

EVIDENCE FOR, AND PROPERTIES OF, THE NEW CHARGED HEAVY LEPTON<sup>\*†</sup>

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

ABSTRACT

This paper summarizes the evidence for, and the properties of, the mass  $1.9 \pm .1 \text{ GeV}/c^2$  charged heavy lepton recently found in  $e^+e^-$  annihilation.

Cet article est un résumé concernant les évidences en faveur et les propriétés du lepton lourd chargé de masse  $1.9 \pm .1 \text{ GeV}/c^2$  découvert récemment dans l'annihilation  $e^+e^-$ .

\*Paper presented at the XII Rencontre de Moriond (Flaine, March 6-18, 1977; to be published in the Proceedings of the XII Rencontre de Moriond, edited by Tran Thanh Van, R.M.I.E.M. Orsay.

†Work supported by the Energy Research and Development Administration.

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## 1. INTRODUCTION

It is very likely that a mass  $1.90 \pm .10 \text{ GeV}/c^2$  charged heavy lepton has been found in  $e^+e^-$  annihilation. This paper summarizes the evidence for the new lepton and then presents what we know so far about its properties. The summary of the evidence is very brief; the original papers must be consulted for details on the event selection criteria, on the elimination of conventional explanations, and for the background calculations.

When we first found evidence for this new particle -- the  $e\mu$  events in the data of the SLAC-LBL Magnetic Detector Collaboration<sup>1</sup> -- we called the particle U as a temporary name because its nature was unknown. Since there is now substantial evidence that it is a lepton, we wish to designate it by a lower case Greek letter. We use  $\tau^+$  because it appears to be the third charged lepton to be found and τριτος means third in Greek. We feel the old use of  $\tau$  to designate the three pion decay mode of the K is now obsolete.

## 2. THEORY

Since the  $\tau$  lepton is experimentally found to decay only thru the weak interactions we consider those theories in which there are no electromagnetic decays or in which the electromagnetic decays are very strongly suppressed.

A. Sequential Heavy Lepton: A sequential heavy lepton<sup>2</sup> has its own unique lepton number giving a sequence:

$$\begin{array}{rcl}
 e^+ & & \nu_e, \bar{\nu}_e \\
 \mu^+ & & \nu_\mu, \bar{\nu}_\mu \\
 \tau^+ & & \nu_\tau, \bar{\nu}_\tau \\
 \cdot & & \cdot \\
 \cdot & & \cdot \\
 \cdot & & \cdot
 \end{array} \tag{1}$$

and all lepton numbers are separately conserved. Hence

$$\tau^- \neq e^- + \gamma, \tau^- \neq \mu^- + \gamma \tag{2}$$

cannot occur. The decay occurs only thru the weak interactions, the purely leptonic modes being

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e \quad (3)$$

$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu$$

For a sufficiently large  $\tau$  mass there are also hadronic decays

$$\tau^- \rightarrow \nu_\tau + \text{hadrons} \quad (4)$$

Table I gives the expected branching ratios for a mass  $1.9 \text{ GeV}/c^2$  sequential heavy lepton using conventional weak interaction theory as worked out by Thacker and Sakurai<sup>3</sup> and by Tsai.<sup>4</sup> For future use we note that most of the decay modes contain only one charged particle, indeed 85% of the decays give one charged particle.

B. Paraleptons: Llewellyn Smith<sup>6</sup> defines paraleptons as charged heavy leptons with the same lepton number as the oppositely charged  $e$  or  $\mu$ ; hence such leptons cannot decay electromagnetically. Thus Bjorken and Llewellyn Smith<sup>7</sup> define the  $E^-$  and  $M^-$  to have the lepton numbers of the  $e^+$  and  $\mu^+$  respectively. The lower bounds on the  $M^+$  mass set by Barish et al.<sup>8</sup> means that the  $M$  cannot be produced by currently operating  $e^+e^-$  colliding beams machines. The  $E^+$  with decay modes

$$E^- \rightarrow \bar{\nu}_e + e^- + \bar{\nu}_e \quad (5a)$$

$$E^- \rightarrow \bar{\nu}_e + \mu^- + \bar{\nu}_\mu \quad (5b)$$

$$E^- \rightarrow \bar{\nu}_e + \text{hadrons} \quad (5c)$$

is not excluded by existing neutrino production data.

C. Ortholeptons: Ortholeptons<sup>6</sup> are charged heavy leptons with the same lepton number as the same charge  $e$  or  $\mu$ . Ordinarily the  $e^*$  with the same lepton number as the  $e^-$  would decay electromagnetically

$$e^{*-} \rightarrow e^- + \gamma \quad (6)$$

However, the coupling constant at the  $e^*e\gamma$  vertex is arbitrary as pointed out by

TABLE I

Predicted branching ratios for a  $\tau^-$  sequential charged heavy lepton with a mass  $1.9 \text{ GeV}/c^2$ , 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  $\bar{u}d$  quark pairs whose final state interaction leads to the hadron continuum

decay mode	branching ratio	number of charged particles in final state
$\nu_{\tau} e^- \bar{\nu}_e$	.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
$\nu_{\tau} (\text{hadron continuum})^-$	.18	1, 3, 5

Low<sup>9</sup>; and we may make it so small that the weak decays

$$e^{*-} \rightarrow \nu_e e^- \bar{\nu}_e, \nu_e \mu^- \bar{\nu}_\mu, \nu_e \text{ hadrons} \quad (7)$$

are stronger than the decay in Eq. 6. A similar remark holds for the  $\mu^{*-}$  with the lepton number of the  $\mu^-$ . We also call such leptons excited electrons or excited muons.

### 3. EVIDENCE FOR EXISTENCE OF THE $\tau$ : $e\mu$ EVENTS

The reaction

$$e^+ + e^- \rightarrow e^+ + \mu^- + \text{no other particles detected} \quad (8)$$

produced thru

$$e^+ + e^- \rightarrow \begin{array}{c} \tau^+ \\ \downarrow \\ \bar{\nu}_\tau e^+ \end{array} + \begin{array}{c} \tau^- \\ \downarrow \\ \nu_\tau \mu^- \bar{\nu}_\mu \end{array}$$

is a very distinctive signature for  $\tau$  pair production.

