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COMMENTS ON THE τ HEAVY LEPTON*†

Martin L. Perl
Stanford Linear Accelerator Center, Stanford
University, Stanford, California 94305

ABSTRACT

There is now substantial published evidence for the existence of a new charged particle of mass 1.9 GeV/c which decays thru the weak interaction. All this evidence is in agreement with the particle being a new lepton, which we call the τ. This paper presents measurements from the data of the SLAC-LBL Magnetic Detector Collaboration of the τ mass, of the mass of the associated neutrino, of the coupling of the τ to the associated neutrinos, and of the decay modes. We also discuss the evidence for the τ being a sequential heavy lepton.

INTRODUCTION

There is now substantial published evidence for the existence of a new charged particle with a mass of $1.90 \pm .10$ GeV/c^2 which decays thru the weak interactions. All this evidence is in agreement with the new particle being a new lepton, which we call the τ. A review of that evidence is being presented by G. Flügge[1] at this conference; and I reviewed the evidence several months ago.[2] Therefore in this talk I will only discuss recent measurements from the data of the SLAC-LBL Magnetic Detector Collaboration on the properties of the τ.

In discussing the data we use a model in which the τ is a sequential charged heavy lepton with a unique and separately conserved lepton number n_τ. The τ then has a unique associated neutrino ν_τ such that τ^- and ν_τ have $\nu_\tau = +1$. Other models will be discussed at the end of this paper. The τ then decays by weak interactions:

$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e \qquad (1a)$$

$$\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu \qquad (1b)$$

$$\tau^- \to \nu_\tau + (\text{hadrons})^- \qquad (1c)$$

Using conventional weak interaction theory, V-A coupling, $m_\tau = 1.9$ GeV/c^2 and $m_{\nu_\tau} = 0.0$ we obtain the branching ratios in Table I.

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TABLE I

Predicted branching ratios for a τ^- sequential charged heavy lepton with a mass 1.9 GeV/c^2, an associated neutrino mass of 0.0, and V-A coupling. The predictions are based on Refs. 3 and 4 as discussed in Ref. 5. The hadron continuum branching ratio assumes a threshold at 1.2 GeV for production of $u\bar{d}$ quark pairs whose final state interaction leads to the hadron continuum. From the third column it is predicted that 85% of the decays of the τ will contain only one charged particle.

decay mode	branching ratio	number of charged particles in final states
$\nu_\tau e^- \bar{\nu}_e$	.20	1
$\nu_\tau \mu^- \bar{\nu}_\mu$	.20	1
$\nu_\tau \pi^-$	.11	1
$\nu_\tau K^-$	.01	1
$\nu_\tau \rho^-$	.22	1
$\nu_\tau K^{*-}$	.01	1
$\nu_\tau A_1^-$	.07	1, 3
ν_τ(hadron continuum)$^-$	.18	1, 3, 5

Before presenting our measurements of the properties of the τ I summarize the two classes of evidence for its existence. The first class consists of $e^{\pm}\mu^{\mp}$ events

$$e^{+} + e^{-} \rightarrow e^{\pm} + \mu^{\mp} + \text{no other detected particles}, \tag{2a}$$

explained by the reaction and decay sequence:

$$e^{+} + e^{-} \rightarrow \tau^{+} + \tau^{-} , \tag{2b}$$

$$\tau^{+} \rightarrow \bar{\nu}_{\tau} + e^{+} + \nu_{e} \quad , \quad \tau^{-} \rightarrow \nu_{\tau} + \mu^{-} + \bar{\nu}_{\mu}; \tag{2c}$$

or the charge conjugate sequence. Such events were first found by our collaboration.[6] They have also been seen[1,7] by the PLUTO Group using the DORIS $e^{+}e^{-}$ colliding beams facility. In this paper I use a newly enlarged sample of 144 $e^{\pm}\mu^{\mp}$ events produced in the E_{cm} range of 3.8 to 7.8 GeV (after the subtraction of background events).

