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LIMIT ON TAU NEUTRINO MASS

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Abstract

Using the complete data sample of 300 pb^{-1} collected by the HRS spectrometer in e^+e^- collisions at 29 GeV, a mass limit for the τ neutrino is set. The end point of the hadronic mass spectrum is determined in the decays $\tau \rightarrow 5\pi^{\pm}\nu_\tau$ and $\tau \rightarrow 5\pi^{\pm}\pi^{o}\nu_\tau$. At 95% confidence level, an upper limit of $M_{\nu_\tau} < 76$ MeV/c^2, is found.

The High Resolution Spectrometer[1] (HRS) has now completed its data taking at PEP having accumulated 300 pb^{-1} using e^+e^- collisions at a center of mass energy of 29 GeV. In a previous paper[2] we established that the τ lepton decays to a τ neutrino and $5\pi^\pm$ as well as $5\pi^\pm\pi^\circ$ by observing several events of each type. In this paper seven $5\pi^\pm$ and six $5\pi^\pm\pi^\circ$ events are used to place an upper limit on the mass of the τ neutrino.

The detector provides charged-particle tracking over 90% of the solid angle in a solenoidal magnetic field of 1.6 T. The momenta of tracks at large angles are measured with a relative accuracy of about 1%. Of particular importance to this analysis is the measurement of electromagnetic shower energy with a lead-scintillator calorimeter covering the angular interval $|\cos\Theta| < 0.60$, where Θ is the angle with respect to the beam direction. The forty-module barrel calorimeter system has an energy resolution of $\sigma_E/E \approx 16\%/\sqrt{E}$ (E in GeV) and an angular resolution for showers of 14 mr along the beam direction and 7 mr transverse. The outer layers of the tracking system are located immediately in front of the barrel calorimeter and can provide information on the pre-conversion of photons, particularly in the cerenkov counter system.

The selection criteria used to obtain the events in this sample are discussed in detail in a previous paper[2]. The topology of the selected events is five charged tracks in one hemisphere with a single charged track in the opposite hemisphere.

The τ neutrino mass limit is obtained by measuring the total hadronic mass associated with the τ decay. To do so requires a detailed understanding of the neutral energy in the events as well as in possible backgrounds, because the $5\pi^{\pm}\pi^{0}$ events are crucial in establishing the limit.

The main problem in understanding the neutral energy deposition is the confusion caused by the ~ 15% probability for a photon to convert in the cerenkov counter system located just in front of the barrel shower counter system. The 1.6 T magnetic field separates the electron-positron pair yielding two distinct clusters of energy in the calorimeter. This problem was solved by allowing up to four clusters of energy to be associated with a single π^{0}, and combining closest neighbors to form a single photon. All shower counter clusters had to be associated with either a charged track or a photon forming the π^{0}, otherwise the event was rejected. Once the clusters had been assigned, the energies of the two photons forming the π^{0} were recalculated, constraining the mass to that of the π^{0} and holding the total energy of the π^{0} fixed. If an ambiguity arose, the lower mass solution was chosen. Three of the six $5\pi^{\pm}\pi^{0}$ events are consistent with having a single conversion in the cerenkov system.

Because the backgrounds can have an important effect when establishing a limit on the τ neutrino mass, they have been studied in detail. The background from hadronic annihilation events was measured using the events that have five charged particles in one jet recoiling against N particles

(N = 3, 5, 7,...) in the opposite jet. Events containing an internal or external photon conversion were rejected.

Only three (5,N) events satisfied the requirement that the effective mass in the five-prong hemisphere, including the photons converting in the shower counters, be less than 1.9 GeV/c^2. The background estimate based on these events must be scaled down by a factor of 14.7, which is the ratio of the (5,N) events to the (5,1) events in the hadronic sample. Finally, by requiring that the effective mass of the charged particle plus any observed photons in the one-prong hemisphere be less that 1.6 GeV/c^2, the estimate of the hadronic background is reduced an additional 60% to 0.08 ± 0.05 events.

