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REVIEW OF HEAVY LEPTON PRODUCTION IN e^+e^- ANNIHILATION*

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ABSTRACT

The existing data on $e^{\pm}\mu^{\mp}$, $e^{\pm}x^{\mp}$, $\mu^{\pm}x^{\mp}$, and related events produced in e^+e^- annihilation are reviewed. All data are consistent with the existence of a new charged lepton, $\tau^{\pm}$, of mass $1.9 \pm .1$ GeV/c^2.

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DISCLAIMER

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I. INTRODUCTION

Since the discovery[1,2] of anomalous $e^{\pm}\mu^{\mp}$ events at SPEAR two and one half years ago, there has been a steady increase in the data on these events and the related two-charged prong $e^{\pm}x^{\mp}$ and $\mu^{\pm}x^{\mp}$ events. All such data which has been published, or has been presented at this or previous conferences, agree on the following points.

a. Anomalous two-charged prong leptonic events ($e^{\pm}\mu^{\mp}$, $e^{\pm}x^{\mp}$, $\mu^{\pm}x^{\mp}$, e^+e^-, $\mu^+\mu^-$) are produced in e^+e^- annihilation.
b. Most of these events do not come from the decays of charmed particles.
c. The behavior of these events is consistent with the hypothesis that a new charged lepton, τ, exists with a mass of 1.9 ± 0.1 GeV/c^2.

Points a and b have been thoroughly discussed by the individual speakers using their own data; and so with respect to these points I will only summarize their data and conclusions. In this paper I will put more emphasis on point c, the consistency of the data with the τ hypothesis; and on using the τ hypothesis to deduce a variety of properties of the τ.

I will try to give a complete set of experimental references in this paper. I will give very few theoretical references because I have given complete lists of older theoretical references in two review articles;[3,4] and T. F. Walsh[5] will provide an up-to-date theoretical summary.

An excellent and recent experimental review[6] of the heavy lepton in e^+e^- annihilation was given by G. Flugge at the 1977 Experimental Meson Spectroscopy Conference; and I gave an earlier review[7] at the XII Rencontre de Moriond.

II. SUMMARY OF THEORY

A. Sequential Lepton Model

In discussing the evidence for the τ I shall distinguish several possible types of leptons. First there is the sequential type:

Charged lepton	Associated neutrinos
$e^{\pm}$	$\nu_e, \bar{\nu}_e$
$\mu^{\pm}$	$\nu_\mu, \bar{\nu}_\mu$
$\tau^{\pm}$	$\nu_\tau, \bar{\nu}_\tau$
.	.
.	.
.	.

(1)

in which the τ^- and its associated neutrino, ν_τ, have a unique lepton number which is conserved in all interactions. This is a simple way to prevent the electromagnetic decays $\tau^- \rightarrow e^-\nu_\tau$, $\mu^-\nu_\tau$. The purely leptonic decay modes are

$$\begin{aligned} \tau^- &\rightarrow \nu_\tau + e^- + \bar{\nu}_e \\ \tau^- &\rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \end{aligned} \qquad (2)$$

Depending on the τ mass, m_τ, and the nature of the coupling there will also be semileptonic decay modes containing hadrons[8,9] such as:

$$\tau^- \rightarrow \nu_\tau + \pi^- \tag{3}$$

$$\rightarrow \nu_\tau + \rho^- \tag{4}$$

$$\rightarrow \nu_\tau + \pi^- + \pi^+ + \pi^- \tag{5}$$

B. Paralepton Model

Another simple way to suppress the electromagnetic decay of the τ is to assume it is a paralepton[10] where the τ has the lepton number of the oppositely charged e or μ.[11] Specifically:

E^- has the same lepton number as e^+

M^- has the same lepton number as μ^+

C. Ortholepton Model

In principle the τ could have the same lepton number as the same sign e or μ. We then call it an ortholepton.[10] Specifically:

e^{*-} has the same lepton number as e^-

μ^{*-} has the same lepton number as μ^- (7)

Then the $e\gamma e^*$ or $\mu\gamma\mu^*$ coupling must be strongly suppressed to make the electromagnetic decay rate small compared to the weak decay rate, as is required by the data (see 10c). I shall not discuss other models.[3,5,11,12]

III. SIGNATURES FOR NEW CHARGED LEPTONS PRODUCED IN e^+e^- ANNIHILATION

A. $e^\pm\mu^\mp$ Events

The cleanest signature for new charged lepton production is

$$e^+ + e^- \rightarrow \underset{\substack{\downarrow \\ \bar{\nu}_\tau e + \nu_e}}{\tau^+} + \underset{\substack{\downarrow \\ \nu_\tau \mu^- \nu_\mu}}{\tau^-} \tag{8}$$

Such events must have:

i. an $e^+\mu^-$ or $e^-\mu^+$
ii. no other charged particles
iii. no photons
iv. missing energy
v. a "hard" heavy lepton momentum spectra for the e and μ as shown in Fig. 1.

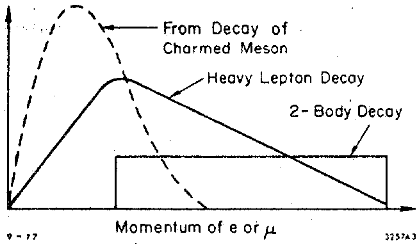

Fig. 1 Schematic comparison of the momentum spectrum for a lepton from a heavy lepton decay compared to the lepton spectrum from a charmed particle semileptonic decay or from a two-body decay.