A. SLAC-LBL Magnetic Detector Collaboration Data: Such  $e\mu$  events were first found in 1975 by this collaboration and analyses of these events have been published.<sup>10,11</sup> It was very important to show that these events did not come from

$$e^+ + e^- \rightarrow e^+ + \mu^- + \text{hadrons} \quad (10)$$

in which the hadrons escaped detection. This is because an alternative source of  $e^+ \mu^-$  pairs is the joint semi-leptonic decay of a pair of charmed hadrons ( $h_c$ ) thru reaction sequences like

$$e^+ + e^- \rightarrow \begin{array}{c} h_c^+ \\ \downarrow \\ e^+ \nu_e \end{array} \text{ hadrons} + \begin{array}{c} h_c^- \\ \downarrow \\ \mu^- \bar{\nu}_\mu \end{array} \text{ hadrons} + \text{perhaps hadrons} \quad (11)$$

This has been eliminated<sup>11</sup> as a major source of the  $e\mu$  events in Eq. 8 because there are simply far too few events of the form

$$e^+ + e^- \rightarrow e^+ + \mu^- + \text{detected hadrons} \quad (12)$$

to explain the number of events of the form of Eq. 8. Charged hadrons,  $\pi^0$ 's and  $K_S^0$ 's are directly eliminated. The possibility of the undetected hadrons being  $K_L^0$ 's is eliminated by the natural assumption that  $K_S^0$ 's and  $K_L^0$ 's would

occur at equal rates in the reaction in Eq. 10. The elimination of the possibility of undetected neutrons is discussed later.

In the paper the analysis of the SLAC-LBL Magnetic Detector Group's  $e\mu$  data is based upon a total of 190 events including a background contamination of 46 events yielding 144 net  $e\mu$  events. These events are produced in the  $E_{cm}$  range of 3.8 to 7.8 GeV.

B. PLUTO Group Data: The PLUTO Group<sup>12,13</sup> has recently described 12  $e\mu$  events with a background of  $< 1.5$  events produced in the  $E_{cm}$  range 4.0 to 4.8 GeV. The importance of these events is that they have much less background contamination than the SLAC-LBL events, they agree with the SLAC-LBL events in their momentum and angle distributions, and they agree with the SLAC-LBL events in their production cross section. It is also very important that they can show directly<sup>12,13</sup> that their events do not come from the reaction in Eq. 10.

#### 4. CONSISTENCY OF THE $e\mu$ EVENT DISTRIBUTIONS WITH THE LEPTON HYPOTHESIS

It is necessary to show that the momentum and angular distributions of the  $e\mu$  events are consistent with the theory of the purely leptonic, 3-body, decay modes of Eq. 3. In comparing the SLAC-LBL data with theory we must take account<sup>10,11</sup> of the geometric acceptance of the apparatus; and of the  $e\mu$  event selection criteria on the  $e$  and  $\mu$  momentum

$$p_e > 0.65 \text{ GeV}/c, \quad p_\mu > 0.65 \text{ GeV}/c, \quad (13a)$$

and of the cut on the acoplanarity angle

$$\theta_{copl} > 20^\circ \quad (13b)$$

To combine the momentum spectra at different  $E_{cm}$  we define a scaled momentum parameter  $r$  (called  $\rho$  in previous papers)

$$r = (p - 0.65)/(p_{max} - 0.65) \quad (14)$$

where  $p$  is  $p_e$  or  $p_\mu$  in GeV/c and  $p_{max}$  is its maximum value. The range of  $r$  is  $0 \leq r \leq 1$ .

