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EVIDENCE FOR, AND PROPERTIES OF, THE τ LEPTON[*, +]

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ABSTRACT

An outline of the evidence on the e^+e^- annihilation of a new charged lepton, the τ, is presented. Measured properties of the τ are summarized and some still open questions as to its properties are discussed.

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1. Introduction

I do not have the time in this short talk to present all the evidence for the existence of a new charged lepton or at least lepton-like particle of mass 1.9 ± 0.1 GeV/c, called the τ. Since the discovery at SPEAR[1] of the $e\mu$ events produced in e^+e^- annihilation, eight different experiments at SPEAR and DORIS have data either requiring such a new particle or consistent with the existence of such a particle. I recently reviewed all the data[2] and an earlier review was given by Flügge.[3] Therefore I will begin the talk with a general description of the signatures for charged heavy lepton production in

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e^+e^- annihilation, and then I will concentrate on the $e\mu$ events as examples of one type of data. The larger portion of the talk will present the measured properties of the new particle. I will conclude with some open questions on the new particle.

2. Signatures for Charged Heavy Lepton Production in e^+e^- Annihilation

If a charged lepton $L^{\pm}$ is produced in e^+e^- annihilation we expect the following kinds of experimental signatures:

A. Pair Production

We expect single pair production

$$e^+ + e^- \rightarrow L^+ + L^- \tag{1}$$

but not

$$e^+ + e^- \rightarrow L^+ + L^- + \text{hadrons}. \tag{2}$$

Reaction (2) would mean that L has strong interactions and is not a lepton.

B. Point Particle Production Cross-Section

For a spin $\frac{1}{2}$ lepton we expect the production cross-section

$$\sigma_{e^+e^-\to L^+L^-} = \frac{2\pi\alpha^2\beta(3-\beta^2)}{3E^2_{c.m.}} \tag{3}$$

where β is the lepton's velocity in units of c, α is the fine structure constant and $E_{c.m.}$ is the total energy. I note that we do not expect a production form factor, whereas in hadron pair production we expect a form factor like

$$F(E_{c.m.}) = \text{constant}/E^n_{c.m.}, \quad n \geq 2 \tag{4}$$

to enter as the square in Eq. 3.

C. Assuming Radiative Decays are Suppressed or Prohibited, Purely Leptonic Decays Will Occur

Assuming the radiative decays

$$L^- \rightarrow e^- + \gamma \qquad (5)$$

$$L^- \rightarrow \mu^- + \gamma$$

are suppressed or prohibited we expect the lepton to decay through the weak interaction into the purely leptonic final states

$$L^- \rightarrow \nu + e^- + \bar{\nu}_e \qquad (6)$$

$$L^- \rightarrow \nu + \mu^- + \bar{\nu}_\mu \,.$$

At this time we need make no assumption as to the precise nature of the ν in Reactions (6). From Reactions (6) we expect the <u>$e^\pm \mu^\mp$ event signature</u>

$$\begin{tikzcd} e^+ + e^- \arrow[r] & L^+ \arrow[d] & + & L^- \arrow[d] \\ & \bar{\nu} e^+ \nu_e & & \nu \mu^- \bar{\nu}_\mu \end{tikzcd} \qquad (7)$$

and its charge conjugate. Such eμ events have only two particles which can be detected by conventional apparatus and have substantial missing energy. Succinctly:

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{missing energy} \qquad (8)$$

D. <u>Momentum Spectrum of e or μ in eμ Events Will Be "Hard", But Not as "Hard" as A Two-Body Decay</u>

As shown in Fig. (1), the e or μ momentum spectrum in the laboratory frame will be "harder" than that of a weakly decaying hadron such as a singly-charmed meson.[4] But the spectrum will not be as "hard" as that from a two-body decay $M^- \rightarrow e^- + \bar{\nu}_e$.

E. <u>Semi-Leptonic Decays May Also Occur</u>

If the L mass is sufficiently large there may be semi-leptonic decays such as

$$L^- \rightarrow \nu^- + \pi^- \qquad (9)$$

$$L^- \rightarrow \nu^- + K^-$$

$$\begin{aligned} &L^- \rightarrow \nu^- + \rho^- && \text{(9) (Continued)} \\ &L^- \rightarrow \nu + K^{*-} \\ &L^- \rightarrow \nu + A_1^- \\ &L^- \rightarrow \nu + \pi^- + \pi^+ + \pi^- + \pi^0 \\ &L^- \rightarrow \nu + \bar{p} + n \\ &\vdots \qquad\quad \vdots \end{aligned}$$

F. Semi-Leptonic Decays Lead to e-Hadron and μ-Hadron Events

If one L decays purely leptonically and the other decays semi-leptonically, we expect e-hadron and μ-hadron events such as

$$\begin{tikzcd} e^+ + e^- \arrow[r] & L^+ \arrow[d] & + & L^- \arrow[d] \\ & \nu\mu^+\nu_\mu & & \nu\rho^- \arrow[d] \\ & & & \pi^-\gamma\gamma \end{tikzcd} \qquad (10)$$

G. Summary of Signatures

I want to emphasize that signatures A through F can provide very substantial evidence for the existence of a new lepton regardless of whether the new lepton fits all the requirements of a particular model. I have made this remark because although there is now substantial evidence that the τ is a lepton-like particle, we do not yet know whether the τ fits any of our usual lepton models. I shall briefly describe next, three of those models. In all of these models we require a mechanism to suppress the radiative decays, Eq. (5), because the radiative decays of the τ have not been found, and we at least want the model to fit that property of the τ.

3. Some Specific Lepton Models

A. Ortholepton

L^- might have the same lepton number as the e^- or μ^-. Llewellyn Smith[5,6] calls this an ortholepton where ortho is for orthodox. To supress the radiative decays, Eq. (5), we must construct a theory which suppresses the $L^- e^- \gamma$ vertex.

B. Paralepton

If L^- has the same lepton number as the e^+ or μ^+, the radiative decays, Eq. (5), are prohibited (if lepton number conservation is assumed). The para in paralepton is taken from paradoxical.[5]

C. Sequential Heavy Lepton

If there is a sequence of charged leptons each with its own unique, conserved, lepton number and its own unique neutrino:

charged lepton	associated neutrino
$e^\pm$	$\nu_e, \bar{\nu}_e$
$\mu^\pm$	$\nu_\mu, \bar{\nu}_\mu$
$L^\pm$	$\nu_L, \bar{\nu}_L$
.	.
.	. ,

(11)

and if ν_L is lighter than L, the purely leptonic decay modes

$$L^- \to \nu_L + e^- + \bar{\nu}_e \ , \ \nu_L + \mu^- + \bar{\nu}_\mu \tag{12}$$

will occur. But the radiative decays, Eq. (5), will be prohibited. This is the model which motivated my interest in looking for new heavy leptons, but as you will see we don't yet know if the τ is a sequential heavy lepton.