B. $e^{\pm}x^{\mp}$, $\mu^{\pm}x^{\mp}$ Events

The decay of a τ with a mass of 1.9 GeV/c^2 is expected to yield only one charged particle (an e, μ, or hadron) a large fraction of the time; perhaps as much as 85% of the time. This leads to a two-charged prong event with or without photons:

$$e^+ + e^- \to \underset{\bar{\nu}_\tau e^+ \nu_e}{\underset{\downarrow}{\tau^+}} + \underset{\nu_\tau x^- + \geq 0\,\gamma\text{'s}}{\underset{\downarrow}{\tau^-}} \quad (9)$$

where x is an e, μ, or charged hadron.

IV. $e^{\pm}\mu^{\mp}$ DATA

Table I lists the eμ data reported previously or at this conference; and Figs. 2-4 show the lepton momentum spectra. All the sets of eμ events in Table I have the following properties:

a. Their production cross section and properties are consistent with their sole source being the pair production of a mass 1.9 ± 0.1 GeV/c^2 charged lepton.

b. No other explanation for these events has been put forth which fits their production cross section and properties.

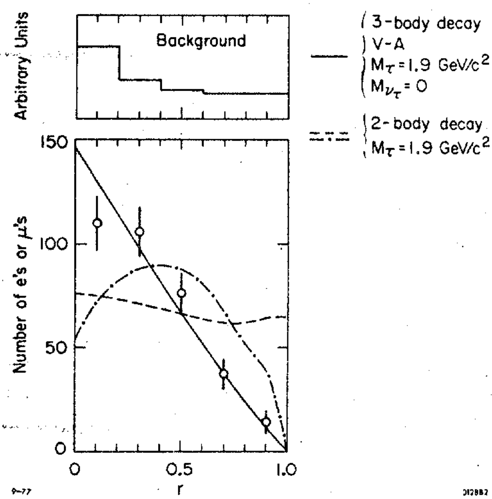

Fig. 2 The momentum spectrum for eμ events, with $3.8 \leq E_{c.m.} \leq 7.8$ GeV, from the SLAC-LBL Magnetic Detector Collaboration[7,15] corrected for background. Here $r = (p-0.65)/(p_{max}-0.65)$ where p is the e or μ momenta in GeV/c. The solid theoretical curve is for the 3-body leptonic decay of a mass 1.9 GeV/c^2 τ; the dashed theoretical curve is for the 2-body decay of an unpolarized boson; and the dash-dotted theoretical curve is for the 2-body decay of a boson produced only in the helicity = 0 state.

TABLE I

Data on $e\mu$ events. In addition to the lower limits on p_e and p_μ all these sets of p_μ events have acoplanarity requirements such as 10^o or 20^o. The references should be consulted for details on the event selection criterion.

Experimental group or detector	$E_{c.m.}$ range (GeV)	Lower limits on p_e p_μ (GeV/c)	Total number of $e\mu$ events	Number of back-ground events	Comment	Ref.
M. Bernardini et al.	1.2 to 3.0				Early search at ADONE, lepton mass ≥ 1.0 GeV/c^2	13
S. Orioto et al.	2.6 to 3.0				Early search at ADONE, lepton mass ≥ 1.15 GeV/c^2	14
SLAC-LBL magnetic detector	3.8 to 7.8	0.65 0.65	190	46	First evidence. Used to determine m_τ, m_{ν_τ}, τ-ν_τ coupling.	1,2, 15, 16
PLUTO Group	3.6 to 5.0	0.3 1.0	23	1.9	Very clean. Strong argument against charm.	6,17, 18, 19
LBL-SLAC lead glass wall	3.7 to 7.4	0.4 0.65	22	0.4	Very clean. Low p_e cutoff.	20, 21
DASP Group	4.0 to 5.2	0.15	11	0.7	Good γ detection. Good hadron identification.	22

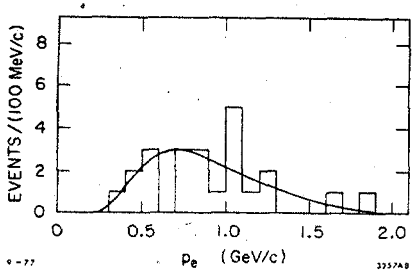

Fig. 3 The electron momentum spectrum for $e\mu$ events with $4.0 \leq E_{c.m.} \leq 5.0$ GeV from the PLUTO Group[6,17,19]; compared with the theoretical curve for the 3-body leptonic decay of a mass 1.9 GeV/c^2 τ.

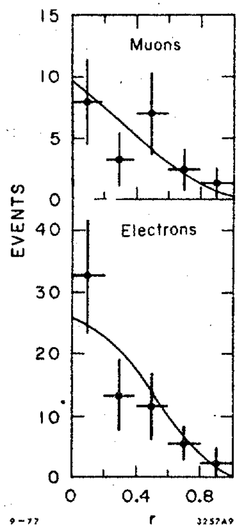

Fig. 4 The muon and electron spectra for $e\mu$ events with $4.0 \leq E_{c.m.} \leq 7.4$ GeV from the LBL-SLAC Lead Glass Wall Experiment[20,21]; compared with the theoretical curve for the 3-body leptonic decay of a mass 1.9 GeV/c^2 τ. Here $r = (p - p_{cut})/(p_{max} - p_{cut})$ where $p_{cut} = 0.65$ GeV, for the muons and 0.40 GeV/c for the electrons.

