SLAC-PUB-2153
July 1978
(T/E)

THE TAU HEAVY LEPTON: A RECENTLY DISCOVERED ELEMENTARY PARTICLE*

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ABSTRACT

This paper recounts the history of the discovery of the tau heavy lepton; summarizes the evidence for the tau being a lepton; and discusses known properties of the tau.

Submitted to Nature

*Work supported by the Department of Energy.

I. LEPTONS AND HADRONS

There is now very substantial evidence for the existence of a new elementary particle called the tau (τ)[1]. Elementary particles are the simplest forms of matter and through studying them, we hope to understand the fundamental nature of matter. As I will show in this article, the properties of the tau are analogous to the properties of the electron (e) and muon (μ). Therefore, the tau has been classified as a member of the lepton particle family (Table I) even though it is much heavier than the e or μ, having a mass of almost 1800 MeV/c^2. The discovery of this new lepton has particular significance in the world of elementary particles because the lepton family has so few members, and because the τ is so relatively massive. One purpose of this paper is to discuss that significance; the other purposes are to outline the evidence for the existence of the τ and to describe its properties as far as we know them.

The first evidence[2] for the existence of τ leptons was found at the SPEAR electron-positron colliding beams facility of the Stanford Linear Accelerator Center (SLAC). The τ's were produced through the electron-positron annihilation reaction

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \; ; \qquad (1)$$

a simple reaction whose theory is well understood. All subsequent studies[3] of the τ at SPEAR and at DORIS, the electron-positron colliding beams facility at the Deutches Elektronen-Synchrotron (DESY), have used reaction (1). Therefore, in this paper, I shall limit my discussion of the production of τ's or other heavy leptons to this reaction.

The unique position of the leptons in elementary particle physics is illustrated by Table II which summarizes the differences between the lepton and hadron families. The hadrons are composite particles made up of constituents we call quarks[4]; the hadrons interact through the strong interactions which at high energies can lead to very complicated reactions in which many hadrons are produced; and the hadrons occur in more than one hundred different types. In stark contrast: the leptons are simple, non-divisible particles; they do not partake in the strong interactions; even at high energies the reactions in which the leptons directly play a role only produce a few particles[5]; and as I have already noted, there are only a few types of leptons. Therefore, the leptons, in contrast to the hadrons, are truly elementary particles; and in studying the leptons we are studying directly the simplest forms of matter which we have yet discovered. The quarks may also be truly elementary particles; however, we do not know if they can be isolated in a free state; and at present, we can only study them very indirectly. Until the discovery of the τ one might have thought that the simplicity and truly elementary nature of the leptons were connected with their small mass. The e, the μ, and their neutrinos have less mass than the lightest hadron--the π^o with a mass of 135 MeV/c^2. (The name lepton means "light one" in Greek.) However, the τ is heavier than many hadrons and its existence once and for all separates the concept of a particle's elementarity from the size of a particle's mass. Indeed, we emphasize this by referring to the τ by the oxymoron "heavy lepton."

II. LEPTON CONSERVATION AND THE SEQUENTIAL HEAVY LEPTON MODEL

Our search for heavy leptons which led to the discovery of the τ was based upon the sequential heavy lepton model[6]. We could have used other models[7,8] in our search; however, the elegance, symmetry, and simplicity of the sequential model appealed to us. To our surprise, the properties of the τ are consistent with its being a sequential heavy lepton! The sequential model is based upon extending the concept of lepton conservation to heavy leptons. Lepton conservation is the explanation of why reactions such as

$$\mu^- \not\rightarrow e^- + \gamma \tag{2}$$

or

$$e^+ + e^- \not\rightarrow \mu^+ + e^- \tag{3}$$

do <u>not</u> occur. Taking reaction (2) as the simplest example, lepton conservation asserts: (a) that the e and the μ each possess a unique property not possessed by the other particle, (b) that those properties cannot be destroyed in a reaction, and hence (c) that a μ cannot change into an e. This concept is codified in a more mathematical form in Table III where the e^- and its associated neutrino ν_e are assigned the "electron lepton number" $\eta_e = +1$, and so forth. Lepton conservation then states that in any reaction the separate sums of η_e and η_μ on one side of a reaction must equal their respective sums on the other side. For example: reaction (2) does not occur because on the left side $\eta_e = 0$ and $\eta_\mu = 0$ while on the right side $\eta_e = +1$ and $\eta_\mu = -1$. In contrast to reaction (3), the reaction

$$e^+ + e^- = \mu^+ + \mu^- \tag{4}$$

can occur because η_e and η_μ are zero on both sides. Indeed, reaction (4) is a well known and well studied reaction.