The other class of evidence uses the theoretical prediction that 85% of τ decays will contain only one charged particle. Then reaction and decay sequences such as:

$$e^{+} + e^{-} \rightarrow \tau^{+} + \tau^{-} \tag{3a}$$

$$\tau^{+} \rightarrow \bar{\nu}_{\tau} + e^{+} + \nu_{e} \tag{3b}$$

$$\tau^{-} \rightarrow \nu_{\tau} + x^{-} + \text{no other charged particles;}$$

lead to 2-charged prong events of the form

$$\left.\begin{aligned} e^{+} + e^{-} &\rightarrow e^{\pm} + x^{\mp} + \text{no other particles} \\ e^{+} + e^{-} &\rightarrow \mu^{\pm} + x^{\mp} + \text{no other particles} \end{aligned}\right\} \tag{3c}$$

Here x is an e, μ, or charged hadron. Cavalli-Sforza et al.[8] were the first to report $\mu^{\pm}x^{\mp}$ events of the form of Eq. 3c which were consistent[9] with the τ heavy lepton production and decay mechanism in Eqs. 3a and 3b. The $\mu^{\pm}x^{\mp}$ events of this collaboration[10] which gave a very significant signal in the E_{cm} range of 5.8 to 7.8 GeV. and are also consistent with Eqs. 3a and 3b, are used in this paper. Finally in the E_{cm} range of 4.0 to 5.0 GeV $\mu^{\pm}x^{\mp}$ events[1,7] and $e^{\pm}x^{\mp}$ events[11] have been reported by the PLUTO and DASP Groups respectively. These events are also consistent with Eqs. 3a and 3b.

PROPERTIES OF THE τ

Mass of the τ: Using the eμ events we find the τ mass, m_{τ}, in three ways. In the first method we define a pseudo-transverse momentum, $p_{\perp}$, by finding an axis AA' in the eμ plane, Fig. 1, such that the perpendicular components of the e and μ with resepect to that axis are equal and a minimum. Explicitly,

$$p_{\perp} = |\underset{\sim}{p}_{e} \times \underset{\sim}{p}_{\mu}| / |\underset{\sim}{p}_{e} - \underset{\sim}{p}_{\mu}|$$

where $\underset{\sim}{p}_e$ and $\underset{\sim}{p}_\mu$ are the momenta of the e and μ respectively. We then compare the average value of $p_\perp$ in our data with a theoretical prediction made with a Monte Carlo method which takes into account the acceptance of the detector[12] and our cuts on the eμ events:

$$p_e > 0.65 \text{ GeV/c}, \; p_\mu > 0.65 \text{ GeV/c}, \; \theta_{copl} > 20^\circ \qquad (4)$$

θ_{copl} is the acoplanarity angle between the plane containing the e and the incident e^+ beam and the plane containing the μ and the incident e^+ beam. Our second way is to use the average value of $\cos \theta_{coll}$ and again compare data with theory. Here

$$\cos \theta_{coll} = -(\underset{\sim}{p}_e \cdot \underset{\sim}{p}_\mu)/(|\underset{\sim}{p}_e||\underset{\sim}{p}_\mu|)$$

Our third way uses the r distribution, Fig. 2, where

$$r = (p - 0.65)/(p_{max} - 0.65), \; 0 \lesssim r \lesssim 1 \qquad (5)$$

Here p is the momentum of the e or μ in GeV/c and p_{max}, its maximum value, depends on m_τ. To determine m_τ by this method we use the ratio[13] of the number of events with $r \gtrsim .6$ to the number with $.2 \lesssim r < .6$. Table II gives the results. For what we shall call our standard model, $m_{\nu_\tau} = 0.0$ and V-A coupling, we combine these methods to obtain

$$m_\tau = 1.90 \pm .10$$

where the error includes sytematic uncertainties.

A direct comparison of this m_τ determination with the observed eμ production cross section, $\sigma_{e\mu}$, is presented in Fig. 3. The curves are given by the equations

$$\sigma_{e\mu}(s) = 2A_{e\mu}(s)B_e B_\mu \sigma_{\tau\tau}(s) \qquad (6a)$$

$$\sigma_{\tau\tau}(s) = \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s} \qquad (6b)$$

B_e and B_μ are the branching ratios for τ^- goes to $\nu_\tau e^- \bar{\nu}_e$ and $\nu_\tau \mu^- \bar{\nu}_\mu$ respectively, βc is the velocity of the τ, $A_{e\mu}(s)$ is a calculated acceptance, $s = E_{cm}^2$, $m_\tau = 1.8$ or 2.0 and the product $B_e B_\mu$ is adjusted to give a best fit. The χ^2 probability of these fits is 90%. As m_τ is increased above 1.9 GeV/c^2, an increasing number of eμ events must be attributed to background.[2] This leads to a probability of less than 0.8% that $m_\tau \gtrsim 2.10$ GeV/c^2.