In Figs. 2 and 4

$$r = (p - p_{cut})/(p_{max} - p_{cut}) \tag{10}$$

is a variable used to consolidate the lepton momentum spectra from different $E_{c.m.}$ energies. Here p is the momentum of the e or μ in GeV/c; p_{max} is its maximum value which depends on $E_{c.m.}$ and m_τ; and p_{cut} is the low momentum cutoff used in the selection of the $e\mu$ events.

V. $\mu^{\pm}x^{\mp}$ DATA

These two-charged prong events have the form

$$e^+ + e^- \to \mu^{\pm} + x^{\mp} + \geq 0 \text{ photons; } x = e \text{ or hadron} \tag{11}$$

Note that unlike the $e\mu$ events, photons are allowed in these events to allow contributions from decay modes like $\tau^- \to \rho + \nu_\tau \to \pi^- + \gamma + \gamma + \nu_\tau$. In these events $\mu^{\pm}\mu^{\mp}$ pairs we excluded either by direct identification of the x as a μ or by μ pair background subtraction. The $\mu^{\pm}x^{\mp}$ data reported previously and at this conference is summarized in Table II.

Figures 5 and 6 show the SLAC-LBL magnetic detector data.[25] Note in Fig. 5 that the 2-prong events have a considerably larger production cross section than any other single multiplicity. This is also true for other μx and ex data and is one of the basic reasons why the 2-prong μx and ex events require a lepton source explanation. Figure 7 shows the beaufitul data of the PLUTO Group.[26]

TABLE II

Data on $\mu^{\pm}x^{\mp}$ events (Eq. (11)) as described in the references. These sets of events have acoplanarity cuts.

Experimental group or detector	$E_{c.m.}$ range (GeV)	Lower limits on p_μ p_x (GeV/c)	Number μx events above background	Comments	Ref.
Maryland-Princeton-Pavia	4.8	1.0 ~0.1		First evidence. Small statistics.	23,24
SLAC-LBL magnetic detector	4.0 to 7.8	1.0 0.2	103 ± 18 above $E_{c.m.}$=5.8 GeV	Strong signal above 5.8 GeV. Clearly different from μ+ > 2 charged particle events.	25
PLUTO Group	4.0 to 5.0	0.7 ~0.1	~230	Strong signal in 3 $E_{c.m.}$ ranges in 4-5 GeV regions.	6, 17,19 26
DASP Group	4.0 to 5.2	0.7 ~0.1	≈12	Can be directly compared to ex events.	22
Maryland-Princeton-Pavia	7	1.15 ~0.1	8^{+4}_{-3}	Good charged prong detection.	27,28

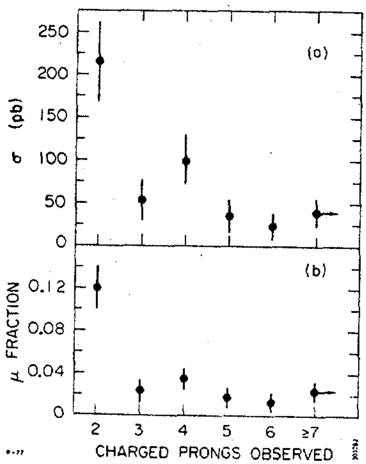

Fig. 5 (a) Anomalous muon production cross section and (b) ratio of anomalous muons to candidates versus the number of observed charged prongs in the $E_{c.m.}$ range 5.8 to 7.8 GeV from the SLAC-LBL Magnetic Detector Collaboration.[25]

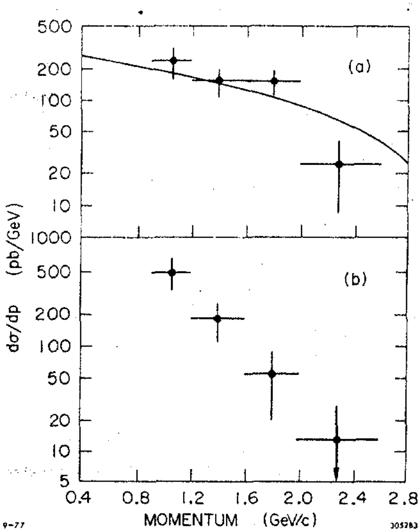

Fig. 6 Differential cross section for anomalous muon production versus momentum for (a) two-prong events and (b) multiprong events in the $E_{c.m.}$ range 5.8 to 7.8 GeV from the SLAC-LBL Magnetic Detector Collaboration.[25] The solid curve represents the expected cross section from the decays of a mass 1.9 GeV/c^2 τ.

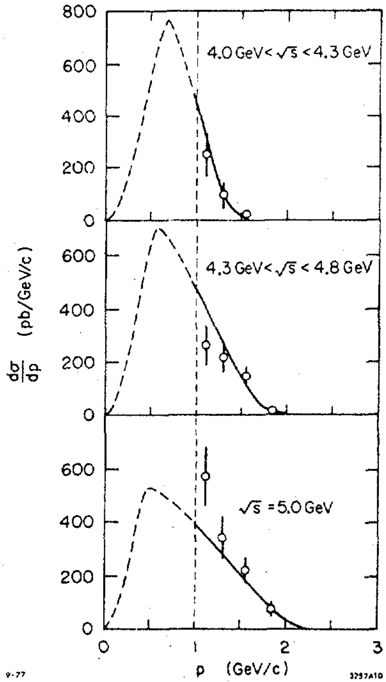

Fig. 7 The muon spectrum for μx events from the PLUTO Group[6,17,19] compared to the theoretical curve for the 3-body leptonic decay of a mass 1.9 GeV/c^2.