The other background contribution is from three-prong τ decays, with accompanying π^o's or γ's that produce an electron-positron pair by conversion before the inner drift chamber. These processes have been estimated by using a Monte Carlo τ event simulator incorporating the Berends and Kleiss[3] lepton generator with α^3 QED corrections. Using the selections reported earlier[2], the expected background is 0.1 ± 0.06 events.

The mass resolution of each event was found by repeated simulation starting each time with the observed event randomly rotated about the beam axis. The full detector simulator was used which includes the effects of multiple scattering, particle decay, photon conversion, neutral energy fluctuations, leakage and the intrinsic resolution of the detector elements. The parameters used in the calorimeter simulation were tuned to agree with the electromagnetic showers observed at PEP. The output from the simulator passed through the tracking routines and all other analysis routines in the same manner as the experimental data. The simulation was checked by comparing it with the observed D° and $D^{\pm}$ signals[4], with the result that the simulated and observed widths agree to within a few MeV/c^2. The resolution functions of the τ events fit well to gaussian shapes, with non-gaussian tails typically contributing less than 2%.

The mass acceptance is flat in the range of these data because the combination of the high magnetic field and two meter long track lengths ensures excellent spatial separation of the charged tracks from τ decay.

The properties of the event sample are listed in Table I and the hadronic mass distribution is shown in Fig. 1. These events have masses approaching the τ lepton mass[5] of 1784 $\pm$ 3 MeV/c^2. At the end point of the hadronic mass spectrum, where the limiting value of the neutrino kinetic energy is zero, the τ neutrino mass is given by the simple expression: $M_{\nu_\tau} = M_\tau - M_{hadrons}$.

To determine the upper limit for M_{ν_τ}, the $5\pi^{\pm}$ and $5\pi^{\pm}\pi^{\circ}$ mass distributions have been fitted using a maximum likelihood technique. The mass resolution of each event represents the uncertainty in the mass calculation using the measured kinematic variables. For events having neutral energy that escapes through cracks in the detector, the true mass can be larger than that measured, but not smaller. From the Monte

Carlo event simulator, it is estimated that for the $5\pi^{\pm}\pi^{\circ}$ events there is a 0.09 ± 0.03 chance of the accompanying π° going unobserved, so that the $5\pi^{\pm}$ event sample includes an estimated 0.6 ± 0.2 events of the $5\pi^{\pm}\pi^{\circ}$ final state.

We have taken into account the possibility that the $5\pi^{\pm}\pi^{\circ}$ events include true $5\pi^{\pm}$ events with a radiative photon incorrectly interpreted as a π°. In addition, in the $5\pi^{\pm}\pi^{\circ}$ sample, the energy of a radiative photon could be incorrectly included in the calculation of the π° energy. The probability of each of these effects is 0.006 ± 0.003, and is included in the fitting procedure.

As is the case for the 2π, 3π and 4π decay modes of the τ, it is likely that the 5π and 6π decays will proceed through hadronic resonances. Although there is no known resonance that can be associated with the $5\pi^{\pm}$ decays, one possibility would be a radial excitation of the $A_1(1270)$ resonance, the A_1', which should be more massive and have a larger width than the ~300 MeV/c^2 reported for the A_1. These properties would place the A_1' mass near the τ mass with a mass distribution extending well above 1784 MeV/c^2. In this case, the exact shape of the resonance is unimportant because the functional form of the hadronic mass distribution near the end point of the spectrum is dominated by the weak interaction matrix element and the effects of phase space[6]. The results of the maximum likelihood fit to the data using a $5\pi^{\pm}\nu_\tau$ phase space ($\rho_{5\pi^{+}\nu}$) times the weak matrix element;[7]

$$\frac{d\,\Gamma}{d\,M_{had}} \sim \rho_{5\pi\nu_\tau}\; M_{had} \;*$$

$$[(M_\tau^2 - M_{had}^2)(M_\tau^2 + 2M_{had}^2) - M_\nu^2(2M_\tau^2 - M_{had}^2 - M_\nu^2)], \quad (1)$$

are shown in Fig. 2. The best fit, shown as a solid line, yields $M_{\nu_\tau} = 0$. The upper limit, at 95% confidence level, of $M_{\nu_\tau} < 118\ \mathrm{MeV}/c^2$ is shown by the dashed line.