If we assume that the lepton decays through the conventional weak interactions, that the neutrino mass is zero, and that the L-ν_L coupling is V-A, then the various decay rates can be calculated.[8,9] Table I gives the predicted branching ratios for a mass 1.9 GeV/c^2 lepton. Figures (2) and (3) show the branching ratios and lifetime for masses less than 10 GeV/c^2. We note that Table I predicts that decay modes of 1.9 GeV/c^2 lepton in this model will usually have only one charged track. (The specific prediction is about 85%.)

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.

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
ν_τ(hadron continuum)$^-$	.18	1,3,5

4. Outline of Evidence for the τ

There is now substantial evidence[2,3] for the existence of a charged lepton we call the τ with:

a) τ mass = 1.9 ± 0.1 GeV/c^2;

b) associated neutrino mass ≤ 0.6 GeV/c^2 with 90% confidence;

c) observed decay modes:

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e$$

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

$$\tau^- \rightarrow \nu_\tau + h^- + \geq 0 \text{ photons}$$

$$\tau^- \rightarrow \nu_\tau + \rho^-$$

$$\tau^- \rightarrow \nu_\tau + h^- + h^+ + h^-$$

where h is a hadron.

From now on we shall refer to the neutrino associated with the τ as ν_τ for convenience, although we have not proven that the τ is a sequential-type lepton. Since this a brief presentation I will only discuss the $e^\pm\mu^\pm$ events in any detail.

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

The eμ events:

$$e^+ + e^- \rightarrow e^\pm + \mu^\pm + \text{no other detected particles,} \qquad (13)$$

have been seen by four experiments, Table II. All experiments find the same production rate and same kinematic distribution properties for these events.

TABLE II

Data on eμ 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° or 20°. 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 eμ Events	Number of Back-ground Events	Comments	Ref.
M. Bernardini *et al.*	1.2 to 3.0				Early search at ADONE, lepton mass $\geq$ 1.0 GeV/c	10

(Table II, continued)

Experimental Group or Detector	$E_{c.m.}$ Range (GeV)	Lower Limits on p_e p_μ (GeV/c)	Total Number of eμ Events	Number of Back-ground Events	Comments	Ref.
S. Orioto <u>et al.</u>	2.6 to 2.0				Early search at ADONE, lepton mass ≥ 1.15 GeV/c^2	11
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
PLUTO Group	3.6 to 5.0	0.3 1.0	23	1.9	Very clean. Strong argument against charm.	3, 12, 13, 14
LBL-SLAC Lead Glass Wall	3.7 to 7.4	0.4 0.65	22	0.4	Very clean. Low p_e cutoff.	15, 16
DASP Group	4.0 to 5.2	0.15 0.1	11	0.7	Good γ detection. Good hadron identification.	17

Figures (4) and (5) show two examples of the "hard" momentum spectrum of the e and μ. Thus the existence of the p_μ events and their momentum spectrum are in agreement with signature requirements C and D (Sec. 2) for a lepton. The eμ events are also consistent with signature A because even at the highest energies very few eμ events with hadrons have been found[1,3,12] relative to the number of pure eμ events, <u>and</u> these eμ events with hadrons are all accounted for as background from hadronic events in which the hadrons have been misidentified as electrons or muons. Indeed, an expected source of eμ events with hadrons - the joint semi-leptonic decay of a pair of singly charmed mesons - has not yet been found. This is because the lepton spectrum from singly-formed meson decays is relatively soft, and such events are eleminated by the lower momentum limits on the e and μ in eμ events.

B. τ Production Cross-Section From eμ events

It is convenient to eliminate the $E_{c.m.}^{-2}$ dependence in Eq. (3) by defining

$$R_{\tau^+\tau^-} = \frac{\sigma_{e^+e^- \to \tau^+\tau^-}}{\sigma_{e^+e^- \to \mu^+\mu^-}} = \frac{\beta(3-\beta^2)}{2} \tag{14}$$

As a preliminary we define

$$R_{e\mu} = \frac{\sigma_{e^+e^- \to e\mu}}{\sigma_{e^+e^- \to \mu^+\mu^-}} = \frac{\beta((3-\beta^2)}{2}\,(2B_e B_\mu A) \tag{15}$$

Here B_e and B_μ are the leptonic branching ratios of the τ, and A is the acceptance taking into account the geometry of the detector and the kinematic cuts. The acceptance A is almost independent of $E_{c.m.}$.

Figure (6) shows $R_{e\mu}$ and Fig. (7) shows $R_{\tau^+\tau^-}$. These figures are consistent with Eqs. (14) and (15), respectively, and are consistent with lepton masses in the range 1.9 ± 0.1 GeV/c^2. Thus the eμ events are consistent with signature A.

C. e-Hadron and μ-Hadron Events

We do not take the time to discuss it here, but events of the form

$$e^+ + e^- \to e^\pm + h^\mp + \geq 0 \text{ photons} \tag{16}$$

$$e^+ + e^- \to \mu^\pm + h^\mp + \geq 0 \text{ photons} \tag{17}$$

have been observed by the following experiments:

SLAC-LBL Magnetic Detector (SPEAR) [18]
PLUTO (DORIS)[12,13,14]
DASP (DORIS)[17]
LBL-SLAC "Lead Glass Wall" Experiment (SPEAR)[15,16]
DELCO (SPEAR)[19]
Maryland-Princeton-Pavia Experiment (SPEAR)[20, 21, 22]

All this data is consistent with the τ being a lepton.

5. Measured Properties of the τ

Table III lists measurements on the τ mass, m_τ .

TABLE III

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

Experiment	Data Used	Method	τ Mass (GeV/c^2)	Comments	Ref.
SLAC-LBL Magnetic Detector	$e\mu$	p	$1.91 \pm .05$	Statistical error	23, 24
		$\cos\theta_{coll}$	$1.85 \pm .10$	Statistical error	
		r	$1.88 \pm .06$	Statistical error	
		composite	$1.90 \pm .10$	Statistical and systematic error	
PLUTO Group	μx	$\sigma_{\mu x}$	$1.93 \pm .05$		14

B. ν_τ Mass

Two upper limits have been set on m_{ν_τ} . Using $e\mu$ events[23,24]: $m_{\nu_\tau} \leq 0.6$ GeV/c^2 with 95% CL. Using μx events[14]: $m_{\nu_\tau} \leq 0.54$ GeV/c^2 with 95% CL.