VI. $e^{\pm}x^{\mp}$ DATA

These events are of the form

$$e^+ + e^- \to e^{\pm} + x^{\mp} + \geq 0 \text{ photons} \qquad x = \mu \text{ or hadron} \tag{12}$$

and are listed in Table III.

Figures 8 and 9 show the preliminary momentum spectrum of the e in the ex event from the DASP[21] and DELCO[30] group respectively. Both spectra are consistent with that expected from a 1.9 ± 0.1 GeV/c^2 charged lepton.

TABLE III

Data on $e^{\pm}x^{\mp}$ events. See references for the acoplanarity cut.

Experimental group or detector	$E_{c.m.}$ range (GeV)	Lower limits on p_e p_x (GeV/c)	Number of ex events above background	Comments	Ref.
LBL-SLAC lead glass wall	3.7 to 7.4	0.4 0.65	70	See hadronic decay modes of τ.	20, 21
DASP Group	4.0 to 5.2	.2 .2	60	See hadronic decay modes of τ. K/π ratio $= 0.07 \pm 0.06$ compared to 0.24 ± 0.05 for ≥ 3 charged prong $\bar{e}$ events	22, 29
DELCO	3.7 to 7.4	.1 .3	230	Very, very clean e selection with large solid angle	30

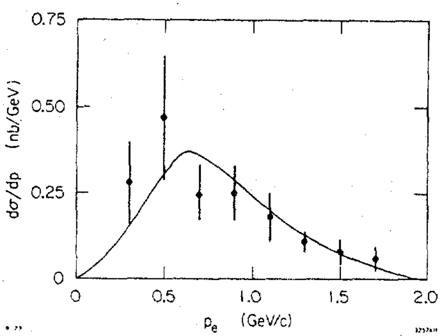

Fig. 8 The electron spectrum for ex events from the DASP Group (Refs. 22, 29) compared to the theoretical curve for the 3-body leptonic decay of a mass 1.9 GeV/c^2 τ.

VII. e^+e^- AND $\mu^+\mu^-$ DATA

If the τ hypothesis is correct one should observe noncoplanar events of the form

$$\begin{aligned} &e^+ + e^- \to e^+ + e^- + \text{missing energy} \\ &e^+ + e^- \to \mu^+ + \mu^- + \text{missing energy} \end{aligned} \tag{13}$$

which are not from QED processes. It is difficult to isolate such anomalous events because of contamination from QED processes such as

$$\begin{aligned} &e^+ + e^- \to \mu^+ + \mu^- + \gamma \\ &e^+ + e^- \to \mu^+ + \mu^- + \gamma + \gamma \\ &e^+ + e^- \to \mu^+ + \mu^- + e^+ + e^- \end{aligned} \tag{14}$$

in which only the $\mu^+\mu^-$ pair is detected. Two results have been reported.

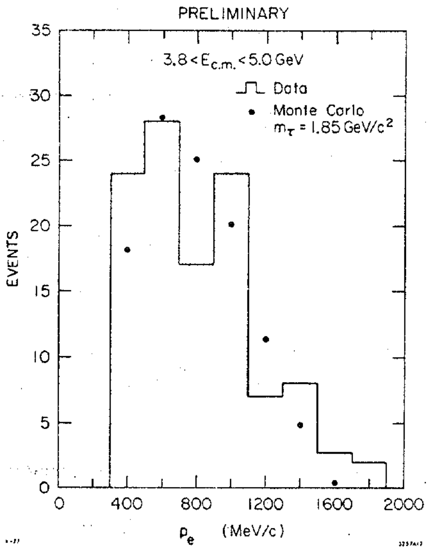

Fig. 9 Preliminary data from the DELCO Group[30] on the electron spectrum for ex events, compared to a theoretical Monte Carlo calculation for the 3-body leptonic decay of a mass 1.85 GeV/c^2 τ.

<u>e^+e^- and $\mu^+\mu^-$ pairs in SLAC-LBL magnetic detector data[31]</u>—e^+e^- and $\mu^+\mu^-$ pairs were selected requiring $p_e > 0.65$ GeV/c, $p_\mu > 0.65$ GeV/c and $\theta_{copl} > 20^o$. After corrections (which are large) for QED processes and for hadronic backgrounds, the following ratios of number of events is found.

$$\frac{\text{Number } ee}{\text{Number } e\mu} = 0.52 \pm .10 \pm {}^{.16}_{.19}$$
$$\frac{\text{Number } \mu\mu}{\text{Number } e\mu} = 0.63 \pm .10 \pm .19 \qquad (15)$$

Here the first error is one standard deviation in the statistical error; and the second error is the limits on the systematic errors added in quadrature.