The shape of the $5\pi^\pm\pi^\circ$ mass spectrum is predicted by the conserved vector current hypothesis which relates the vector part of the weak interaction to the isovector part of the total annihilation cross section[6] for $e^+e^- \to 6\pi$. Specifically:[7]

$$\frac{d\Gamma}{dM_{had}} \sim M_{had}\,[(M_\tau^2 - M_{had}^2)(M_\tau^2 + 2M_{had}^2) - M_\nu^2(2M_\tau^2 - M_{had}^2 - M_\nu^2)]\,*$$

$$[(M_\tau^2 - M_{had}^2)^2 - M_\nu^2(2M_\tau^2 + 2M_{had}^2 - M_\nu^2)]^{1/2}\,\frac{\sigma^1{}_{e^+e^-}(M_{had})}{\sigma_{pt}(M_{had})}, \qquad (2)$$

where $\sigma^1{}_{e^+e^-}$ is the isospin one part of the cross section and $\sigma_{pt}(M_{had})$ is the point cross section which varies as $1/M^2{}_{had}$.

Measurements of the $e^+e^- \to 6\pi$ annihilation cross section for center of mass energies in the τ mass region have been reported by Cosme et al.[8] In these data there is a threshold-like behavior near 1.5 GeV/c^2. Our observed 6π events all cluster above 1.6 GeV/c^2. Using a linear fit to the measured 6π cross section in the τ mass region, a 95% confidence level upper limit of 77 MeV/c^2 is found for M_{ν_τ}, shown as the dashed line in Fig. 3. If the cross section "threshold" is varied by $\pm$50 MeV/c^2, the limit changes by less than 1.5 MeV/c^2. The best fit to the data, $M_{\nu_\tau} = 0$, is shown as the solid line in Fig. 3.

Fig. 4 shows the normalized likelihood as a function of τ neutrino mass for the combined results of the $5\pi^{\pm}$ and $5\pi^{\pm}\pi^{\circ}$ data. Also in Fig. 4 is the integral of the normalized likelihood showing the 95% and 68% confidence level points. Using the combined data, an upper limit for the mass of the τ neutrino is found at 76 MeV/c^2 at the 95% confidence level.

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Figure Captions

Figure 1. The hadronic invariant mass of the events $\tau \to 5\pi^{\pm}\pi^{\circ}\nu_{\tau}$ and $\tau \to 5\pi^{\pm}\nu_{\tau}$. The $5\pi^{\pm}\pi^{\circ}\nu_{\tau}$ events have been plotted twice, once excluding the π° to show the effect of adding the π° to the mass calculation.

Figure 2. a.) The hadronic invariant mass of the 5 events $\tau \to 5\pi^{\pm}\nu_{\tau}$. The solid line is phase space times the weak matrix element for the best fit $M_{\nu_{\tau}} = 0$.

Figure 3. The hadronic invariant mass of the 5 events $\tau \to 5\pi^{\pm}\pi^{\circ}\nu_{\tau}$. The solid line shown is the best fit, $M_{\nu_{\tau}} = 0$, based on the data of Cosme et. al.[8] The dashed lines show the 95% confidence level limits on $M_{\nu_{\tau}}$.

Figure 4. The Likelihood function for the combined $5\pi^{\pm}\nu_{\tau}$ and $5\pi^{\pm}\pi^{\circ}\nu_{\tau}$ data. The confidence level as a function of tau neutrino mass is also plotted.