C. τ-ν_τ Coupling

The SLAC-LBL $e\mu$ events cannot be fit by V + A coupling of the τ to the ν_τ[23]. However V - A, pure V or pure A coupling is acceptable.

D. τ Lifetime

The PLUTO group finds the τ lifetime is less than 1.0×10^{-11} sec with 95% confidence. Using the SLAC-LBL $e\mu$ events I find the τ lifetime is less than 1.1×10^{-11} sec with 95% confidence.

E. Type of Lepton

Experiments using muon neutrinos rule out the τ being a muon-related ortholepton or paralepton with conventional coupling strengths.[26-29] Our measurements on anomalous ee and $\mu\mu$ events produced in e^+e^- annihilation have ruled out the τ being an electron-related paralepton.[30] All data is consistent with the τ being a sequential lepton or an electron-related ortholepton.

6. Observed Decay Modes of the τ

A. Purely Leptonic Decays

Table IV lists all measurements on the purely leptonic decay modes of the τ. The agreement is surprisingly good considering the difficulty of making these measurements and the variety of methods used. A safe overall value assuming $B_e = B_\mu$ is 18 ± 4%, which is in excellent agreement with Table I.

TABLE IV

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	Comments	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.	23, 24
SLAC-LBL Magnetic Detector	μx	$0.175 \pm .027 \pm .030$	Assume $B_x = 0.85$ First error is statistical, second is systematic.	23, 24
PLUTO Group	μx	$B_\mu = 0.14 \pm .034$		14
PLUTO Group	$\mu x, e\mu$	$B_e = 0.16 \pm .06$		14
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.	15, 16
DASP Group	$e\mu$	$0.20 \pm .03$	Assume $B_e = B_\mu$.	17

(Table IV, continued)

Experimental Group or Detector	Data Used	B_e or B_μ	Comments	Ref.
DELCO Group	ex	0.15	No error given.	19
Iron Ball	$\mu\mu$	$0.22\,^{+.07}_{-.08}$		31
Maryland-Princeton-Pavia	μx	0.20±.10		22

B. Semi-Leptonic Decay Modes

The semi-leptonic decay modes of the τ which have been observed are listed in Table V.

TABLE V

Observed semi-leptonic 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	15, 16
DASP Group	$\rho^- + \nu_\tau$	0.24±.09	17
PLUTO Group	$(3h)^- + \nu_\tau$		14
LBL-SLAC Lead Glass Wall and SLAC-LBL Magnetic Detector	$(3h)^- + \nu_\tau$		32

In Table V $(3h)^-$ means a resonant state containing three hadrons which are probably all pions and has a mass of about 1100 MeV/c^2 and a width of several hundred MeV/c^2. The motivation for looking for this state is that the τ should decay into an A_1.[33] The data on the $(3h)^-$ state is consistent with it being an A_1 but there is as yet no proof that it is an A_1 .

C. Upper Limits on Rare Decay Modes

Table VI gives upper limits on radiative and other rare decay modes of the τ. The limits in Table VI are the reason we have emphasized models in Sec. (3) in which radiative decays are suppressed.

TABLE VI

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%	3
PLUTO Group	$\tau^- \to$ (3 charged leptons)$^-$	0.01	95%	3
SLAC-LBL Magnetic Detector	$\tau^- \to$ (3 charged leptons)$^-$	0.006	90%	34
SLAC-LBL Magnetic Detector	$\tau^- \to \rho^- + \pi^0$	0.024	90%	35
PLUTO Group	$\tau^- \to e^- + \gamma$ $\tau^- \to \mu^- + \gamma$	0.12	90%	3
LBL-SLAC Lead Glass Wall	$\tau^- \to e^- + \gamma$	0.026	90%	36
LBL-SLAC Lead Glass Wall	$\tau^- \to \mu^- + \gamma$	0.013	90%	36

7. Open Questions

A. Precise Mass of the τ

We do not understand why the τ mass, 1.9 ± 0.1 GeV/c^2, is close to the mass of the singly-charmed D^+ meson, 1.865 GeV/c^2. Is it a coincidence, does it have some significance, or is it related to the relative closeness of the π and μ mesons? We have no answer to these questions. In spite of the very strong evidence that the τ is a lepton and is not the D^+ meson, it is still very desireable to have a precise measurement of the τ mass. If the τ mass is different from the D^+ mass this is a final proof that the particles are different. If the τ mass is the same as the D^+ mass, it means that we understand neither singly-charmed hadrons nor leptons. Therefore it is important to make a precise measurement of the τ mass.

B. The $\tau^- \to \nu_\tau + \pi^-$ Decay Mode

The sequential lepton model with conventional weak interactions and V - A coupling predicts about a 10% branching ratio to this mode (Table I). The DASP group[17] and the PLUTO group[25] have both looked for this mode. Their results are preliminary and their statistics are small. However, neither group has found this mode. Each result is null by about 2 or 3 standard deviations. If the $\tau^- \to \nu_\tau + \pi^-$ mode is absent then the τ does not fit any of the specific lepton models in Sec. (3). Nevertheless, all the other data still requires the τ to be a lepton. The τ would then be a lepton of a new and very strange kind, a kind stranger than we ever expected. Therefore it is important not to draw conclusions from these preliminary results, but to wait for higher statistics experiments. The continued data-taking at SPEAR by the DELCO group and the new experiment at SPEAR by the SLAC-LBL collaboration using the new MARK II magnetic detector will hopefully help to answer both this question and the mass question in the coming year.