<u>$\mu^+\mu^-$ pairs in Colorado-Pennsylvania-Wisconsin "Iron Ball" experiment at SPEAR[32,28]</u>—Using $p_\mu > 1.2$ GeV/c and $\theta_{copl} > 10^o$ this experiment finds 25 $\mu^+\mu^-$ events. The expected background from QED processes and hadronic contamination is 14 events, leaving 11 anomalous $\mu^+\mu^-$ events. The authors report[32] that this number is consistent with that expected from the τ.

VIII. WHY THESE ANOMALOUS TWO-CHARGED PRONG EVENTS ARE NOT FROM CHARMED PARTICLE DECAYS

There are two reasons why there is a natural tendency to try to explain these anomalous two-prong events as due to the semileptonic decays of a pair of charmed particles. First the $e\mu$ events were found just as the hunt for singly charmed mesons began. Second as shown in Section IX. A the τ mass lies within 100 MeV/c^2 of the D meson masses. Nevertheless it has been shown repeatedly that almost all of $e\mu$ events and most of the ex and μx events require a <u>non</u>-charm explanation. The best way to see why this is so is to read the papers of each experimental group to see why they each came to this conclusion using their own data. Here I will summarize the reasons for this conclusion.

A. <u>Summary of Why Anomalous Two-Prong Events are not From Charm</u>

i. Very few or no $\geq$ three-charged prong $e^\pm\mu^\mp$ events have been found compared to the number of two-charged prong, 0 photons $e^\pm\mu^\mp$ events.[15,17,19] Since charm will produce more $\geq$ three-charged prong $e\mu$ events than two-charged prong $e\mu$ events, particularly at high $E_{c.m.}$ energy, the two-charged prong, 0 photon, $e\mu$ events cannot come from charm.

ii. The momentum spectra of the e or μ in $e\mu$, ex and μx events is too hard for charm (the charm e or μ spectra is now known experimentally[19,21,22,30]).

iii. The ratio of eK to $e\pi$ events is too small for charm.[22,33]

iv. The production cross sections for $e\mu$, ex, and μx events are all compatible with the point particle production of a mass 1.9 ± 0.1 lepton.[6,7,19,21,22,30] These production cross sections do not follow the ups and downs of the charm production cross section. A recent example is the production cross section for ex events presented by the DELCO Group[30] at this conference. There is a sharp dip in the ≥ 3 prong e events (the signature for charm events) at about 4.28 GeV/c. But there is no dip in the 2-prong e events (the signature for τ events) at this point. At the $\psi(3772)$ there is a peak in the raw number of 2-prong e events, but according to Kirkby[30] about half of these events are from charm because the e and x momentum go down to the hundred MeV/c range. Once this correction is made, there is no peak in the 2-prong e event at $\psi(3772)$.

In the next section I will show in more detail the production cross section for $e\mu$ events including new data at $\psi(3772)$.

B. New Data on $e\mu$ Production Cross Sections

The LBL-SLAC lead glass wall experiment[20,21] found 8 $e^{\mp}\mu^{\pm}$ events ($p_e > 0.65$ GeV/c, $p_\mu > 0.65$ GeV/c, $\theta_{copl} > 20^o$, no other charged tracks, 0 photons) at $E_{c.m.} = 3.772$ GeV, which is the peak of the ψ''. One of these events had its e in the lead glass wall. There are three types of backgrounds:

a. background from hadronic events = 2.3 events
b. background from joint semileptonic decays of a $D\bar{D}$ pair ≤ 0.2 events
c. background from the semileptonic decay of a D and the misidentification of a hadron $\lesssim 1.9$ events.

There may be some double counting between a and c because a study of ≥ 3-prong $e^{\pm}\mu^{\mp}$ events at ψ'' finds 65 events with a calculated background of 64; and this background of 64 events is calculated using the same method as the 2.3 events in a. The small statistics and the presence of the ψ'' make it impossible to prove we have heavy lepton $e\mu$ events at the ψ''. The observed $e\mu$ production cross section is $5.4 \begin{smallmatrix} +2.8 \\ -4.7 \end{smallmatrix}$ where the lower error takes into account the uncertainty as to how to do the backgrounds.

To display this result in comparison with earlier $e\mu$ data we define

$$R_{e\mu,\text{observed}} = \sigma_{e\mu,\text{observed}}/\sigma_{ee\to\mu\mu} \tag{16}$$

Note that $R_{e\mu,\text{observed}}$ is corrected for background contamination but is not corrected for acceptance or triggering efficiency. Figure 10 shows $R_{e\mu,\text{observed}}$. The points at the $\psi(3772)$ is consistent with a monotonic rise in $R_{e\mu,\text{observed}}$ and shows no effect of the peak in R (Fig. 11) at that resonance. Comparing Fig. 10a with Fig. 11, we also see no peak in $R_{e\mu,\text{observed}}$ at the 4.1 or 4.4 peaks in R. Thus $R_{e\mu,\text{observed}}$ does not follow charm production as reflected in the variations in R.