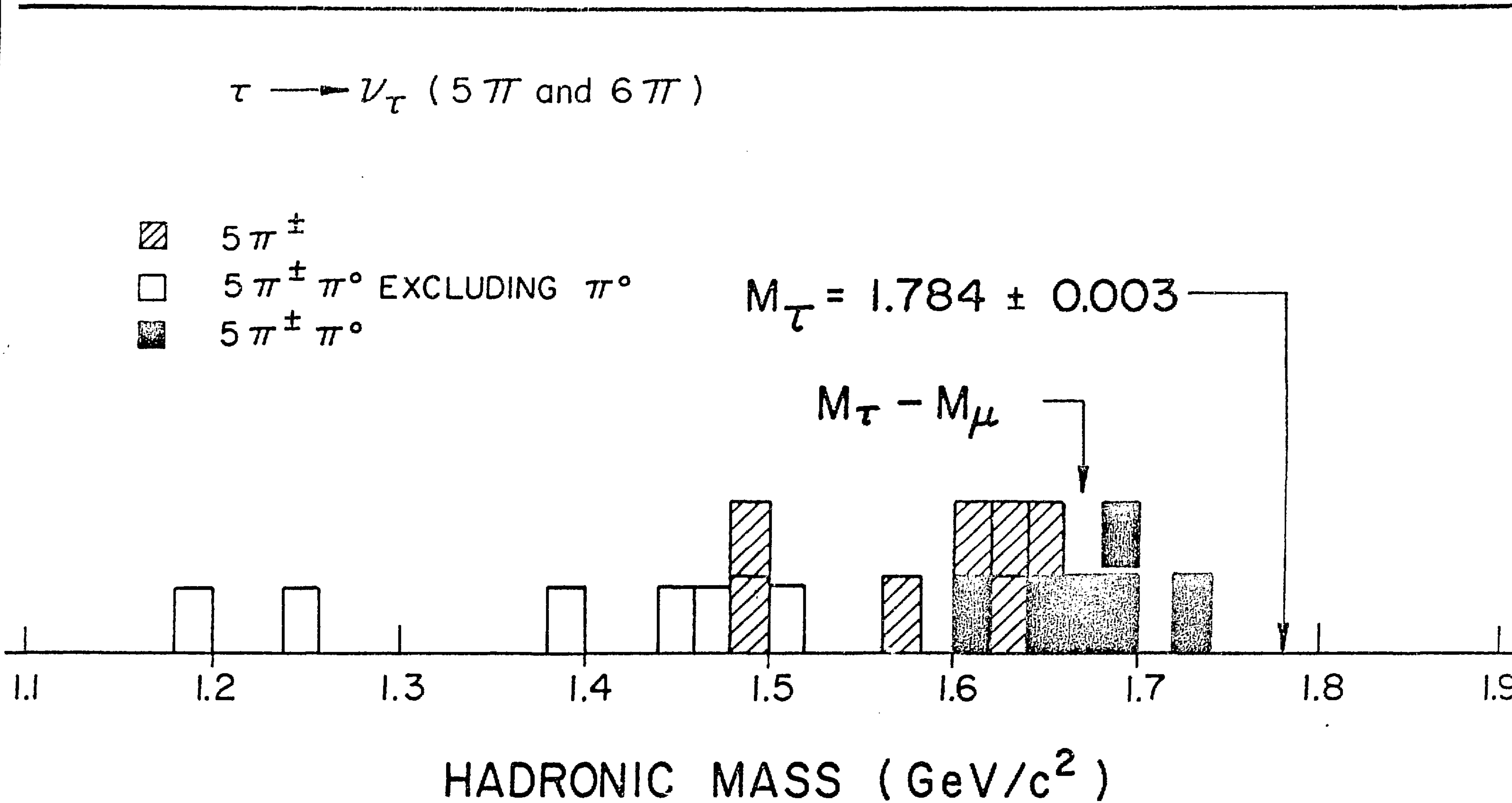
Table I. Properties of the Events.