REFERENCES

1. M. L. Perl et al., Phys. Rev. Lett 35, 1489 (1975); Phys. Lett. 63B, 117 (1976).
2. M. L. Perl in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published); also issued as SLAC-PUB-2022.
3. G. Flügge in Proceedings of the 1977 Experimental Meson Spectroscopy Conference (Northeastern University, Boston, Mass., 1977); also issued as DESY 77/35.
4. For a discussion on this point and experimental illustrations see references (14), (16), and (17).
5. C. H. Llewellyn Smith, Oxford University preprint 33/76 (1976).
6. J. D. Bjorken and C. H. Llewellyn Smith, Phys. Rev. D7, 88 (1973).
7. A. Ali and T. C. Yang, Phys. Rev. D14, 3052 (1976).
8. H. B. Thacker and J. J. Sakurai, Phys. Lett. 36B, 103 (1971).
9. Y. S. Tsai, Phys. Rev. D4, 2821 (1971).
10. M. Bernardini et al., Nuovo Cimento 17, 383 (1973).
11. S. Orioto et al., Phys. Lett. 48B, 165 (1974).
12. H. Meyer in Proceedings of the Orbis Scientiae (Coral Gables, Fla., 1977).
13. J. Burmester et al., DESY 77/25.
14. G. Knies in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published).
15. A. Barbaro-Galtieri et al., Phys. Rev. Lett. 39, 1058 (1977).

16. A. Barbaro-Galtieri in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published).

17. S. Yamada in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published).

18. G. J. Feldman *et al.*, Phys. Rev. Lett. **38**, 1977 (1976).

19. J. Kirkby in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published).

20. M. Cavalli-Sforza *et al.*, Phys. Rev. Lett. **36**, 588 (1976).

21. G. Snow, Phys. Rev. Lett. **36**, 766 (1976).

22. H. Sadrozinski in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published).

23. M. L. Perl *et al.*, Phys. Lett. (to be published); also issued as SLAC-PUB-1997 (1977).

24. M. L. Perl in Proceedings of the XII Rencontre de Moriond (Flaine, France, 1977), edited by Tran Thanh Van (R. M. I. E. M., ORSAY).

25. H. Meyer, talk given at the Stanford Linear Accelerator Center, Stanford, Calif. (September 1977).

26. B. C. Barish *et al.*, quoted by D. C. Cundy in Proceedings of the XVII International Conference on High Energy Physics (London, England, 1974), p. IV-147.

27. C. H. Albright, Phys. Rev. **D13**, 2508 (1970).

28. M. Murtagh in Proceedings of the 1977 International Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published).

29. C. Baltay, private communication.

30. F. B. Heile *et al.*, to be published.

31. U. Camarini *et al.*, paper submitted to the 1977 Symposium on Lepton and Photon Interactions at High Energies (Hamburg, West Germany, 1977, to be published).

32. J. Jaros *et al.*, to be published.

33. J. J. Sakurai in *Proceedings of the 1975 International Symposium on Lepton and Photon Interactions at High Energies* (Stanford University, Stanford, Calif. (1975), p. 353.

34. G. J. Feldman, private communication.

35. H. K. Nguyen, private communication.

36. J. Jaros, private communication.

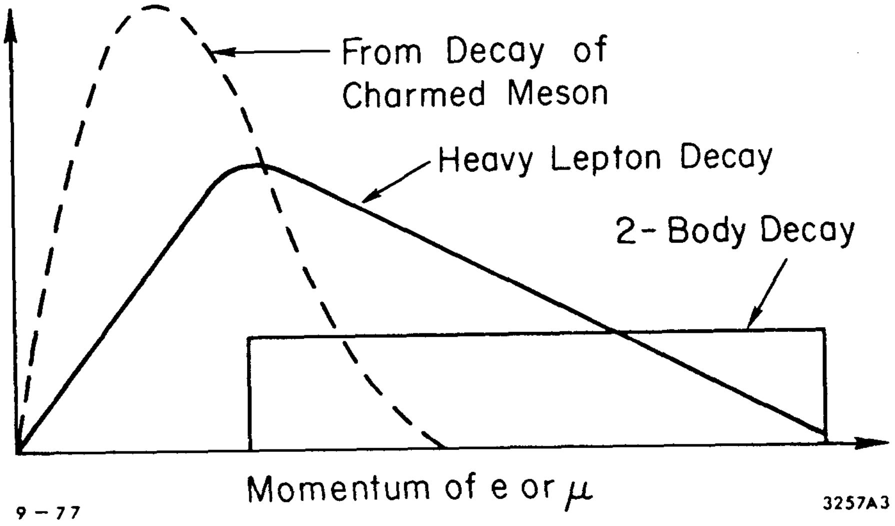

Fig. 1 Schematic comparison of the momentum spectrum for a lepton from a heavy lepton decay compared to the lepton spectrum from a charmed particle semileptonic decay or from a two-body decay.