In Fig. 12 we define

$$R_\tau = R_{e\mu,\text{observed}}/(2B_e\, B_\mu\, A_{e\mu}) \tag{17}$$

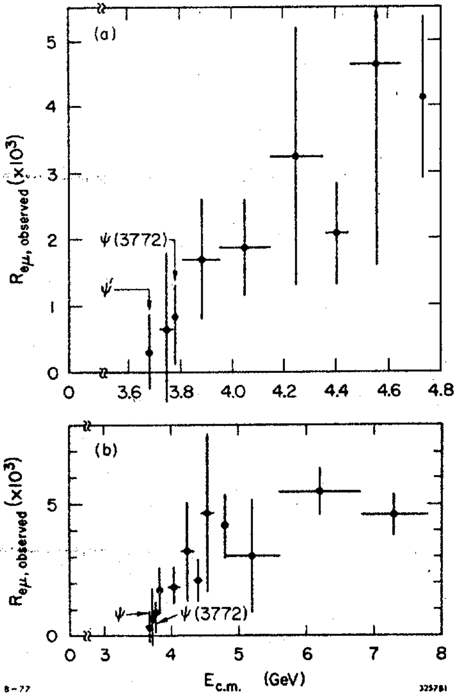

Fig. 10 $R_{e\mu}$, observed for (a) $3.6 \le E_{c.m.} \le 4.8$ GeV and (b) $3.6 \le E_{c.m.} \le 7.8$ GeV.

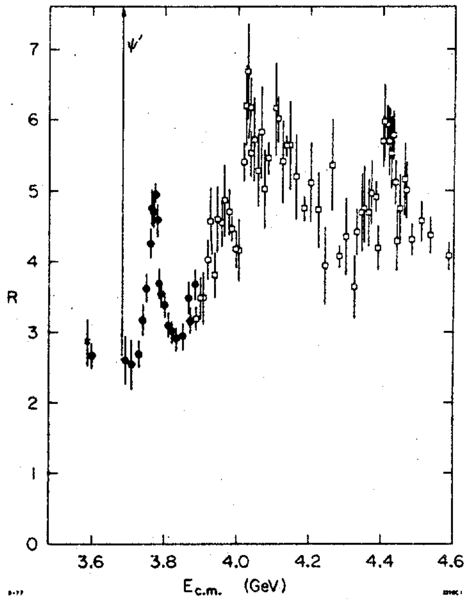

Fig. 11 R for $3.6 \le E_{c.m.} \le 4.6$ GeV.

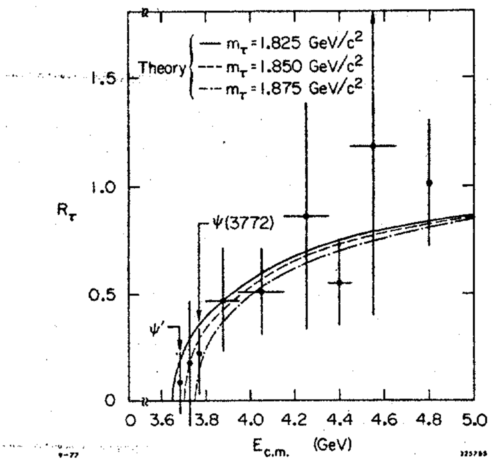

Fig. 12 R_τ compared to theoretical R_τ curves for various τ masses.

where the branching ratios to e and μ are taken to be[16] $B_e = B_\mu = .186$ and $A_{e\mu}$ is the product of the acceptance, the trigger efficiency, and various particle loss corrections. From Fig. 12 we see that if we take R_τ at the $\psi(3772)$ as being its nonzero value, the τ mass lies in the range of 1800 to 1875 MeV/c^2. In any case we see that R_τ is a monotonic function of $E_{c.m.}$ as it must be for the heavy lepton.

IV. PROPERTIES OF THE τ

A. τ Mass

Table IV gives those m_τ values which have been reported. I have not included information where data is said to be consistent with a certain m_τ but no error on that m_τ is given.

TABLE IV

Measurements of m_τ assuming V-A coupling and $m_{\nu_\tau} = 0.0$.

Experiment	Data Used	Method	τ Mass (GeV/c^2)	Comment	Ref.
SLAC-LBL magnetic detector	$e\mu$	p_1	1.91 ± .05	Statistical error	7,16
		$\cos\theta_{coll}$	1.85 ± .10	Statistical error	
		r	1.88 ± .06	Statistical error	
		composite	1.90 ± .10	Statistical and systematic error	
PLUTO Group	μx	$\sigma_{\mu x}$	1.93 ± .05		19
LBL-SLAC lead glass wall	$e\mu$'s at 3.772	p_e, p_μ	1.800 to 1.875	If $e\mu$'s at 3.772 are from τ	this paper
LBL-SLAC lead glass wall	ex at 3.772	σ_{ex}	1.800 to 1.875	If ex's at 3.772 are from τ	21

B. ν_τ Mass

Two upper limits have been set on m_{ν_τ}. Using $e\mu$ events[7,16]: $m_{\nu_\tau} \leq 0.6$ GeV/c^2 with 95% CL. Using μx events[19]: $m_{\nu_\tau} \leq 0.54$ GeV/c^2 with 95% CL.

C. τ-ν_τ Coupling

Using Fig. 13 we find[7,16] that V+A coupling has a χ^2 probability of less than 0.1% to fit the r distribution (Eq. (10)) of the $e\mu$ events. V-A coupling has a 60% χ^2 probability. If we ignore the r=.1 point the χ^2 probability for V+A is 5%. An

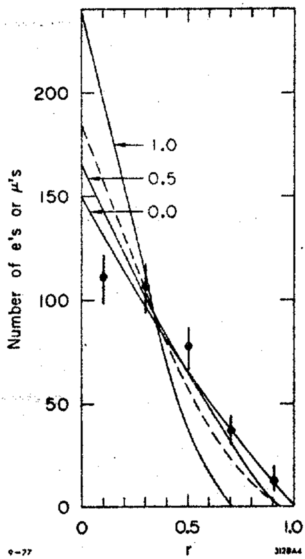

Fig. 13 r for all eμ events from the SLAC-LBL Magnetic Detector Collaboration. r is defined in the caption of Fig. 2.

additional argument against V+A coupling is that one cannot obtain a consistent m_τ value as shown in Table V.