τ Neutrino Mass: To set a limit on m_{ν_τ} we use the r distribution in Fig.4. The solid curves are for $m_\nu = 1.90$ GeV/c^2, V-A coupling, and $m_{\nu_\tau} = 0.0$, 0.5 and 1.0 GeV/c^2 respectively. As m_{ν_τ} increases the quality of fit decreases. The 95% confidence upper limit on m_{ν_τ} is

$$m_{\nu_\tau} < 0.6 \text{ GeV/c}^2 \quad ; \quad \text{for } m_\tau = 1.90 \text{ GeV/c}^2,$$

$$m_{\nu_\tau} < 0.7 \text{ GeV/c}^2 \quad ; \quad \text{for } m_\tau = 1.80 \text{ GeV/c}^2,$$

TABLE IIA

Mass measurements of the τ in GeV/c^2, assuming V-A coupling for the τ-ν, and m_{ν_τ} = 0.0. The three methods are based on: $p_\perp$, the pseudo-transverse momentum; cos θ_{coll}, the cosine of the collinearity angle; and r, the scaled momentum distribution. They are explained in the text. The errrors are statistical.

E_{cm} range (GeV)	Method		
	$p_\perp$	cos θ_{coll}	r
$3.8 \leq E_{cm} < 4.8$	1.88 ± .08	1.91 ± .25	1.83 ± .06
$E_{cm} = 4.8$	2.11 ± .13	1.82 ± .22	1.83 ± .08
$4.8 < E_{cm} \leq 7.8$	1.86 ± .08	1.85 ± .12	2.27 ± .31
$3.8 \leq E_{cm} \leq 7.8$	1.91 ± .05	1.85 ± .10	1.88 ± .06

TABLE IIB

Mass measurements of the τ in GeV/c^2 for two models: V-A coupling for the τ-ν_τ and m_{ν_τ} = 0.5 GeV/c^2; and V+A coupling for the τ-ν_τ and m_{ν_τ} = 0.0. The three methods: $p_\perp$, cos θ_{coll}, and r; are explained in the text. The entire $3.8 \leq E_{cm} \leq 7.8$ range is used and the errors are statistical.

Model	Method		
	$p_\perp$	cos θ_{coll}	r
V-A m_{ν_τ} = 0.5 GeV/c^2	2.01 ± .05	1.90 ± .09	1.70 ± .12
V+A m_{ν_τ} = 0.0	2.12 ± .05	1.95 ± .10	upper limit is 1.76 with 95% confidence.