Figure 1 and 2 show that the  $r$  distributions are well fit by a lepton with

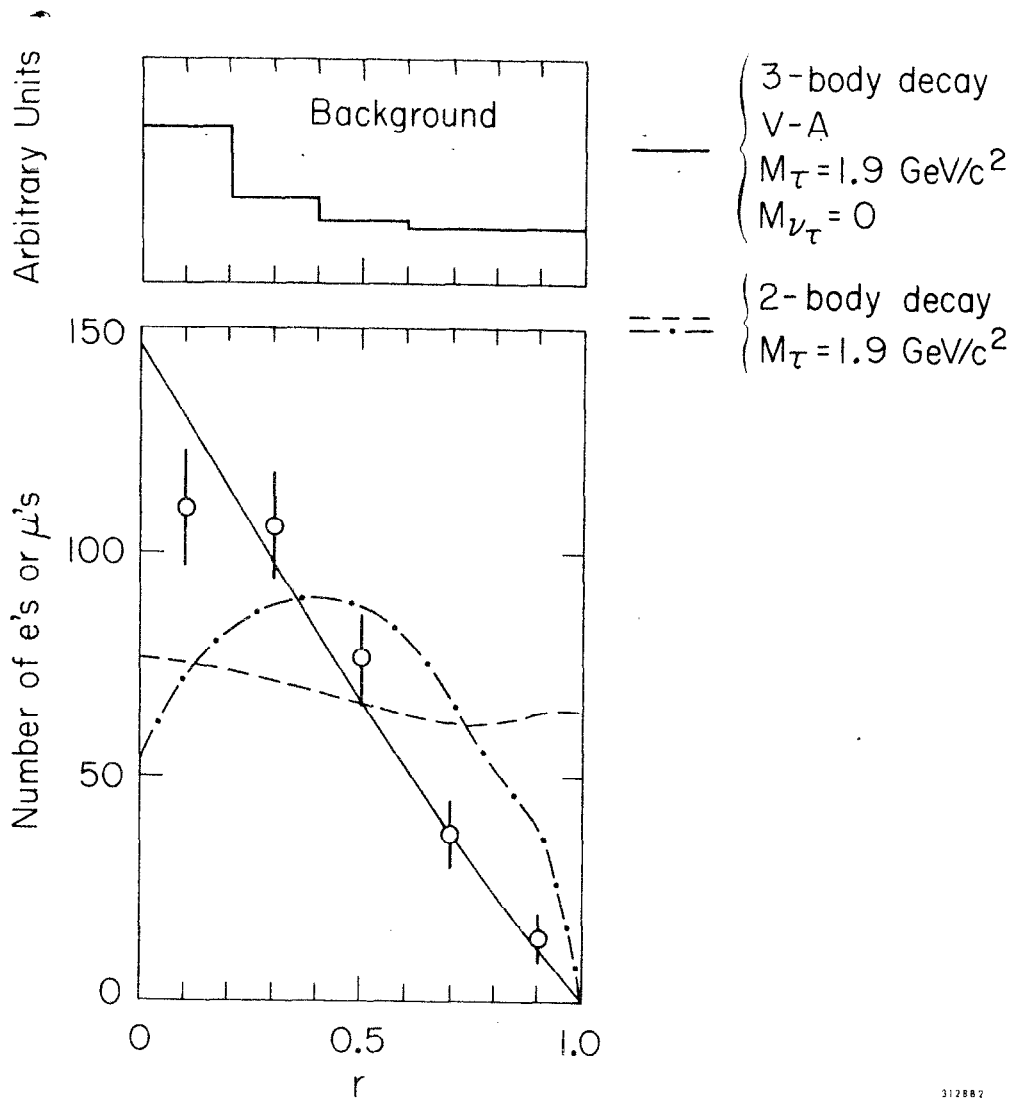


FIG. 1 -- The lower figure shows the  $r$  distribution (Eq. 14) for  $3.8 \leq E_{\text{cm}} \leq 7.8 \text{ GeV}$  with background subtracted. The solid curve is for the 3-body, leptonic decay of the  $\tau$  (Eq. 3) with the indicated parameters. The dash and dash-dot curves are for 2-body leptonic decay modes of a 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.



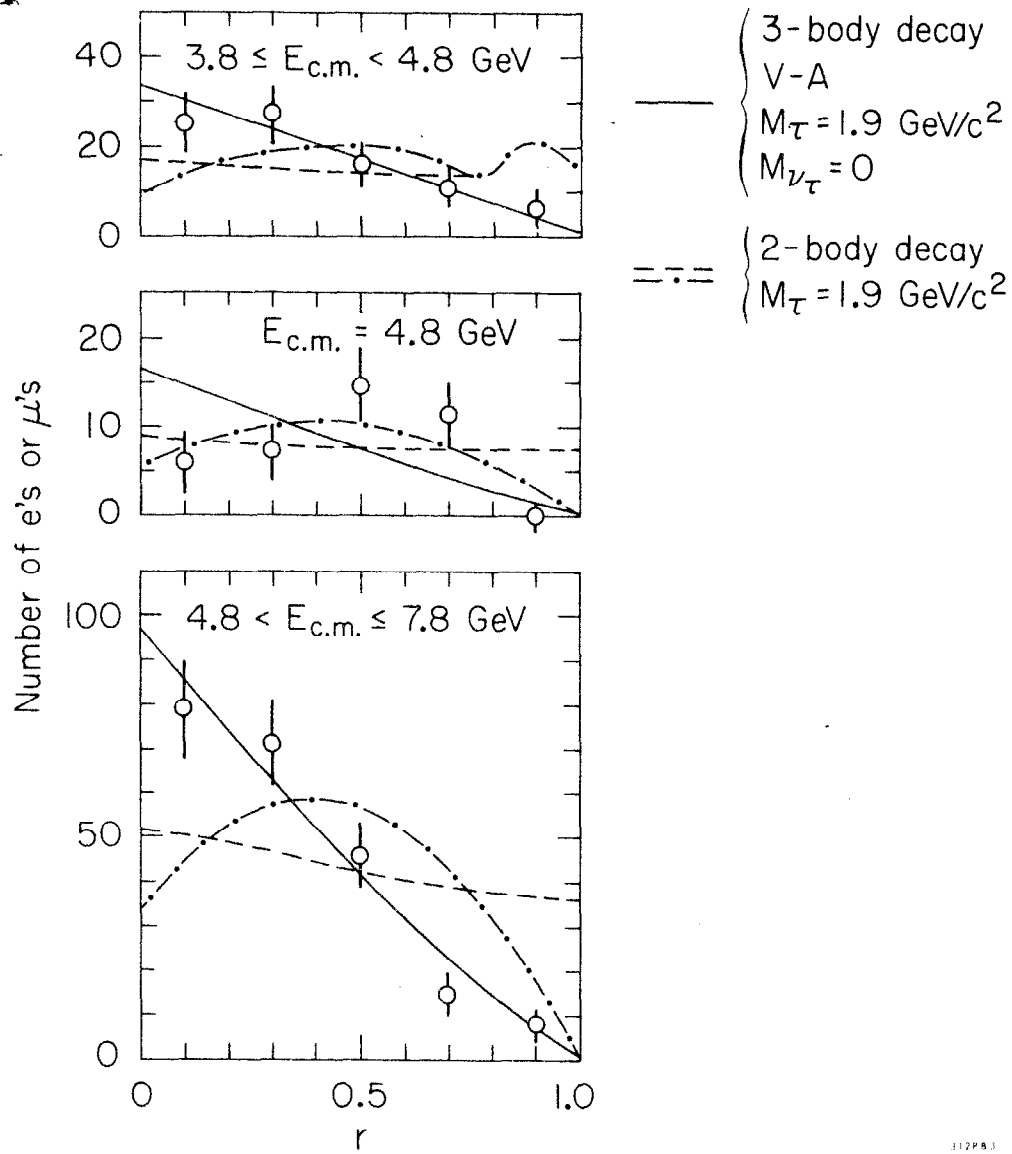


FIG. 2 -- The  $r$  distributions for three  $E_{cm}$  ranges with background subtracted. See the caption to Fig. 1.