TABLE V

m_τ for V+A coupling and $m_{\nu_\tau} = 0.0$.

Method	$p_\perp$	$\cos\theta_{coll}$	r
Mass (GeV/c^2)	$2.12 \pm .05$	$1.95 \pm .10$	Upper limit is 1.76 with 95% CL.

Using μx events, the PLUTO Group also finds[6,19] the V-A coupling is favored over V+A coupling. Neither experiment is able to say anything about coupling intermediate between V+A and V-A such as pure V or pure A.

X. DECAY MODES OF T

A. Purely Leptonic Decay Modes

Table VI gives the existing data on the purely leptonic decay rates: B_e for $\tau^- \to e^- \nu_\tau \bar{\nu}_e$ and B_μ for $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$.

We note that these purely leptonic branching ratios are in agreement within the errors. This is a very pleasing result considering the wide variety of methods and the difficulty of working with these small signals. These measurements are also in agreement with the theoretical calculations for a $m_\tau = 1.9$ GeV/c, $m_{\nu_\tau} = 0.0$, V-A coupling, sequential charged lepton, and Table VII.

B. Semileptonic Decay Modes

Table VIII gives the existing information on semileptonic decay modes of the τ. Comparing this table with Table VII we see that several of the predicted decay semileptonic modes of the τ have been seen, and within errors they have the expectant branching ratios. The $\tau^- \to \pi^- + \nu_\tau$ has not been seen; using $B_e = .2$, the DASP Group finds[22] a preliminary result $B_\pi = .02 \pm .025$. If further experiments confirm this relatively low value of B_π then the present theory of the nature of the τ lepton will have to be revised. For example: the τ might not have V-A coupling to the conventional weak currents.

Since this is the first presentation of the "A_1" + ν_τ decay mode by the SLAC-LBL Collaborators;[35] I will show some preliminary graphs. (Incidently the notation "A_1" is used because the expected spin (1^+) of the A_1 has not been tested and

TABLE VI

The measured fractional decay rates B_e and B_μ. V-A coupling, $m_\tau = 1.9$ GeV/c and $m_{\nu_\tau} = 0.0$ was used to calculate acceptances.

Experimental group or detector	Data Used	B_e or B_μ	Comment	Ref.
SLAC-LBL magnetic detector	$e\mu$	$0.186 \pm .010 \pm .028$	Assume $B_e = B_\mu$. First error is statistical, second is systematic.	7,16
SLAC-LBL magnetic detector	μx	$0.175 \pm .027 \pm .030$	Assume $B_x = 0.85$. First error is statistical, second is systematic.	7,16
PLUTO Group	μx	$B_\mu = 0.14 \pm .034$		19
PLUTO Group	$\mu x, e\mu$	$B_e = 0.16 \pm .06$		19
LBL-SLAC lead glass wall	$e\mu$	$0.224 \pm .032 \pm .044$	Assume $B_e = B_\mu$. First error is statistical, second is systematic.	20,21
DASP Group	$e\mu$	$0.20 \pm .03$	Assume $B_e = B_\mu$.	22
DELCO Group	ex	0.15	No error given.	30
Iron Ball	$\mu\mu$	$0.22 \begin{smallmatrix} +.07 \\ -.08 \end{smallmatrix}$		32
Maryland-Princeton-Pavia	μx	$0.20 \pm .10$		27

TABLE VII

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. 8 and 9 as discussed in Ref. 34. 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. 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
$\nu_\tau \bar{e}^- \bar{\nu}_e$	.20	1
$\nu_\tau \nu^- \bar{\nu}_\mu$	.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

TABLE VIII

Observed semileptonic decay modes of the τ. V-A coupling, $m_\tau = 1.9$ GeV/c^2 and $m_{\nu_\tau} = 0.0$ was used to calculate acceptances. Here h means hadron.

Experimental group or detector	Decay mode (for τ^-)	Branching ratio	Ref.
LBL-SLAC lead glass wall	$h^- + \nu_\tau + \geq 0\ \gamma$'s	0.45 ± 0.19	20,21
DASP Group	$\rho^- + \nu_\tau$	$0.24 \pm .09$	22
DASP Group	$\pi^- + \nu_\tau$	$B_e B_\pi = 0.004 \pm .005$	22
PLUTO Group	"A_1"$^-$ + ν_τ	$0.11 \pm .04 \pm .03$ for "A_1" $\rightarrow$ all	19
LBL-SLAC lead glass wall and SLAC-LBL magnetic detector	"A_1"$^-$ + ν_τ		35

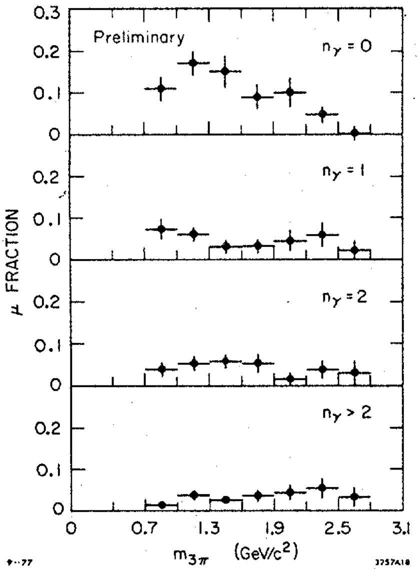

Fig. 14 μ/μ candidates versus invariant mass of remaining three prongs in 4-prong events.