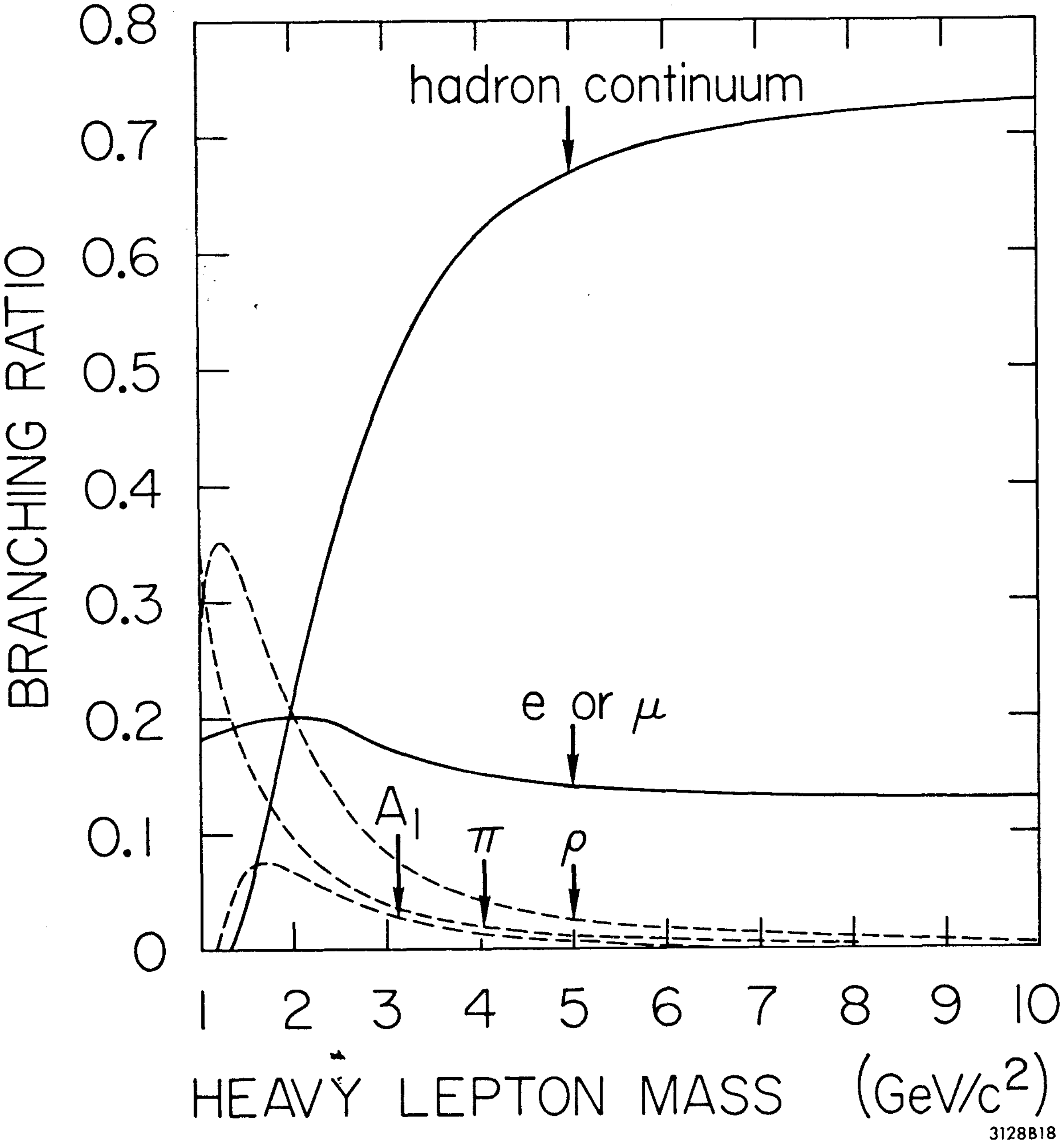

Fig. 2 Branching ratios versus mass for a charged lepton with conventional weak interactions, V - A coupling, and a massless neutrino.

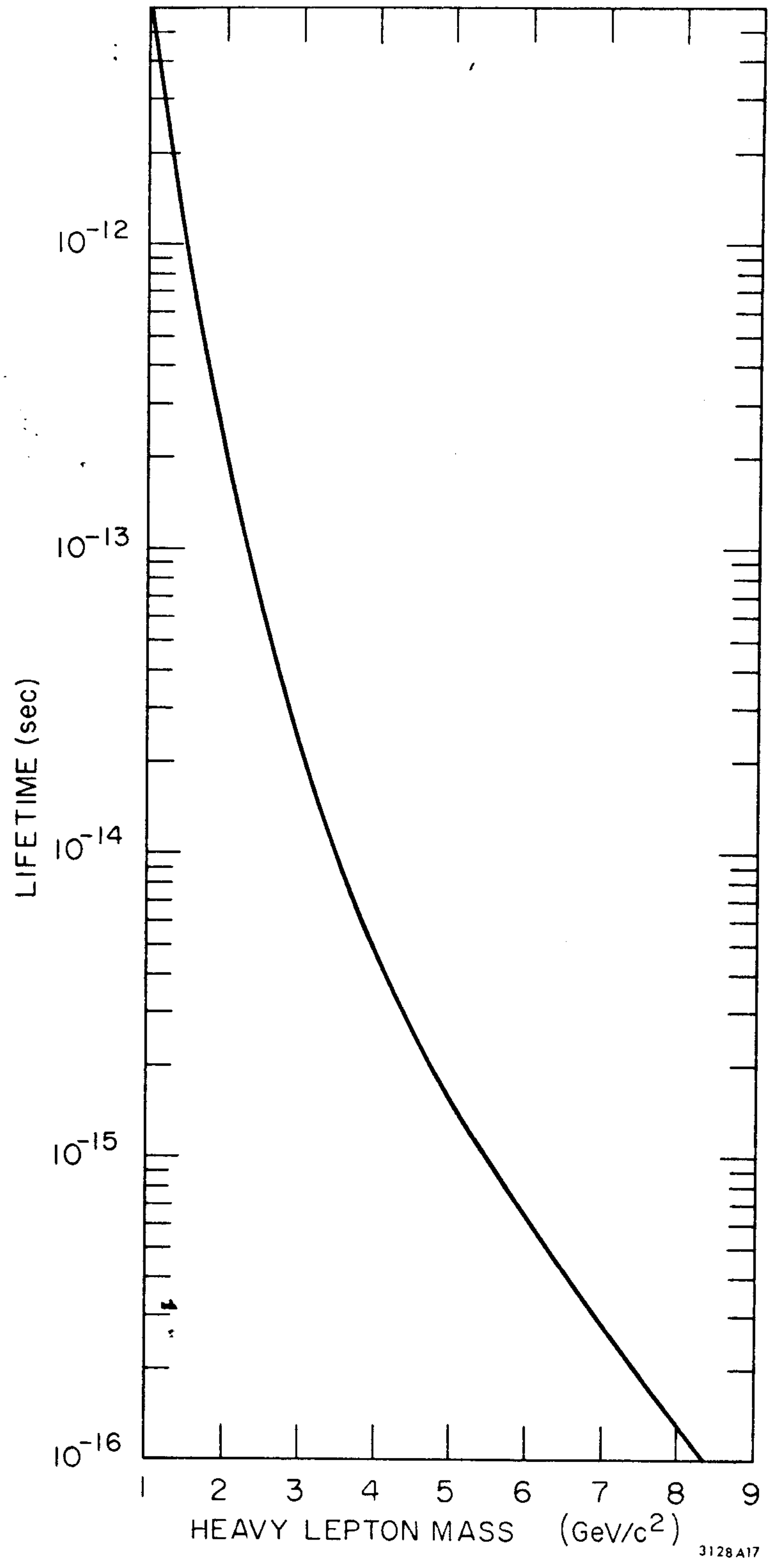

Fig. 3 Lifetime versus mass for a charged lepton with conventional weak interactions, V - A coupling, and a massless neutrino. The conventional weak coupling constants are assumed.