$\tau \rightarrow \nu_\tau 5\pi^+$

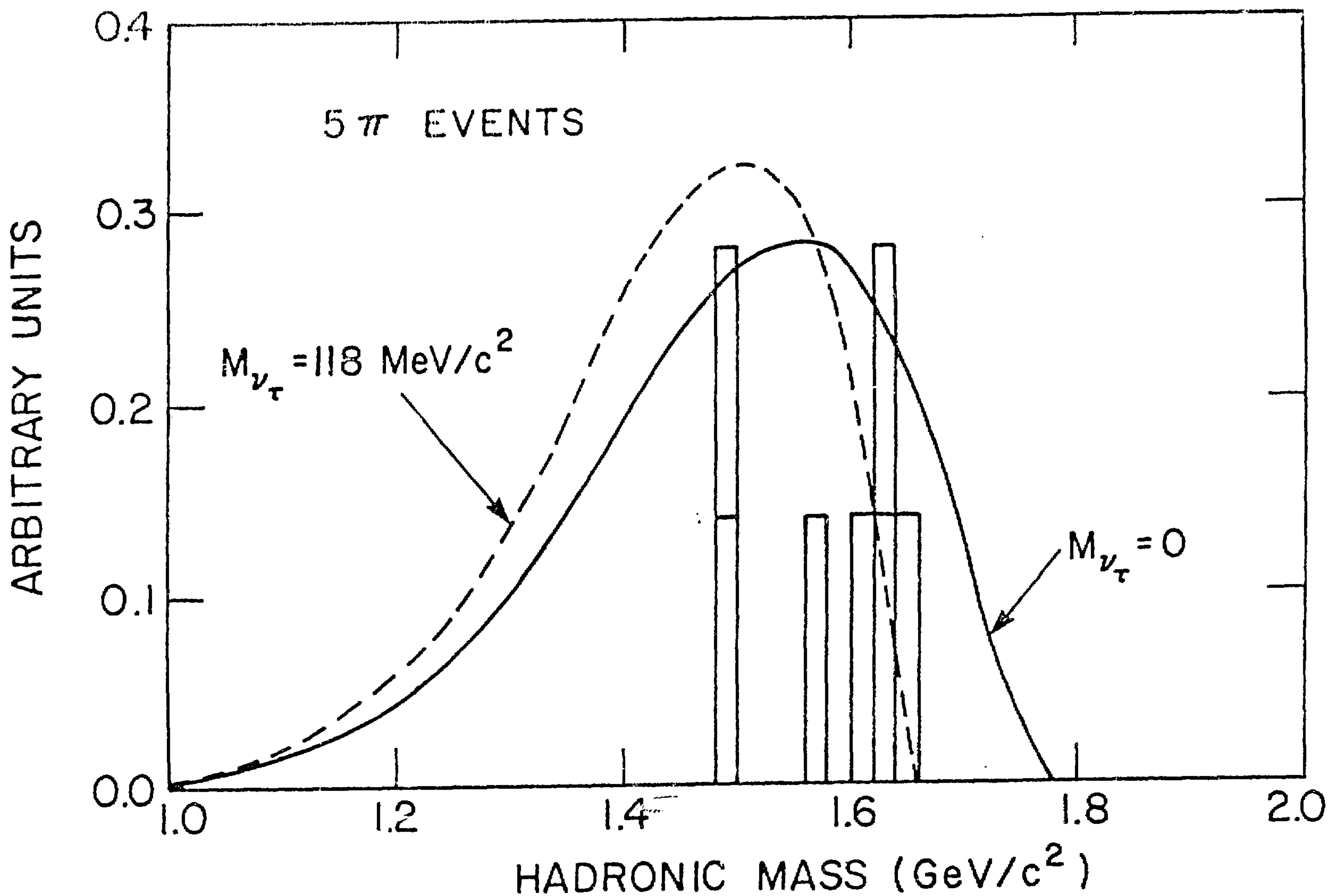
	MASS MeV/c^2	σ_M MeV/c^2	Single track momentum GeV/c
1	1486	13	1.3
2	1488	8	2.7
3	1574	13	6.0
4	1608	10	13.4
5	1630	12	1.6
6	1633	14	1.7
7	1645	17	1.2