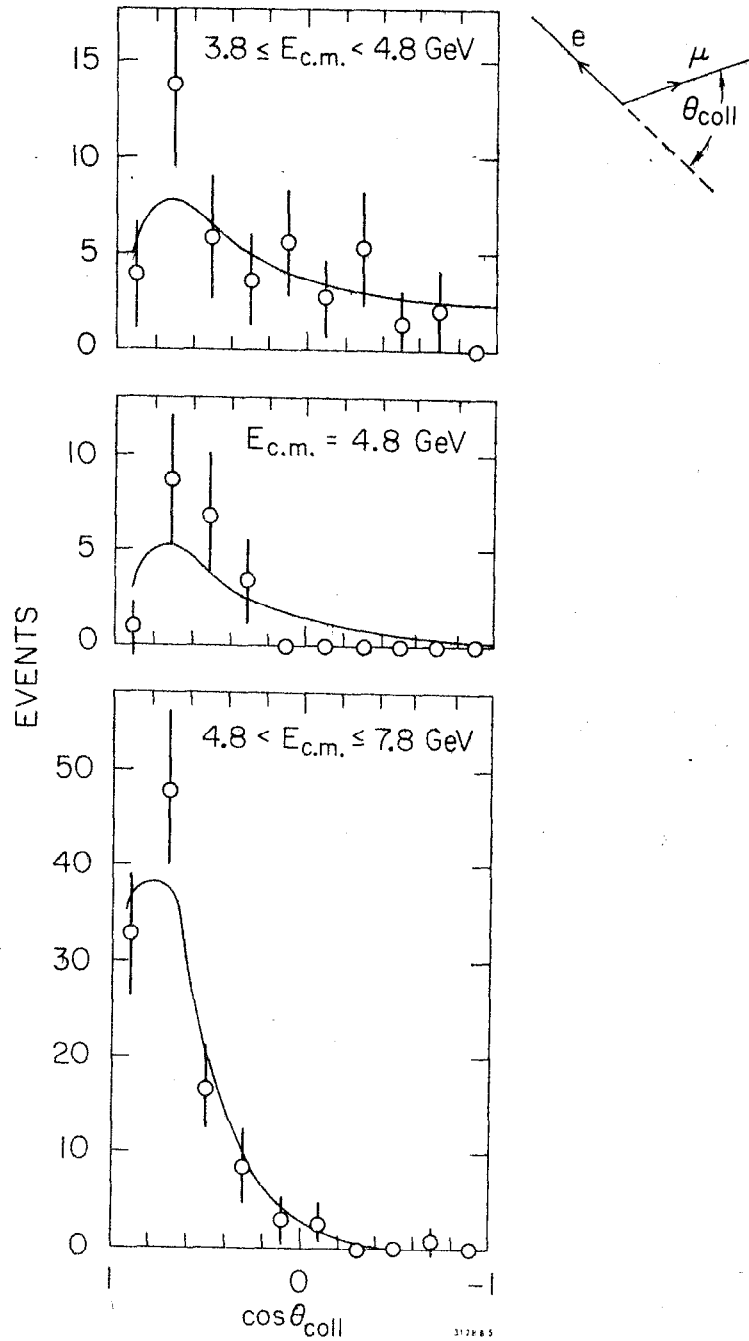


FIG. 3 -- The  $\cos \theta_{\text{coll}}$  distribution for three  $E_{\text{cm}}$  energy ranges. The solid line is for  $m_{\tau} = 1.9 \text{ GeV}/c^2$ ,  $m_{\nu_{\tau}} = 0.0$  and V-A coupling.

$m_\tau = 1.9 \text{ GeV}/c^2$ ,  $m_{\nu_\tau} = 0.0$  and V-A coupling. Only our old  $E_{\text{cm}} = 4.8 \text{ GeV}$  data is a poor fit as we have noted previously.<sup>10,11</sup> Incidentally the hypothesis that the  $\tau$  is a boson, with the purely leptonic 2-body decays  $\tau^- \rightarrow e^- \bar{\nu}_e$ ,  $\mu^- \bar{\nu}_\mu$ , is eliminated by this data.

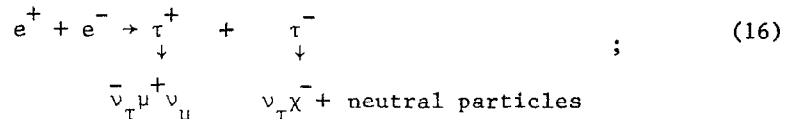
Figure 3 shows that the collinearity angle distributions,

$$\cos \theta_{\text{coll}} = -(\underline{p}_e \cdot \underline{p}_\mu) / (|\underline{p}_e| |\underline{p}_\mu|) \quad (15)$$

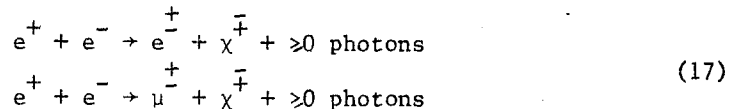
are also fit by the  $m_\tau = 1.9$ ,  $m_{\nu_\tau} = 0.0$ , V-A model.

#### 5. EVIDENCE FOR EXISTENCE OF THE $\tau$ : $e^+ \chi^+$ , $\mu^+ \chi^+$ EVENTS

Another strong signature for the  $\tau$  is the sequence of reactions



because as pointed out in Sec. 2A, 85% of the decay modes of a  $1.9 \text{ GeV}/c^2$   $\tau$  contain only 1 charged particle. Explicitly the signature is a 2-charged prong lepton inclusive event of the form



Here  $\chi$  is a charged lepton or hadron. Such events, called  $e^+ \chi^+$  or  $\mu^+ \chi^+$ , are unlikely to come from charmed hadrons, because as indicated by Eq. 11, relatively high multiplicities occur when charmed hadrons are produced and decay.

A. Maryland-Princeton-Pavia  $\mu^+ \chi^+$  Data: Such events were first found by

M. Cavalli-Sforza et al.<sup>14</sup> As analyzed by Snow<sup>15</sup> these events are consistent with the existence of the  $\tau$ .

B. SLAC-LBL Magnetic Detector Collaboration  $\mu^+ \chi^+$  Data: Feldman et al.,<sup>16</sup> have published  $\mu^+ \chi^+$  data which requires the existence of the  $\tau$  and will be used later in this paper. This data gives a very significant signal in the  $E_{\text{cm}}$  range of 5.8 to 7.8 GeV.

C. PLUTO Group  $\mu^+ \chi^+$  Data: The PLUTO group has reported<sup>12,13</sup> a significant  $\mu^+ \chi^+$  signal in the  $E_{\text{cm}}$  range of 4.0 to 4.8 GeV. They have attributed these

events to a charged lepton with a mass of roughly  $1.95 \text{ GeV}/c^2$ .

