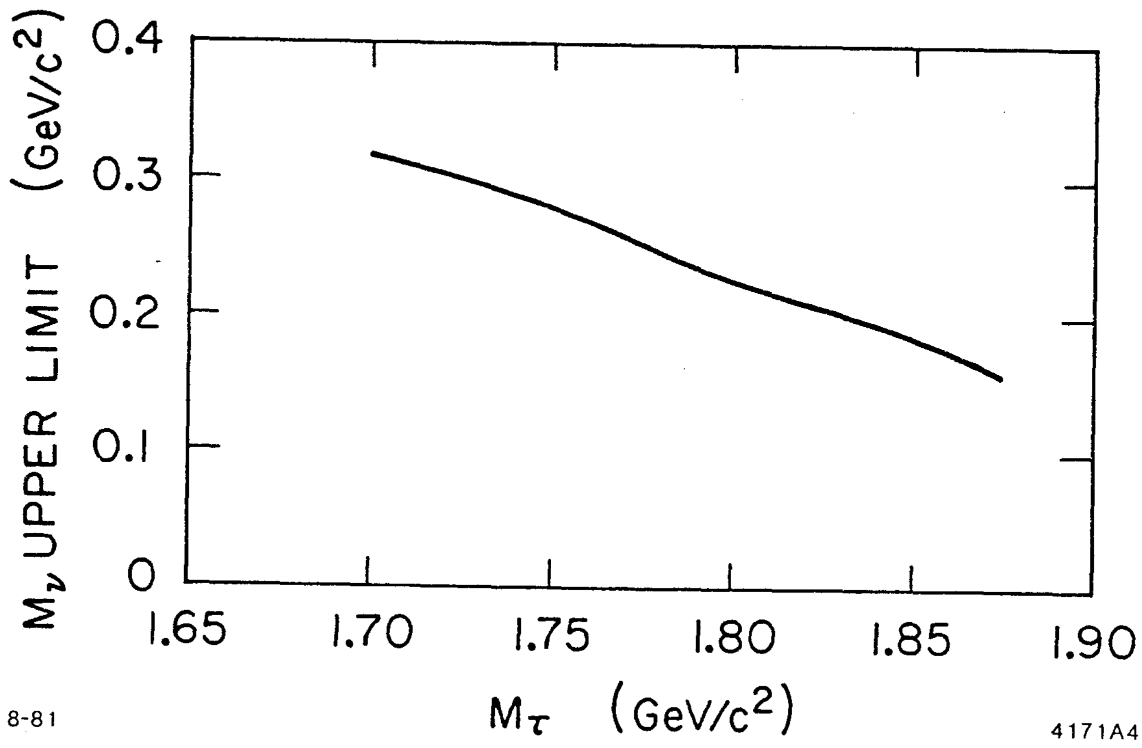

0.3
0.2
0.1
0
Spin 0
Spin 1/2
Spin 1
$\sigma \times B_\pi / \sigma_{\mu\mu}$
3
4
5
6
7
$E_{c.m.}$ (GeV)
8-81
4171A2

Fig. 2



EVENTS / (0.1 GeV)
$\sqrt{s}$ = 3.67 GeV
3.88 ≤ $\sqrt{s}$ < 4.5
4.5 ≤ $\sqrt{s}$ < 6
$\sqrt{s}$ = 3.77 GeV
$\sqrt{s}$ = 5.2
6 ≤ $\sqrt{s}$ ≤ 6.7
E_π (GeV)
8 – 81
4171A3

Fig. 3



0.4
0.3
0.2
0.1
0
M_ν UPPER LIMIT (GeV/c²)
1.65
1.70
1.75
1.80
1.85
1.90
M_τ (GeV/c²)
8-81
4171A4

Fig. 4