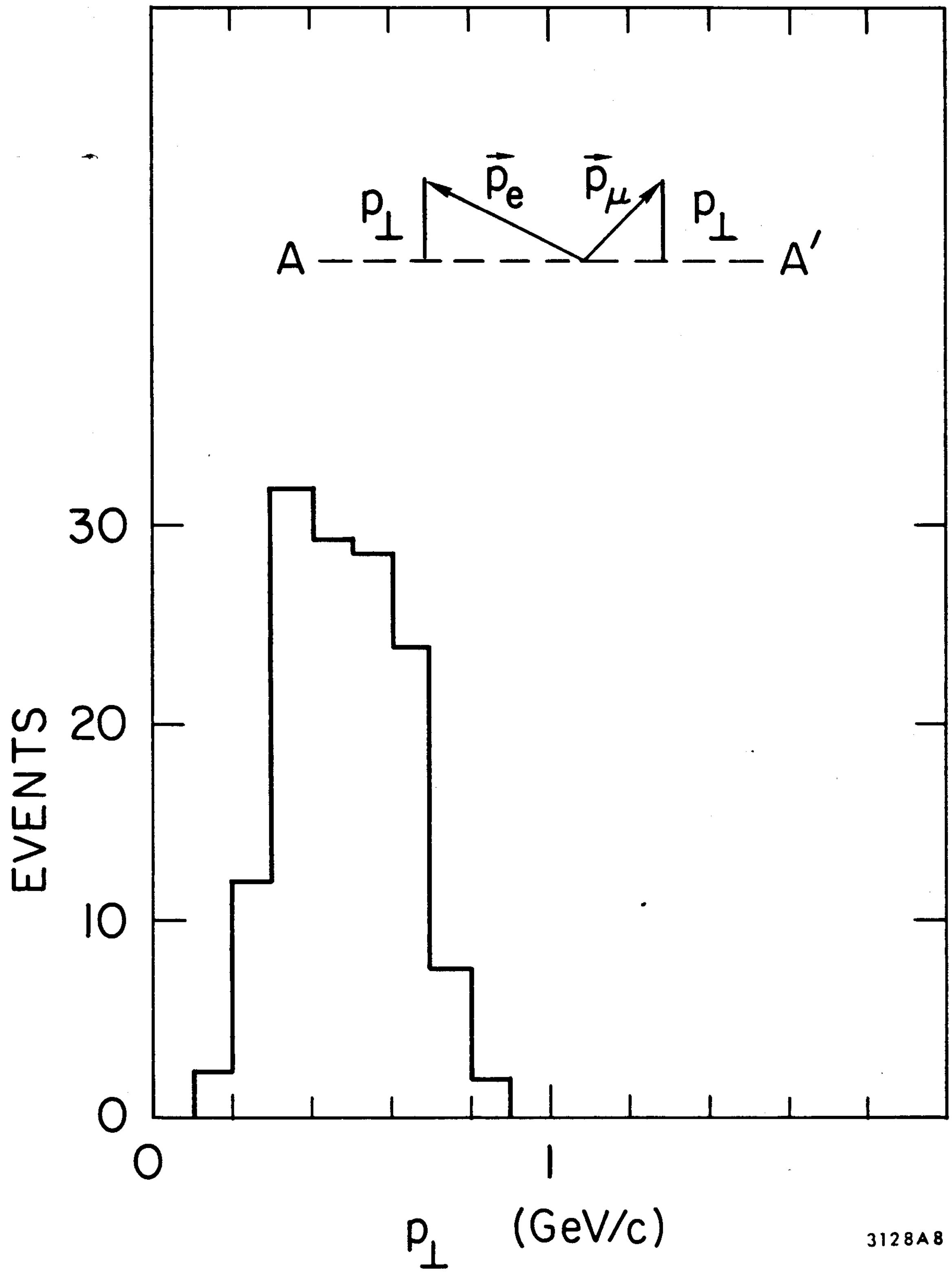

Fig. 1. The $p_\perp$ distribution for all eμ events not corrected for background.