D. DASP Group  $e^+e^- \rightarrow \chi^+ \chi^-$  Data: Very recently the DASP Group reported<sup>17,18</sup>  $e^+e^- \rightarrow \chi^+ \chi^-$  events in the  $E_{\text{cm}}$  range of 4.0 to 5.0. The observed production cross section<sup>17,18</sup> and the  $e$  momentum distribution<sup>17</sup> are those expected from the  $\tau$ .

To summarize, all  $e^+e^-$  annihilation experiments which should see the  $e^+e^- \rightarrow \chi^+ \chi^-$  or  $\mu^+ \mu^- \rightarrow \chi^+ \chi^-$  signature of the  $\tau$  have seen such events.

## 6. LEPTONIC NATURE OF THE $\tau$

There are two kinds of data which argue for the leptonic nature of the  $\tau$ .

First, the existence of  $e^+e^- \rightarrow \mu^+ \mu^-$  and  $\mu^+ \mu^- \rightarrow \chi^+ \chi^-$  events at large  $E_{\text{cm}}$  means that the pure pair production reaction  $e^+e^- \rightarrow \tau^+ \tau^-$  is occurring at large  $E_{\text{cm}}$ . It is very unlikely that  $1.9 \text{ GeV}/c^2$  mass hadrons can be produced in a pure pair production reaction at large  $E_{\text{cm}}$ .

Second, as shown in Fig. 4, the observed  $e\mu$  production cross sections,  $\sigma_{e\mu}$ , fits the point particle production cross sections for a heavy lepton. Here (with  $s = E_{\text{cm}}^2$ )

$$\sigma_{e\mu}(s) = 2A_{e\mu}(s)B_e B_\mu \sigma_{\tau\tau}(s) \quad (18a)$$

where

$$\sigma_{\tau\tau}(s) = \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s} \quad (18b)$$

$B_e$  and  $B_\mu$  are the branching ratios for  $\tau^-$  goes to  $\nu_\tau e^- \bar{\nu}_e$  and  $\nu_\tau \mu^- \bar{\nu}_\mu$  respectively  $\beta c$  is the velocity of the  $\tau$ , and  $A_{e\mu}(s)$  is a calculated acceptance. The solid curves in Fig. 4 are for  $m_\tau = 1.8$  or  $2.0$  and the product  $B_e B_\mu$  is adjusted to give a best fit. If we multiply the right side of Eq. 18a by a form factor squared  $F_\tau^2$ , where  $F_\tau = \text{constant}/s$ , we get a very poor fit -- the dashed curve in Fig. 4. Hence while we cannot rule out a weak form factor effect,  $\sigma_{e\mu}$  is certainly consistent with the  $\tau$  being a point particle, as a lepton is expected to be.

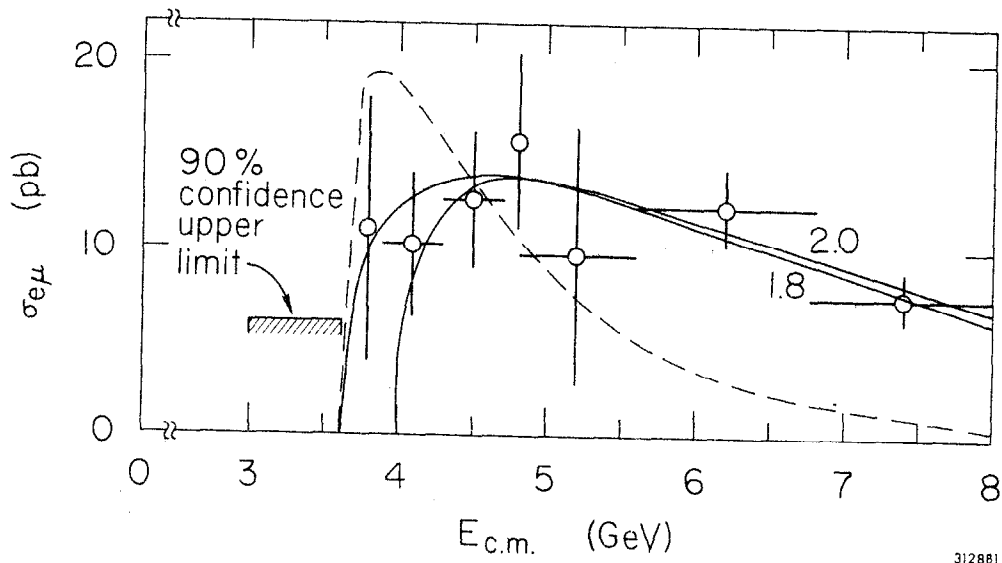


FIG. 4 -- The observed  $e\mu$  production cross section,  $\sigma_{e\mu}$ . The vertical lines are statistical errors, the horizontal lines show the  $E_{cm}$  range covered by each point. No events before background subtraction were found in the  $E_{cm}$  range of 3.0 to 3.6 GeV. We show the 90% confidence upper limit on  $\sigma_{e\mu}$  if 2.3 events had been found. The curves are explained in the text.

7. ANOMALOUS  $e^+e^-$  AND  $\mu^+\mu^-$  PAIRS AND ELIMINATION OF THE ELECTRON RELATED PARALEPTON HYPOTHESIS

→ If the  $\tau$  is a lepton with conventional weak interactions we must see non-coplanar, anomalous  $e^+e^-$  and  $\mu^+\mu^-$  pairs as well as  $e^+\mu^+$  pairs. For example  $\mu^+\mu^-$  pairs come from

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \quad (19a)$$

$$\begin{array}{ccc} \downarrow & & \downarrow \\ \bar{\nu}_\tau \mu^+ \nu_\mu & & \nu_\tau \mu^- \bar{\nu}_\mu \end{array}$$

giving

$$e^+ + e^- \rightarrow \mu^+ + \mu^- + \text{no other detected particles} \quad (19b)$$