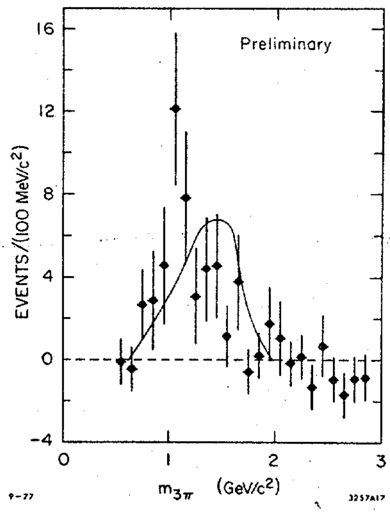

Fig. 15 3-particle invariant mass distribution opposite muons corrected for hadron misidentification. The curve gives the mass distribution expected from nonresonant production ($\tau \rightarrow \nu\pi\rho$), corrected for acceptance effects, and normalized to the data in the range $.7 < m_{3\pi} < 1.8$.

and because the evidence from hadronic experiments on the A_1 is confusing. The SLAC-LBL analysis which was carried out by J. Jaros selects events using the following criteria

i. $E_{c.m.} > 6$ GeV
ii. 4-charged prongs with total charge 0
iii. one of the prongs must be identified as a muon by the muon tower or mini-muon tower of the magnetic detector
iv. $p_\mu > 0.9$ GeV/c.

Figure 14 shows the ratio μ/μ candidates versus the mass of the 3π system. (The non-μ particles are assumed to be pions.) Only the 0 photon data shows a ratio greater than the ~0.05 expected from π decay, K decay, and punchthru. Figure 15 shows the 3π mass spectra of the 0 photon events corrected for background. The peak in the 1.-1.2 GeV/c^2 region is too narrow to come from the nonresonant $\tau \rightarrow \nu_\tau + \pi + \rho$ decay mode. Figure 16 shows that the μ in these events have "hard" spectrum required for the τ.

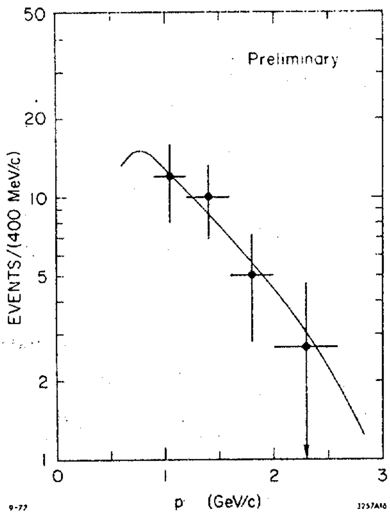

Fig. 16 Muon spectrum opposite tri-pions with $1.0 < m_{3\pi} < 1.3$. The curve is the Monte Carlo prediction for $m_\tau = 1.85$, $m_{\nu_\tau} = 0$, V-A, $E_B = 3.5$, normalized to the data.

C. Upper Limits on Rare Decay Modes

TABLE IX

Upper limits on rare decay modes of the τ using V-A coupling, $m_\tau = 1.9$ GeV/c^2, $m_{\nu_\tau} = 0.0$ for acceptance calculations.

Experimental group or detector	Mode	Upper limit on branching ratio	C. L.	Ref.
PLUTO Group	$\tau^- \to$ (3 charged particles)$^-$	0.01	95%	6
PLUTO Group	$\tau^- \to$ (3 charged leptons)$^-$	0.01	95%	6
SLAC-LBL magnetic detector	$\tau^- \to$ (3 charged leptons)$^-$	0.006	90%	36
SLAC-LBL magnetic detector	$\tau^- \to \rho^- + \pi^0$	0.024	90%	37
PLUTO Group	$\tau^- \to e^- + \gamma$ $\tau^- \to \mu^- + \gamma$	0.12	90%	6
LBL-SLAC lead glass wall	$\tau^- \to e^- + \gamma$	0.026	90%	38
LBL-SLAC lead glass wall	$\tau^- \to \mu^- + \gamma$	0.013	90%	38

XI. CONCLUSIONS

a. All data on anomalous $e\mu$, ex, μx, ee and $\mu\mu$ events produced in e^+e^- annihilation is consistent with the existence of a mass 1.9 ± 0.1 GeV/c^2 charged lepton, the τ.

b. This data cannot be explained as coming from charmed particle decays.

c. Many of the expected decay modes of the τ have been seen. A very important problem is the existence of the $\tau^- \rightarrow \nu_\tau \pi^-$ decay mode.

d. There has not been the space to discuss it here, but ν_μ experiments[6,7] say that the τ cannot be a muon-related ortholepton or paralepton with conventional coupling strengths. The results in Eq. (15) say that the τ is not an electron-related paralepton[7,31] using the theoretical work of Ali and Yang.[40] The τ may be a sequential lepton or an electron-related ortholepton.

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