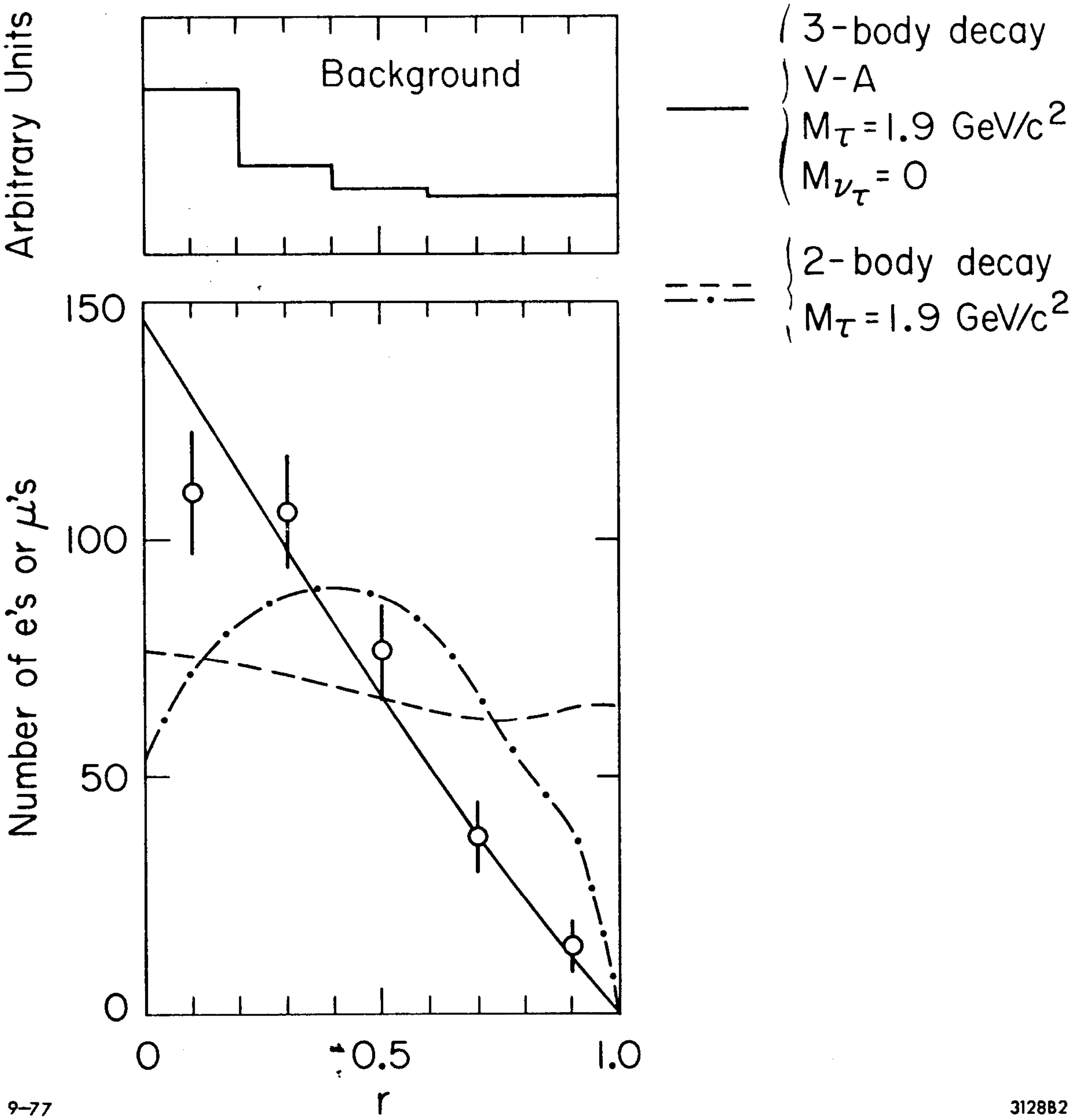

Fig. 4 The momentum spectrum for eμ events, with $3.8 \leq E_{c.m.} \leq 7.8$ GeV, from the SLAC-LBL Magnetic Detector Collaboration[1,2] corrected for background. Here $r = (p - 0.65)/(p_{max} - 0.65)$ where p is the e or μ momenta in GeV/c. The solid theoretical curve is for the three-body leptonic decay of a mass 1.9 GeV/c^2 τ; the dashed theoretical curve is for the two-body decay of an unpolarized boson; and the dash-dotted theoretical curve is for the two-body decay of a boson produced only in the helicity = 0 state.

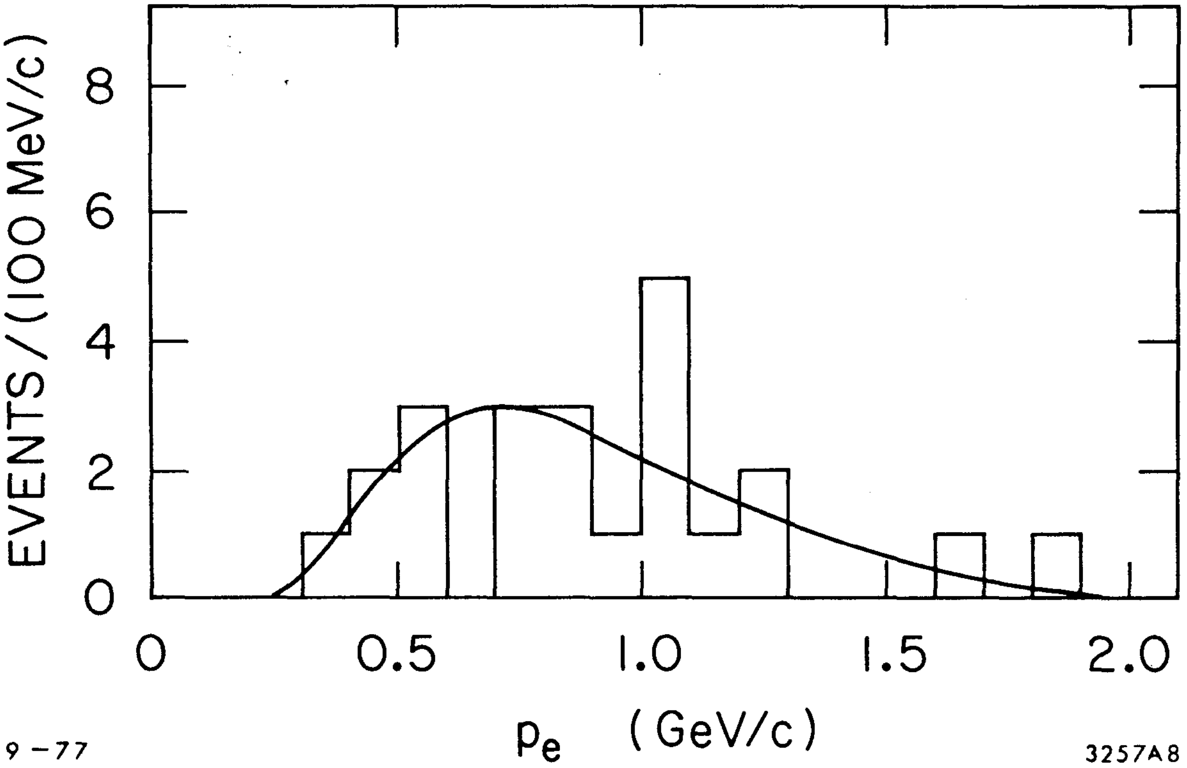

Fig. 5 The electron momentum spectrum for eμ events with $4.0 \leq E_{c.m.} \leq 5.0$ GeV from the PLUTO Group,[14] compared with the theoretical curve for the three-body leptonic decay of a mass 1.9 GeV/c^2 τ.