Unfortunately the reaction in Eq. 19 has large backgrounds from quantum electrodynamic processes such as  $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$  and  $e^+e^- \rightarrow \gamma\gamma\mu^+\mu^-$  in which the  $e^+e^-$  or  $\gamma\gamma$  are not detected. After subtracting these backgrounds, the SLAC-LBL Magnetic Detector Collaboration data gives<sup>19</sup> for the ratios of the observed cross sections :

$$\begin{aligned} \text{For } 4.8 < E_{\text{cm}} \leq 6.8 \quad & \frac{\sigma_{ee}}{\sigma_{e\mu}} = .54 \pm .3, \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = .50 \pm .2 \\ \text{For } 6.8 < E_{\text{cm}} \leq 7.8 \quad & \frac{\sigma_{ee}}{\sigma_{e\mu}} = .59 \pm .3, \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = .47 \pm .2 \end{aligned} \quad (20)$$

These results are preliminary, in particular  $\sigma_{ee}$  may be systematically 20 or 30% too high. The cuts in Eq. 13 were used, as well as requiring

$$(\text{missing mass})^2 > 2.0(\text{GeV}/c^2)^2 \quad (21)$$

Equations 21 eliminates background from  $ee \rightarrow ee\gamma$  and  $ee \rightarrow \mu\mu\gamma$ .

For sequential heavy leptons or for ortholeptons  $B_e = B_\mu$ . Hence we expect

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.5 \quad (22)$$

in agreement with the data in Eq. 20. However in a paralepton theory the decay mode  $\tau^+ \rightarrow e^+ \nu_e \nu_e$  has two identical neutrinos in the final state which interfere constructively.<sup>7,20</sup> This leads to  $B_e = 2B_\mu$  and we expect<sup>21</sup>

$$\frac{\sigma_{ee}}{\sigma_{e\mu}} = 1.0, \quad \frac{\sigma_{\mu\mu}}{\sigma_{e\mu}} = 0.25 \quad (23)$$

This contradicts the data in Eq. 20 and eliminates the possibility that the  $\tau$  is an electron related paralepton. As we pointed out in Sec. 2B the muon related paralepton possibility was already ruled out.

#### 8. PROPERTIES OF THE $\tau$

Using the data of the SLAC-LBL Magnetic Detector Collaboration we find the  $\tau$  to have the following properties

A.  $\tau$  Mass: Using the  $e\mu$  events we can find the  $\tau$  mass,  $m_\tau$ , in three ways.

First as shown in Fig. 5, we define a pseudo-transverse momentum,  $p_\perp$ , by finding an axis AA' such that the perpendicular momentum components of the e and  $\mu$  are equal and minimum. We then compare the average value of  $p_\perp$  in the data with a theoretical prediction made with a Monte Carlo method. Our second way is to use the average value of  $\cos \theta_{coll}$ , Eq. 15, and again compare data with theory. A third way<sup>22</sup> uses the  $r$  distribution comparing the number of events with  $.6 \leq r \leq 1.0$  to the number with  $.2 \leq r < .6$ . Table II gives the results. For what we shall call our standard model,  $m_{\nu_\tau} = 0.0$  and V-A coupling, we combine the  $p_\perp$  and  $\cos \theta_{coll}$  methods to obtain

$$m_\tau = 1.90 \pm .10 \quad (24)$$

where the error includes systematic uncertainties.

Some other observations on Table II are:

- a. The high and low  $E_{cm}$  ranges give the same values within errors of  $m_\tau$ , a nice demonstration that we are dealing with the same particle over the entire  $E_{cm}$  range.
- b. The  $p_\perp$  value for  $E_{cm} = 4.8$  GeV is high, we have noted before<sup>11</sup> that this set of data looks different in the  $r$  distribution, but the difference is not statistically significant.

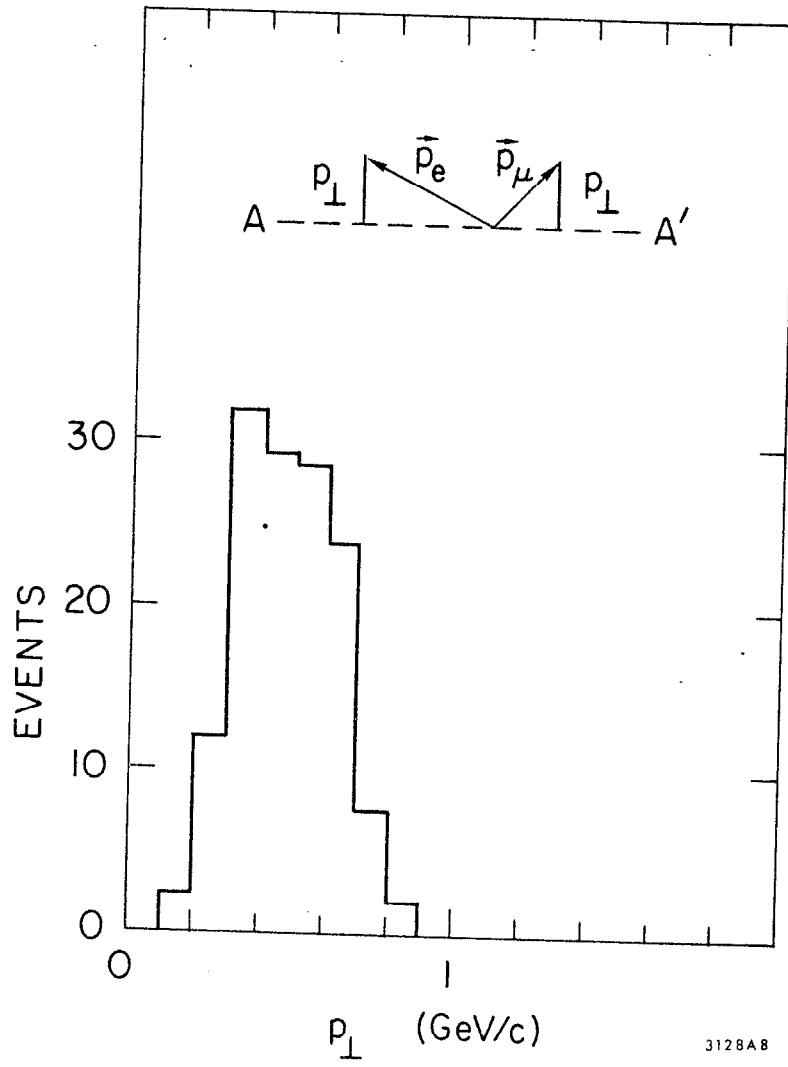


FIG. 5 -- The  $p_{\perp}$  distribution for all  $e\mu$  events not corrected for background.