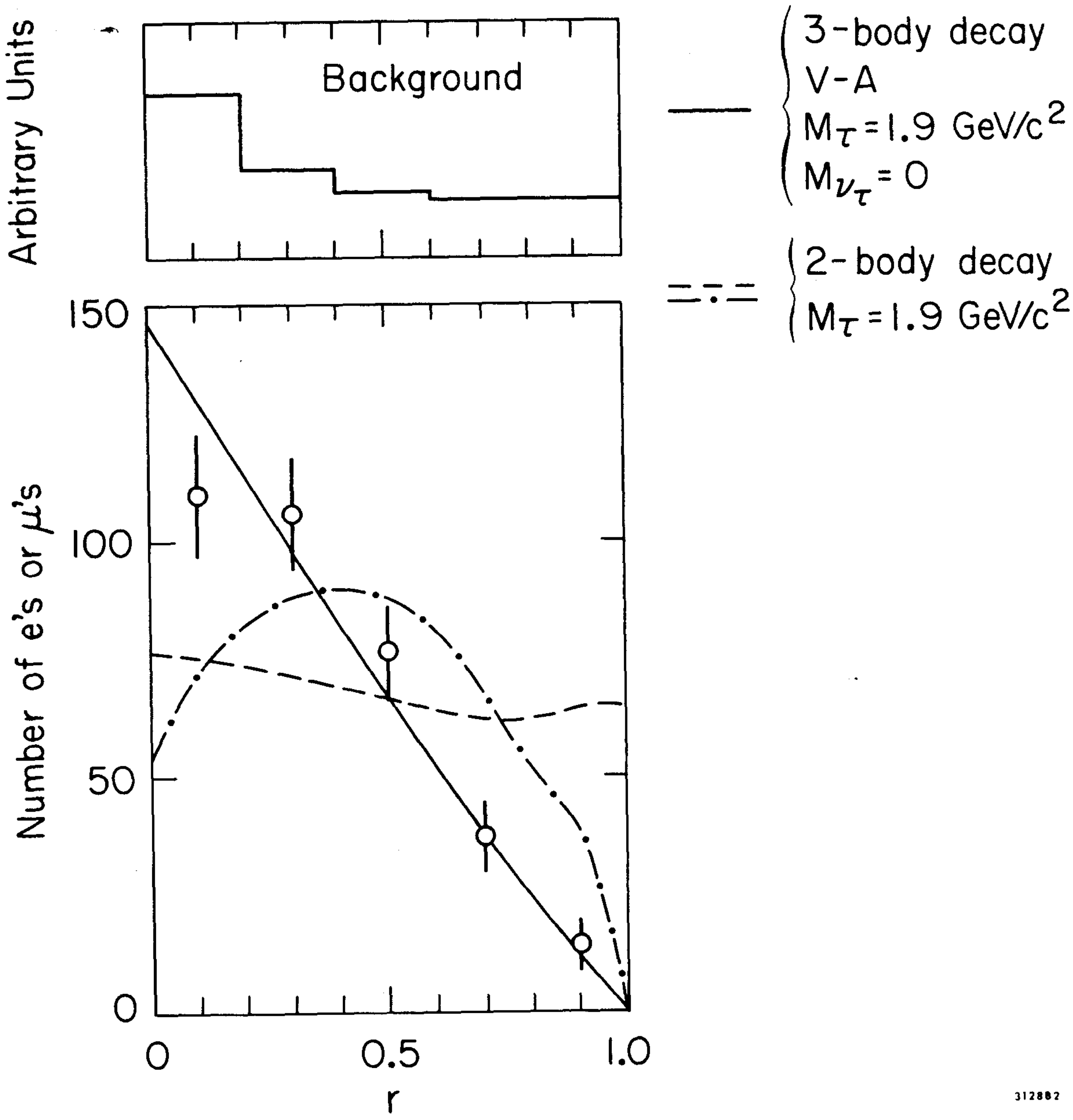

Fig. 2. The lower figure shows the r distribution (Eq. 5) for $3.8 \leqslant E_{cm} \leqslant 7.8$ GeV with background subtracted. The solid curve is for the 3-body, leptonic decay of the τ (Eq. 3) with the indicated parameters. The dash and dash-dot curves are for 2-body leptonic decay modes of the boson; the former is for no spin alignment of the boson, and the latter is for a spin 1 boson produced only in the helicity = 0 state.