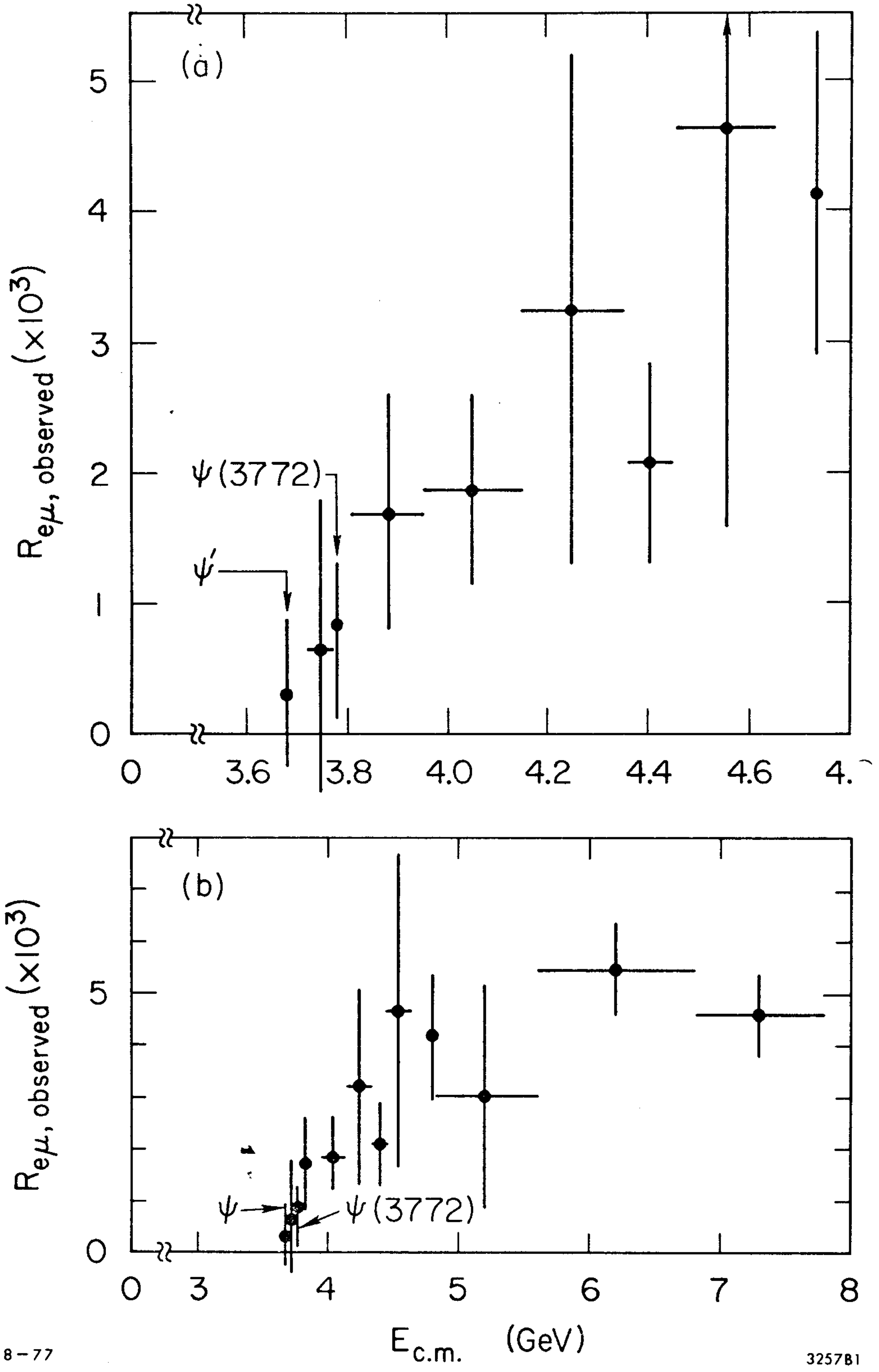

Fig. 6 $R_{e\mu,\text{observed}}$ for (a) $3.6 \leq E_{c.m.} \leq 4.8$ GeV and (b) $3.6 \leq E_{c.m.} \leq 7.8$ GeV.