TABLE IIA

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

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

TABLE IIB

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

Model	Method		
	$p_\perp$	$\cos \theta_{\text{coll}}$	$r$
V-A $m_{\nu_\tau} = 0.5 \text{ GeV}/c^2$	$2.01 \pm .05$	$1.90 \pm .09$	$1.70 \pm .12$
V+A $m_{\nu_\tau} = 0.0$	$2.12 \pm .05$	$1.95 \pm .10$	upper limit is 1.76 with 95% confi- dence.

- c. If  $m_{\nu_\tau}$  is  $0.5 \text{ GeV}/c^2$ ,  $m_\tau$  increases a little.
- d. A model with V+A coupling and  $m_{\nu_\tau} = 0.0$  gives inconsistent values of  $m_\tau$ .

As a check of these  $m_\tau$  determinations, we show in Table III  $P_T(m_\tau)$ , the probability that all  $e\mu$  events produced at  $E_{\text{cm}} \leq 2m_\tau$  come from background. Since we have no  $e\mu$  events at  $E_{\text{cm}} < 3.8 \text{ GeV}$ ,  $P_T(m_\tau < 1.9) = 100\%$ . Thus  $P_T(m_\tau)$  is a threshold probability. Table III also gives a  $\chi^2$  goodness of fit probability,  $P_F(m_\tau)$ , which uses Eq. 18 and ignores all data with  $E_{\text{cm}} \leq 2m_\tau$ . Table III agrees with Eq. 24. The  $P_T$  values in Table III show that we should not take  $m_\tau > 2.05 \text{ GeV}/c^2$  unless forced to do so by other measurements.

B.  $\tau$  Neutrino Mass: To set a limit on  $m_{\nu_\tau}$  we use the  $r$  distribution in Fig. 6. The solid curves are for  $m_\tau = 1.90 \text{ GeV}/c^2$ , V-A coupling, and  $m_{\nu_\tau} = 0.0, 0.5$  and  $1.0 \text{ GeV}/c^2$  respectively. As  $m_{\nu_\tau}$  increases the quality of fit decreases. The 95% confidence upper limit on  $m_{\nu_\tau}$  is

$$m_{\nu_\tau} < 0.6 \text{ GeV}/c^2 ; \text{ for } m_\tau = 1.90 \text{ GeV}/c^2, \text{ V-A} \quad (25)$$

We note; this limit on  $m_{\nu_\tau}$  eliminates the possibility that  $\nu_\tau$  is actually a neutron, in the decay

$$\tau^- \rightarrow e^- + \bar{\nu}_e + n ; \quad (26)$$

$\tau$  being then a heavy proton -- an old conjecture of M. Goldhaber.<sup>24</sup> As indicated indirectly by Table II, if we increase  $m_\tau$  we can increase the limit on  $m_{\nu_\tau}$ . We have not yet determined how much we can increase the limit on  $m_{\nu_\tau}$  in this way because the three methods of determining  $m_\tau$  (using  $p_\perp$ , using  $\cos \theta_{\text{coll}}$ , and using  $r$ ) are affected differently.

C.  $\tau$ - $\nu_\tau$  Coupling: As shown in Fig. 6 with  $m_\tau = 1.9 \text{ GeV}/c^2$  and  $m_{\nu_\tau} = 0.0$ , a V+A coupling of the  $\tau$  to the  $\nu_\tau$  is a poor fit. The  $\chi^2$  probability is about 0.1% compared to a  $\chi^2$  probability of 50% for V-A. However most of the poor fit comes from the  $r = .1$  point and we should be a little suspicious of this point since it is closest to the  $p = 0.65 \text{ GeV}/c$  cut. If we use only the four higher  $r$  points, the  $\chi^2$  probability for V+A coupling is 5%. Also from Table II we note that V+A coupling gives inconsistent  $m_\tau$  fits. Therefore in our present

TABLE III

Probabilities that the mass  $m_\nu$  can yield the observed  $\sigma_{e\mu}$  cross section in Fig. 4.  $P_T(m_\nu)$  is the probability that all  $e\mu$  events produced at  $E_{cm} \leq 2 m_\tau$  come from background.  $P_F(m_\tau)$  is the  $\chi^2$  goodness of fit probability for the data in Fig. 4.

$m_\tau$ (GeV/c <sup>2</sup> )	$P_T(m_\tau)$	$P_F(m_\tau)$
1.7	} no $e\mu$ events with $E_{cm} < 3.8$ GeV	.9
1.8		.9
1.9	0.10	.9
1.95	0.06	.9
2.00	0.06	.9
2.05	0.06	.9
2.10	0.008	.8
2.15	0.002	.7

TABLE IV

Values of the leptonic branching ratios  $B_e$  and  $B_\mu$ , and  $R_\tau = \sigma_{\tau\tau}(\text{measured})/\sigma_{\tau\tau}(\text{Eq. 18b})$  from  $e\mu$  and  $\mu^\pm\chi^\mp$  events in Refs. 11 and 16. We assume V-A coupling,  $m_\tau = 1.9$  GeV/c<sup>2</sup>,  $m_{\nu_\tau} = 0.0$ .