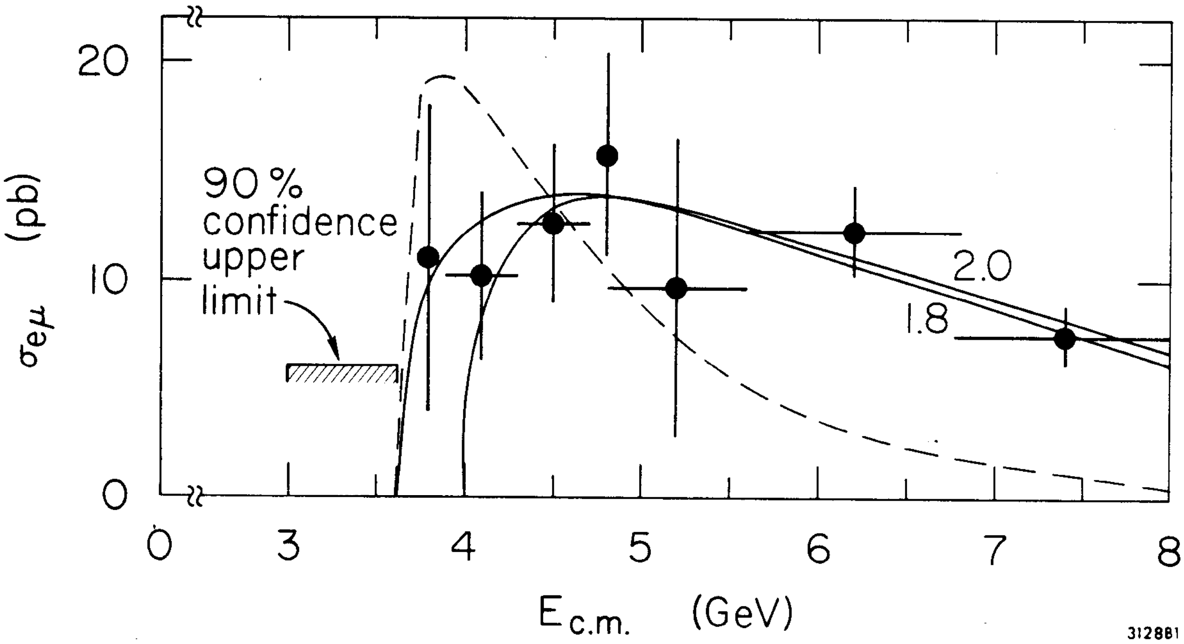

Fig. 3. The observed eμ production cross section, $\sigma_{e\mu}$. The vertical lines are statistical errors, thehorizontal lines show the E_{cm} range covered by each point. No events before background subtraction were found in the E_{cm} range of 3.0 to 3.6 GeV. We show the 90% confidence upper limit on $\sigma_{e\mu}$ if 2.3 events had been found. The curves are explained in the text.