$\tau \rightarrow \nu_\tau 5\pi^+\pi^0$

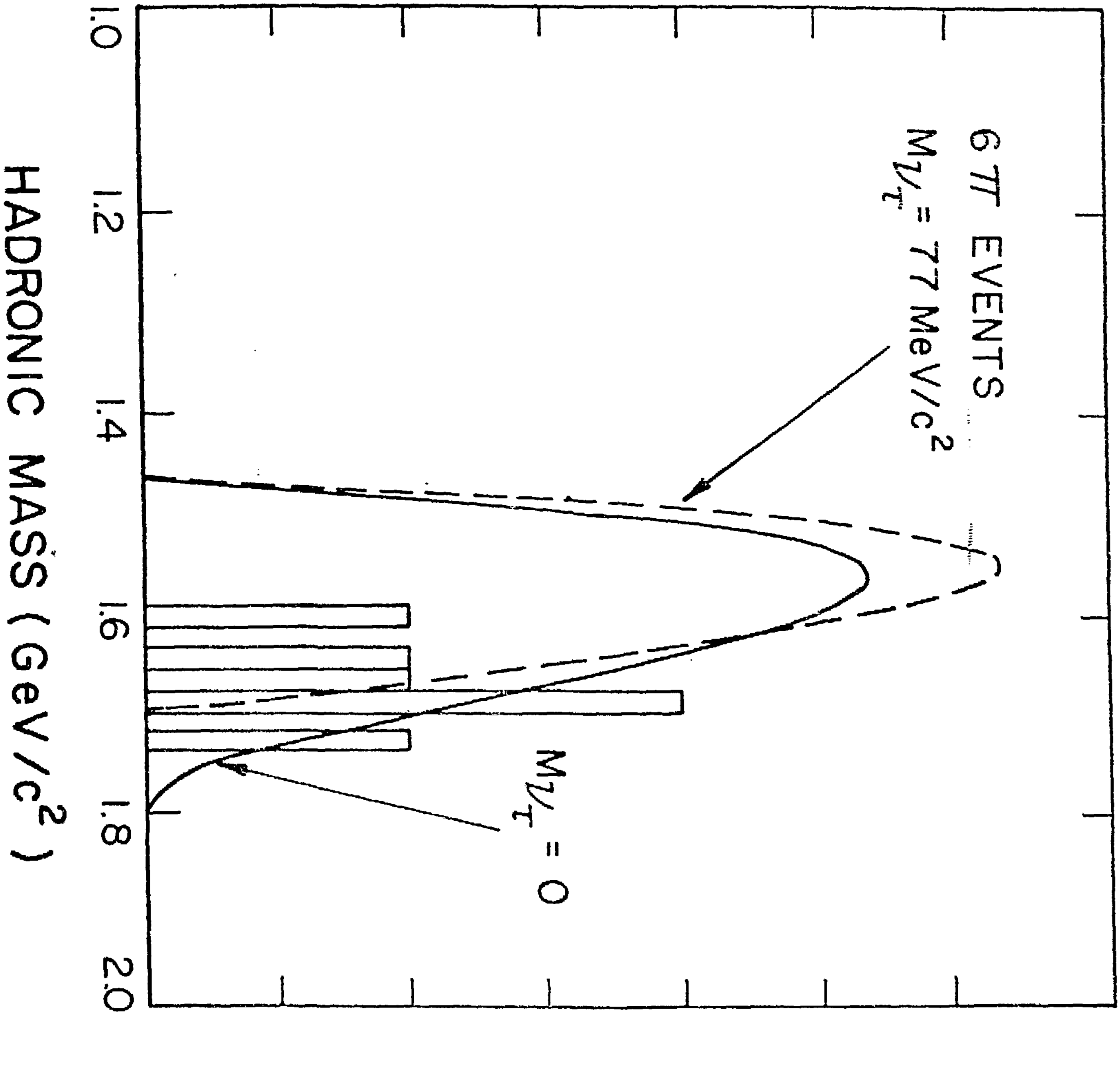
	MASS MeV/c^2	σ_M MeV/c^2	Single track momentum GeV/c
1	1618	15	4.0
2	1655	44	5.2
3	1666	57	1.8
4	1688	54	3.8
5	1693	18	5.8
6	1731	41	2.1