An important consequence of lepton conservation is that decay of the μ to an e occurs not through the simple reaction in equation (1) but through the complicated reactions

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e \qquad (5a)$$

$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e \qquad (5b)$$

It is important to note that the decays in equation (5) take place through the weak interactions. The μ cannot decay through the strong interactions because it is not affected by the strong interactions; and the μ cannot decay through the electromagnetic interaction because the electromagnetic decay channel, reaction (2), violates lepton conservation. Lepton conservation also dictates how hadrons can decay to leptons. For example, the decays

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad (6a)$$

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

can and do occur.

Before returning to the sequential heavy lepton model, I should remark that we have no deep understanding of lepton conservation; that is, we do not know how or in what way a μ differs from an e. As an experimenter, I regard lepton conservation simply as an empirical rule whose underlying significance we may one day understand through further experimentation with leptons.

The sequential heavy lepton model[6] simply assumes that there is a mass sequence of charged leptons and associated neutrinos:

Charged lepton	Associated neutrino
$e^{\pm}$	ν_e, $\bar{\nu}_e$
$\mu^{\pm}$	ν_μ, $\bar{\nu}_\mu$
$\tau^{\pm}$	ν_τ, $\bar{\nu}_\tau$
.	.
.	.
.	.

It further assumes that each type of lepton has a unique lepton number which is separately conserved in every reaction. Using this idea and assuming that the mass of the τ (m_τ) is sufficiently large, the τ should decay through the reactions

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e \tag{7a}$$

$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \tag{7b}$$

These decay channels are analogous to the μ decay channel in reaction (5a): they take place through the weak interactions and they obey lepton conservation. (In the remainder of this paper, I shall only write decay reactions for the τ^- since the τ^+ decay can simply be obtained by reversing the signs of all the charged particles and interchanging neutrinos and antineutrinos.) An exciting consequence of this model is that a sufficiently massive heavy lepton ought to decay to hadrons--just the reverse of reaction (6) in which a hadron decays to leptons. For example, decays such as

$$\begin{aligned} \tau^- &\rightarrow \nu_\tau + \pi^- \\ \tau^- &\rightarrow \nu_\tau + \pi^- + \pi^0 \end{aligned} \tag{8}$$

and

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

should occur. These decays would occur through the weak interactions.

The lifetime of a sequential heavy lepton decreases as its mass increases because as the mass of a particle increases it becomes more unstable, and because more decay channels, such as those in equation (8), are available. If one assumes that the sequential heavy lepton has the same type and strength of weak interactions as the μ and e, then its lifetime can be calculated[8,9,10], (Fig. 1). When we began our search, we already knew that there were no sequential heavy leptons with masses less than 1000 MeV/c^2. This lower limit had been set by experiments[11,12] carried out at the ADONE electron-positron colliding beams facility at Frascati, Italy. Therefore, as shown in Fig. 1, the heavy leptons we were seeking would have lifetimes so short that they would decay before reaching our detection apparatus; hence they would have to be detected through their decay products. How this was done is the subject of the next section.

III. THE EVIDENCE FOR THE TAU

A. eμ Events. We used the SLAC-LBL magnetic detector, Fig. 2, at SPEAR for our search. This detector gathered information on electron-positron annihilation events in which at least two charged particles appeared in the apparatus. We knew that the vast majority of these events had nothing to do with heavy leptons. However, we searched through the events for the events in which only two particles were observed: one an electron and the other a muon, the two particles having opposite electric charge.

These eμ events could come from the reaction and decay sequence

$$
\begin{array}{ccccc}
e^+ + e^- \rightarrow & \tau^+ & + & \tau^- & \\
 & \downarrow & & \downarrow & \quad (9) \\
 & e^+ + \bar{\nu}_\tau + \nu_e & & \mu^- + \nu_\tau + \bar{\nu}_\mu &
\end{array}
$$

since neutrinos pass unobserved through the detector, Fig. 3. This is a strong signature for heavy lepton production because lepton conservation forbids the production of only an e and μ in the final state; and there are very few reactions in which only an e, a μ and neutrinos are produced. Furthermore, reaction (9) is distinctive because there is on the average a large amount of energy carried off by the neutrinos and hence unobserved.