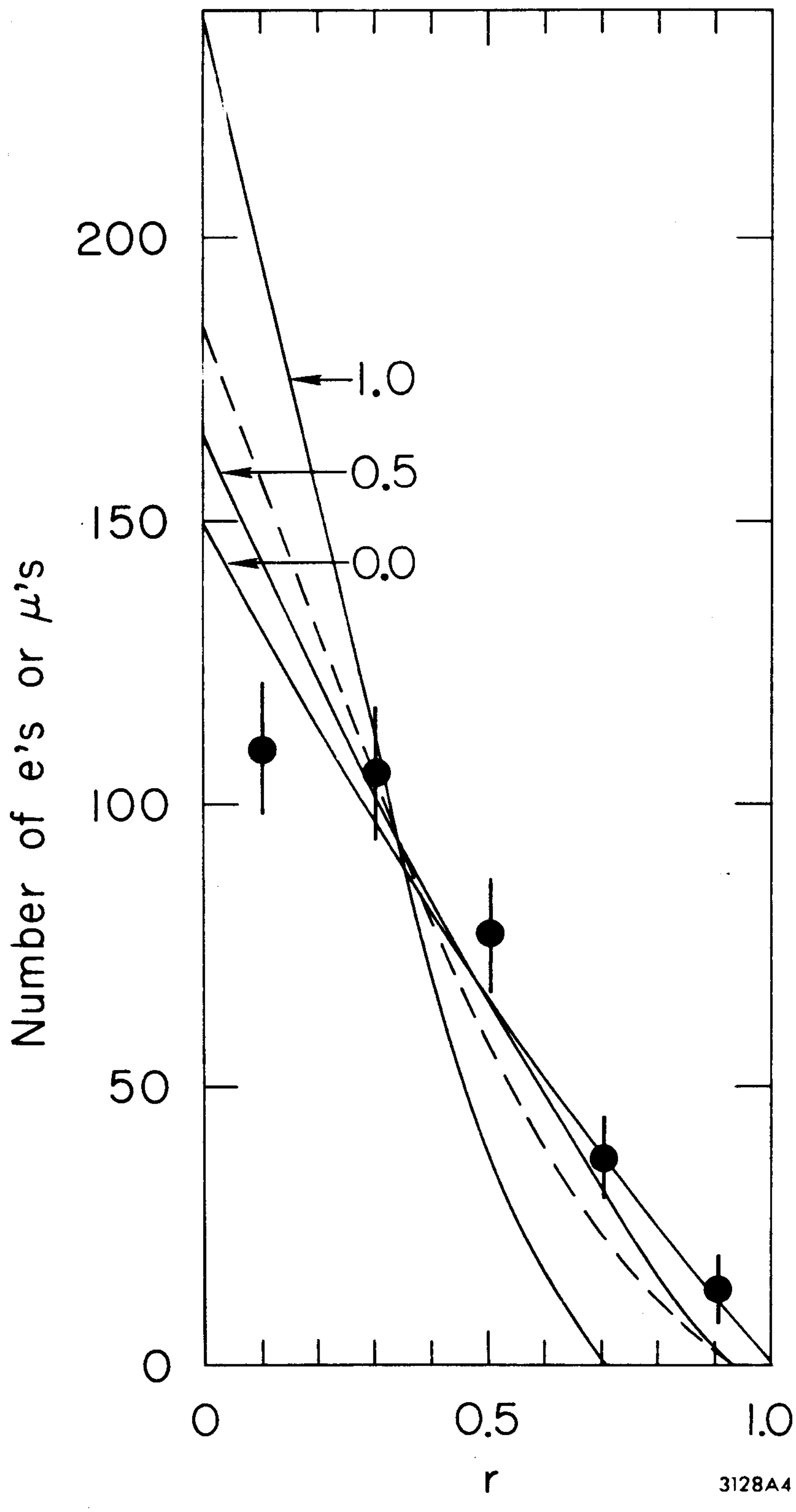

Fig. 4. The r distribution for all events corrected for background. The solid curves are for $m_\tau = 1.9$ GeV/c^2 and V-A coupling with m_{ν_τ} in GeV/c^2 as indicated. The dashed curve is for V+A coupling with $m_\tau = 1.90$ GeV/c^2 and $m_{\nu_\tau} = 0.0$.

$\underline{\tau\text{-}\nu_\tau}$ Coupling: As shown in Fig. 4 with $m_\tau = 1.9$ GeV/c^2 and $m_{\nu_\tau} = 0.0$ a V+A coupling of the τ to the ν_τ is a poor fit. The χ^2 probability is about 0.1% compared to a χ^2 probability of 50% for V-A. However most of the poor fit comes from the r = .1 point which is closest to the $p \doteq 0.65$ GeV/c cut. If we use only the four higher r points, the χ^2 probability for V+A coupling is 5%. A stronger argument against V+A coupling is given in the bottom line of Table IIB. The $p_\perp$ and r methods of determining the τ mass give very inconsistent results. This inconsistency occurs for the following reasons. V+A coupling compared to V-A coupling predicts smaller average values of p_e and p_μ, and fewer e's or μ's having momentum near p_{max}. This can be seen from Fig. 4. The smaller, predicted, average values of p_e or p_μ lead to smaller theoretical values of $\langle p_\perp \rangle$ for V+A compared to V-A. Therefore, to fit the measured $\langle p_\perp \rangle$ m_τ must be larger for V+A coupling than for V-A coupling. On the other hand the theoretically predicted fewer e's or μ's with p near p_{max} requires a larger p_{max} for V+A coupling compared to V-A coupling. To increase p_{max} we must decrease m_τ; and this leads to the inconsistency. Incidently, increasing m_{ν_τ} makes the V+A mass inconsistency worse. Based on the statistical errors this V+A mass inconsistency is many standard deviations. However it is premature to conclude that V+A coupling is definitely ruled out. We are still studying the question as to whether there could be subtle systematic errors in our data which favor V-A coupling. Therefore the statement I prefer is that our data is more comfortable with V-A coupling that with V+A coupling.

Leptonic Branching Ratios: For the observed $\mu^\pm x^\mp$ cross sections we have (compared to Eq. 6a)

$$\sigma_{\mu x}(s) = 2A_{\mu x}(s) B_\mu B_x \sigma_{\tau\tau}(s) \qquad (7)$$

where B_x is the branching ratio of the τ to all one charged particle decay modes (Table I). Using the SLAC-LBL Magnetic Detector Collaboration $e\mu$ and $\mu^\pm x^\mp$ data we obtain the results in Table III. The leptonic branching ratios obtained in different ways are consistent with each other and with the theoretical expectation, Table I. We have set the following 90% confidence upper limits on other leptonic decay modes.

$$\frac{\Gamma(\tau^- \to e^- + \gamma) + (\tau^- \to \mu^- + \gamma)}{\Gamma(\tau^- \to \text{all})} \lesssim 6.0\%$$

$$\frac{\Gamma(\tau^- \to \ell^- \ell^+ \ell^-)}{\Gamma(\tau^- \to \text{all})} \lesssim 0.6\%$$

Here ℓ means e or μ and $\ell^- \ell^+ \ell^-$ means the sum over all combinations of e's and μ's.

TABLE III

Values of the leptonic branching ratios B_e and B_μ, assuming V-A coupling, m_τ = 1.9 GeV/c^2, m_{ν_τ} = 0.0.