Parameter	Value	Statistical Error	Systematic Error	Data Used	Assumptions
$B_e = B_\mu$	0.186	$\pm 0.010$	$\pm 0.028$	$e\mu$	$B_e = B_\mu, R_\tau = 1$
$B_\mu$	0.175	$\pm 0.027$	$\pm 0.030$	$\mu^\pm\chi^\mp$	$B_\chi^* = .85, R_\tau = 1$
$R_\tau$	0.89	$\pm 0.29$	$\pm 0.27$	$e\mu, \mu^\pm\chi^\mp$	$B_e = B_\mu, B_\chi^* = .85$

\*see Eq. 27b

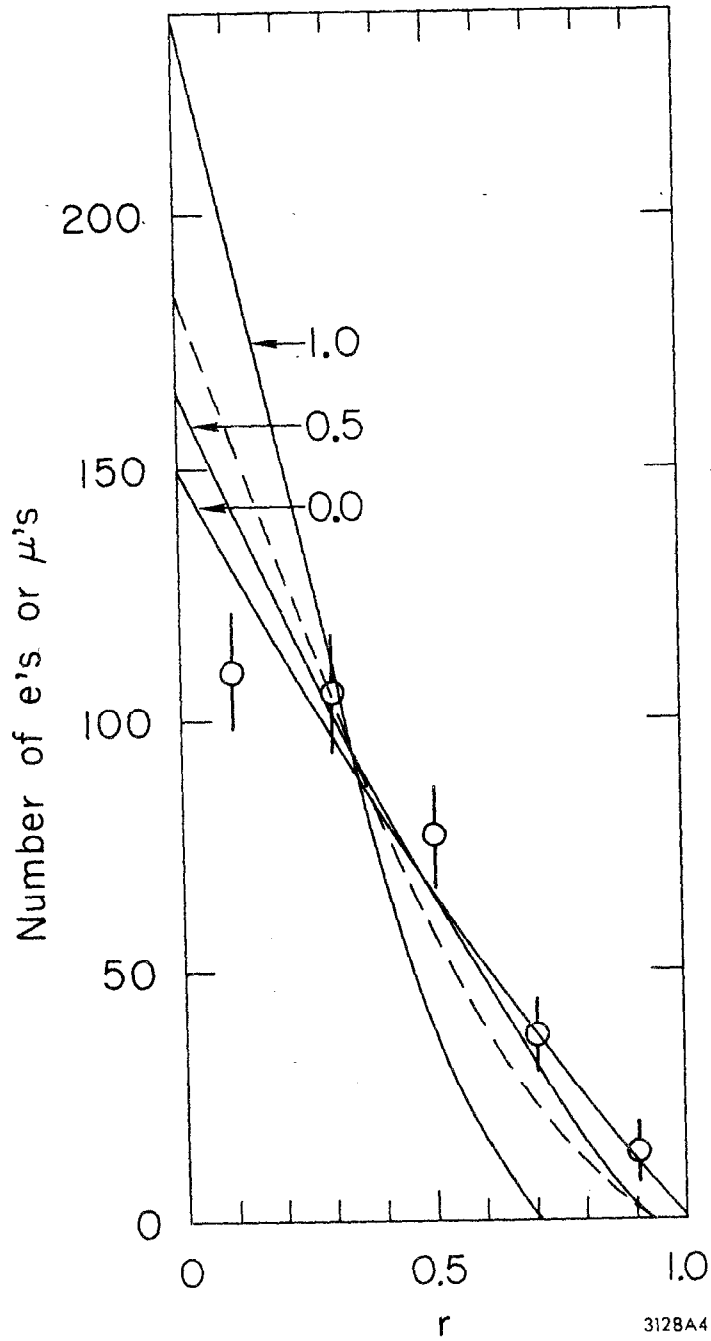


FIG. 6 -- The  $r$  distribution for all events corrected for background. The solid curves are for  $m_\tau = 1.9 \text{ GeV}/c^2$  and V-A coupling with  $m_{\nu_\tau}$  in  $\text{GeV}/c^2$  as indicated. The dashed curve is for V+A coupling with  $m_\tau = 1.90 \text{ GeV}/c^2$  and  $m_{\nu_\tau} = 0.0$ .

data V-A coupling gives a better fit than V+A coupling for  $m_\tau = 1.9$  and  $m_{\nu_\tau} = 0.0$ . Increasing  $m_{\nu_\tau}$  makes the V+A fit worse. However we have to study our systematic errors before we can make a definitive statement as to how poor is the fit to our data for V+A coupling.

D. Leptonic Branching Ratios and the Contribution of  $\tau^+\tau^-$  Pair Production To R: From Eq. 18a we have:

$$\sigma_{e\mu}(s) = 2A_{e\mu}(s)B_e B_\mu \sigma_{\tau\tau}(s) \quad (27a)$$

For the observed  $\mu^+\chi^-\mu^+$  cross sections we have

$$\sigma_{\mu\chi}(s) = 2A_{\mu\chi}(s)B_\mu B_\chi \sigma_{\tau\tau}(s) \quad (27b)$$

where  $B_\chi$  is the branching ratio of the  $\tau$  to all one charged particle decay modes (Table I). Using the SLAC-LBL Magnetic Detector Collaboration  $e\mu$  and  $\mu^+\chi^-\mu^+$  data we obtain the results in Table IV. The leptonic branching ratios obtained in different ways are consistent with each other and with the theoretical expectation, Table I. And the contribution to R of  $\tau^+\tau^-$  pair production is consistent with 1 as expected for a spin  $\frac{1}{2}$  point particle.

E. Hadronic Branching Ratios: At present we only know from the measured purely leptonic branching ratios that  $1 - .37 \pm .06 = .63 \pm .06$  of the decay modes are not pure leptonic and that some hadrons have been detected in the  $\tau$  decay.<sup>5,16</sup> But we do not know if this .63 fraction consists of the other decay modes listed in Table I, or if the various modes are in the expected proportions.

F. Other Decay Modes: G. Feldman<sup>25</sup> using SLAC-LBL Magnetic Detector Collaboration data has set the following 90% confidence upper limits on decay modes.

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

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

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

## 9. Acknowledgement

The SLAC-LBL Magnetic Detector Collaboration data presented here, perhaps more than any other data of the collaboration, represents the combined efforts of the collaboration because to acquire this data every part of the detector had to work well.

I wish to thank F. Gilman and Y.S. Tsai for numerous theoretical discussions.

I am greatly indebted to G.J. Feldman who has been a constant companion in this work.

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21. As pointed out by Y.S. Tsai, due to our kinematic cuts the predicted ratio are  $\sigma_{ee}/\sigma_{e\mu} = 0.86$ ,  $\sigma_{\mu\mu}/\sigma_{e\mu} = 0.29$ .
22. This method avoids the  $0 \leq r < .2$  region where the  $r$  distribution may be affected by the  $p \geq 0.65$  GeV/c cut, and emphasizes the  $0.6 \leq r \leq 1.0$  region which is sensitive to the maximum observed  $p$ 's.
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