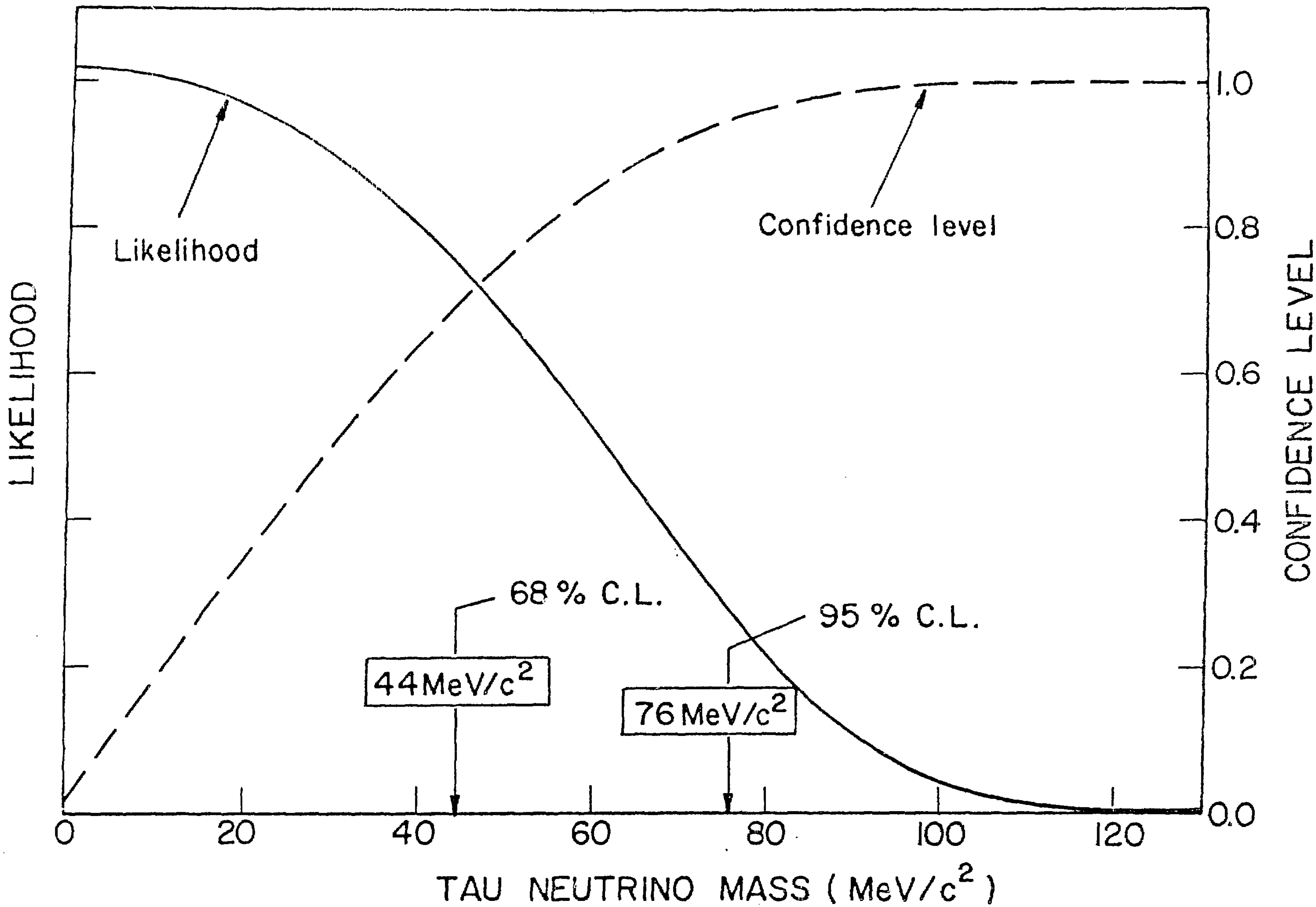


τ → ν_τ (5π and 6π)
5π±
5π± π° EXCLUDING π°
5π± π°
M_τ = 1.784 ± 0.003
M_τ − M_μ
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
HADRONIC MASS (GeV/c²)


5 π EVENTS
M ντ = 118 MeV/c²
M ντ = 0
ARBITRARY UNITS
0.0
0.1
0.2
0.3
0.4
1.0
1.2
1.4
1.6
1.8
2.0
HADRONIC MASS (GeV/c²)

LINEAR SCALE





LIKELIHOOD
CONFIDENCE LEVEL
Likelihood
Confidence level
1.0
0.8
0.6
0.4
0.2
0.0
68 % C.L.
95 % C.L.
44 MeV/c²
76 MeV/c²
0
20
40
60
80
100
120
TAU NEUTRINO MASS (MeV/c²)