Parameter	Value	Statistical Error	Systematic Error	Data Used	Assumptions
$B_e=B_\mu$	0.186	±.010	±.028	eμ	$B_e=B_\mu$
B_μ	0.175	±.027	± .030	μx	B_x=.85

ALTERNATIVE LEPTONIC MODELS

Two alternative leptonic models for the τ are that it is an ortholepton[14] or paralepton.[14] If the τ were an ortholepton the τ^- would have the lepton number of the e^- or μ^- with the $\tau e\gamma$ or $\tau\mu\gamma$ electromagnetic coupling suppressed relative to the weak interaction coupling. The τ cannot be a μ-related ortholepton,[15] because if it were, muon neutrino experiments would contain an excess of events of the form μ_ν + nucleon $\rightarrow e^-$ + other particles. If the τ were an e-related ortholepton we would expect to see decays such as $\tau^- \rightarrow e^-e^+e^-$, $e^-\mu^+\mu^-$. No such events have been seen, we only have the upper limit on the relative decay rate given in Eq. 8. Depending on the model[16], this upper limit can eliminate the e-related ortholepton explanation of the τ. However it is possible to find e-related ortholepton models in which these decays are also suppressed below the limit in Eq. 8. Incidently as discussed in Ref. 16, Eq. 8 eliminates the possibility that the τ is a singlet of SU(2) × U(1).

In the paralepton[14,17] model, the τ^- has the lepton number of the e^+ or μ^+. The μ^+-related paralepton model for the τ has been eliminated by a μ_ν experiment.[18] The e^+-related paralepton has been eliminated by using the prediction that the decay mode $\tau^+ \rightarrow e^+ + \nu_e + \nu_e$ would have twice the branching ratio of the decay mode $\tau^+ \rightarrow \mu^+ + \nu_\mu + \nu_e$, and showing that this disagrees with our data.[19] Explicitly, we define the observed production cross sections σ_{ee} and $\sigma_{\mu\mu}$ for the reactions

$$e^+ + e^- \rightarrow e^+ + e^- + \text{no other detected particles} \tag{9a}$$

$$e^+ + e^- \rightarrow \mu^+ + \mu^- + \text{no other detected particles} \tag{9b}$$

analogous to Eq. 2a, with kinematic cuts

$$\begin{aligned} &p_{e^+} > 0.65 \text{ GeV/c} \quad , \quad p_{e^-} > 0.65 \text{ GeV/c} \\ &p_{\mu^+} > 0.65 \text{ GeV/c} \quad , \quad p_{\mu^-} > 0.65 \text{ GeV/c} \\ &\theta_{copl} > 20^\circ \end{aligned} \tag{10}$$

as in Eq. 4.

Theory predicts for a sequential lepton or an ortholepton

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = 0.5 \quad , \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.5 \tag{11a}$$

For an e-related paralepton with our kinematic cuts (Eq. 10) theory predicts

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = 0.86 \quad , \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.29 \tag{11b}$$

Comparison of Eqs. 11 with Table IV shows that our results are consistent with Eq. 11a but are inconsistent with Eqs. 11b. Hence our conclusions is that the τ cannot be an e-related paralepton.

Summarizing this discussion of leptonic models, the τ is either a sequential lepton; or given a theory that strongly suppresses the $e\gamma$, eee and $e\mu\mu$ decay modes, it could be an e-related ortholepton.

ACKNOWLEDGEMENT

I am greatly indebted to my colleagues in the SLAC-LBL Magnetic Detector Collaboration for their help in this work.

TABLE IV

The measured ratios $\sigma_{ee}/\sigma_{e\mu}$ and $\sigma_{e\mu}/\sigma_{e\mu}$ for all events from the data of the SLAC-LBL Magnetic Detector Collaboration (19). The maximum systematic errors are given. The relative signs indicate the correlation between the effect of the systematic errors on the two ratios, except in the bottom row.

	$\sigma_{ee}/\sigma_{e\mu}$	$\sigma_{\mu\mu}/\sigma_{e\mu}$
Value	0.52	0.63
Statistical error (standard direction)	.10	.10
Systematic errors due to background subtractions	$\pm.07$	$\pm.09$
Systematic error due to μ loss correction	$\pm.06$	$\mp.11$
Systematic error due to e loss correction	$\pm.08$	$\pm.09$
Systematic error due to subtraction of purely electromagnetic background	$+.10$ $-.15$	$\pm.08$
TOTAL systematic errors if combined in quadrature	$+.16$ $-.19$	$\pm.19$

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