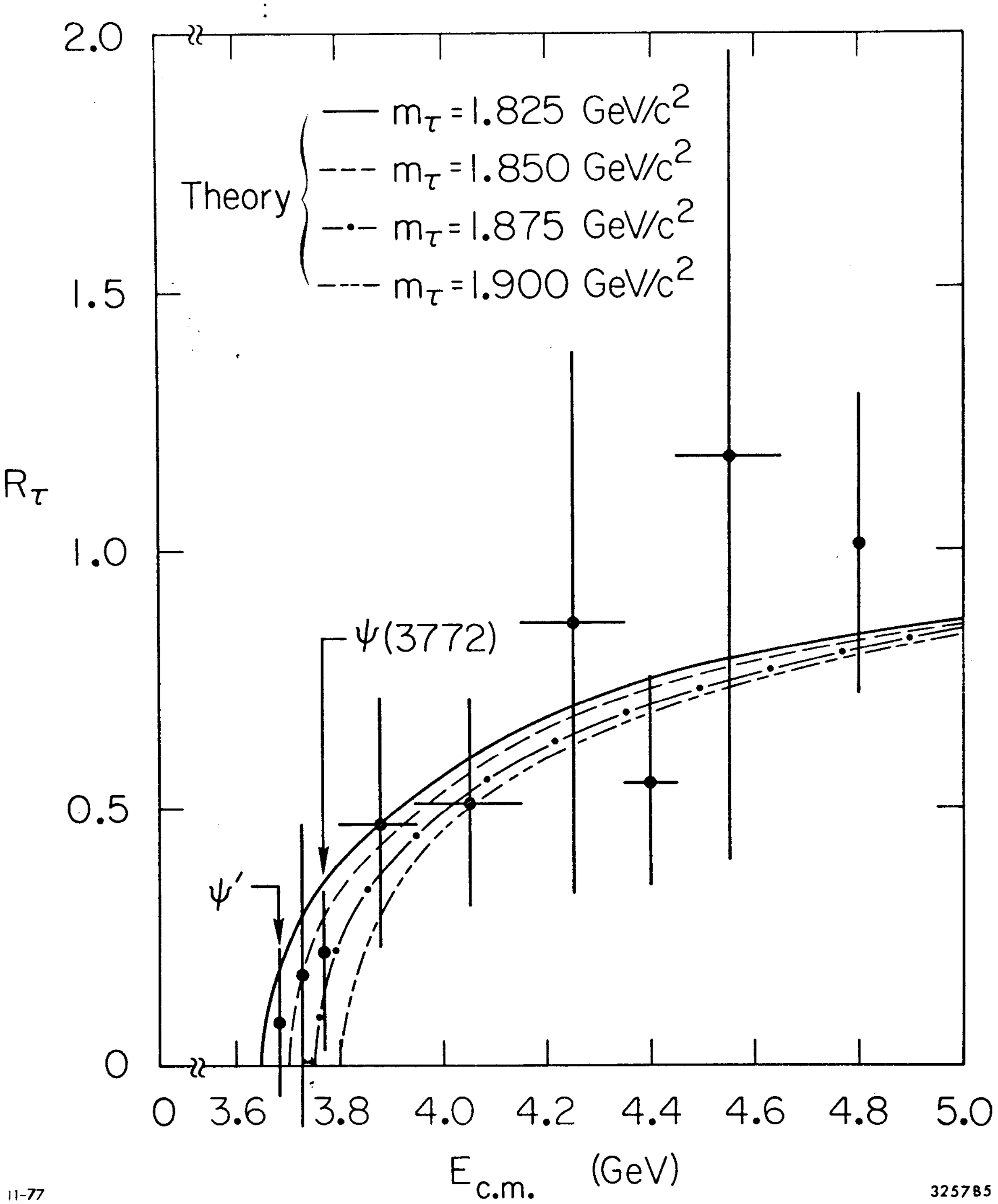

Fig. 7a R_τ for $3.6 \leq E_{c.m.} \leq 4.8$ GeV, compared with the theoretical R_τ for various τ masses.

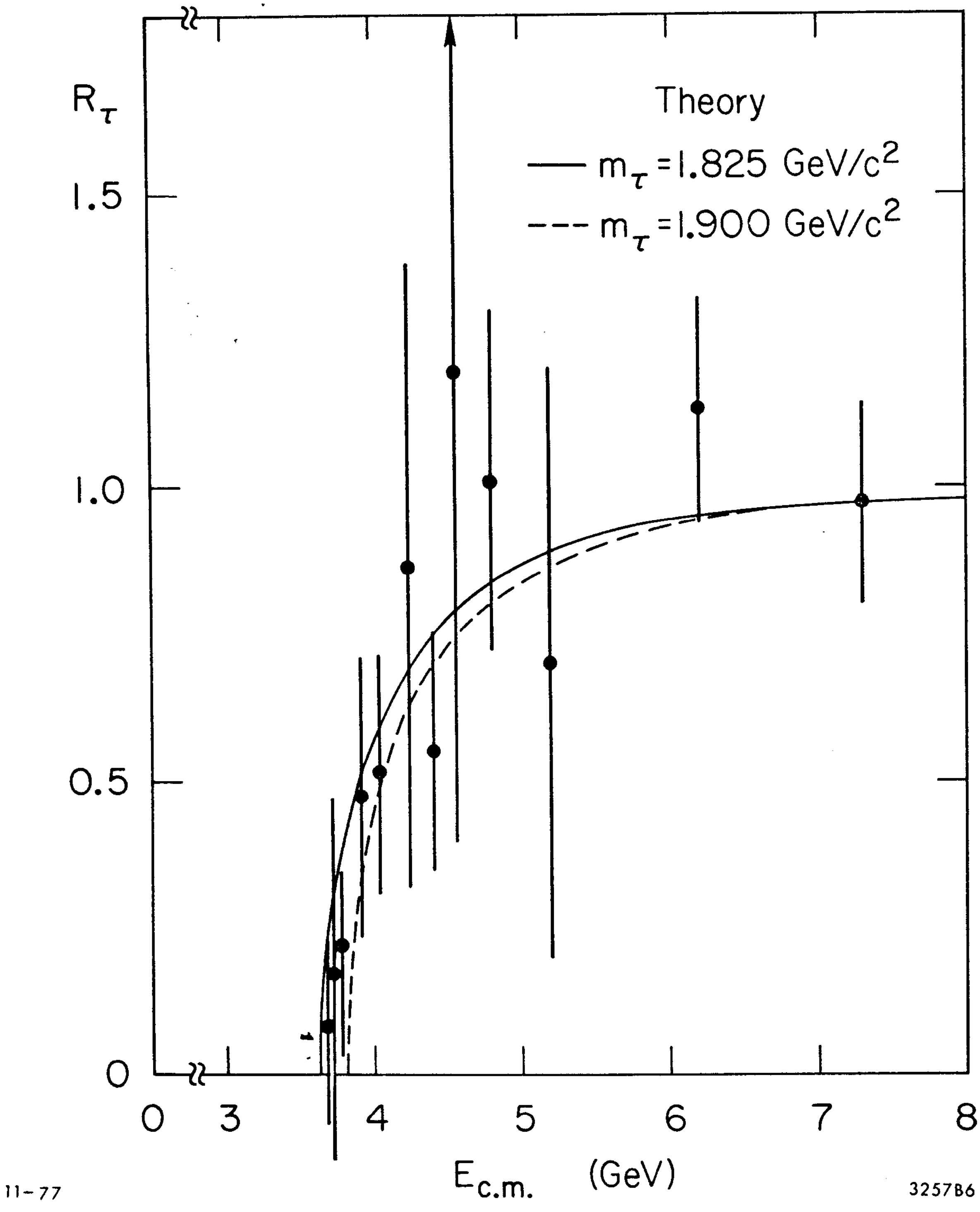

Fig. 7b R_τ for $3.6 \leq E_{c.m.} \leq 7.8$ GeV, compared with the theoretical R_τ for various τ masses.