In the winter of 1974-1975 we began to find[2] eμ events when the total energy, E_{total}, of the e^+ and e^- beams at SPEAR was above about 4000 MeV. Since in the reaction $e^+ + e^- \rightarrow \tau^+ + \tau^-$ two τ's must be produced, this meant that the mass of the τ had to be less than 2000 MeV/c^2. We were also able to place a lower limit of about 1600 MeV/c^2 on m_τ by studying the momentum distribution of the e and μ in reaction (9). By the summer of 1976, we were able to show[13] that all the properties of the 105 eμ events we had by then accumulated were consistent with these events being from heavy lepton production.

Figure 4 illustrates one of the consistency tests. The momentum spectrum of the e or the μ produced in reaction (9) through the three-body decays of the τ's, reactions (7), is described by the solid curve in Fig. 4a. If the τ decayed differently, say by a two-body decay $\tau \rightarrow e + \nu$ or $\tau \rightarrow \mu + \nu$, then the dashed curve would result. Figure 4b shows our measurement[14] of the e and μ spectrum. We could not detect the slow e's or μ's required for the low momentum, ascending part of the solid curve in Fig. 4a; however, our measurement was clearly consistent with the high momentum part of that curve. And our measurement is clearly inconsistent with the two-body decay of the τ. A later but more complete measurement of the e momentum spectrum from eμ events is shown in Fig. 4c. This was obtained by J. Burmeister et al.[15] using the PLUTO detector at DESY.

Of course the existence of a heavy lepton is not demonstrated simply by showing that eμ events have properties consistent with that of a lepton. One must also show that there is no other source of the eμ events. One alternative source which was often suggested was the production and decay of a pair of charmed mesons.

$$
\begin{array}{cccc}
e^+ + e^- \rightarrow & D^+ & + & D^- \\
& \downarrow & & \downarrow \\
& e^+ + \nu_e + \text{hadrons} & & \mu^- + \bar{\nu}_\mu + \text{hadrons}
\end{array} \qquad (10)
$$

If the final hadrons were not detected, then reaction (10) might resemble reaction (9). My colleague, Gary J. Feldman, was able to show[13] that the majority of our eμ events did not have undetected hadrons accompanying them.

A very clear proof that eμ events did have accompanying hadrons, detected or not detected, was produced by the group using the PLUTO detector. They showed[15] that in a data sample which contained 23 eμ events there were no events of the type eμ + hadrons.

There was another important result of demonstrating that eμ events did not have accompanying hadrons. It showed that the reaction

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \tag{11}$$

and not the reaction

$$e^+ + e^- \rightarrow \tau^+ + \tau^- + \text{hadrons} \tag{12}$$

was the source of eμ events. We do not expect reaction (12) to be a source of heavy leptons, and the absence of reaction (12) was an additional proof that the τ was a lepton.

B. μ-Hadron Events. If we accepted the eμ events as coming from the production and decay of a pair of τ heavy leptons, then the sequential heavy lepton model and the mass of the τ being greater than 1600 MeV/c^2 would require the existence of other rather strange types of events. Thus the reaction and decay sequence

$$\begin{array}{ccccc} e^+ + e^- \rightarrow & \tau^+ & + & \tau^- \\ & \big\downarrow & & \big\downarrow \\ & \mu^+ + \nu_\mu + \bar{\nu}_\tau & & \text{hadron} + \nu_\tau \end{array} \tag{13}$$

should occur, where the $\tau^- \rightarrow$ hadrons + ν_τ decay is one of the types in equation (8). These events are called μ-hadron events. We were particularly interested in the μ-one-charged-hadron events in which there was just one charged hadron, because such events were unlikely to come from other sources such as charmed meson production. In 1976 a small sample of μ-one-charged-hadron events was found at SPEAR by Cavilla-Sforza et al.[16]. Later in 1976, after having added an improved muon detection system to the SLAC-LBL magnetic detector, Fig. 2, we were able to report the finding of a large sample of μ-one-charged-hadron events.[17] And physicists using the PLUTO detector at DORIS also found[18] such events. As with the eμ events, all the properties of these μ-hadron events were consistent with the τ being a heavy lepton.

C. e-Hadron Events. The symmetry of the sequential heavy lepton model with respect to τ decays to μ's and e's, equation (7), requires that e-hadron events as well as μ-hadron events exist. In order to find such events it was necessary to have a detector which could precisely separate electrons from hadrons. The DASP detector[19] at DORIS was the first e^+e^- colliding beams detector to have that ability. As shown in Fig. 5, this separation is obtained by using Cerenkov counters. In 1977 the group using DASP was able to find[20] the e-one-charged-hadron events expected from the reaction

$$e^+ + e^- \to \underset{\downarrow \; e^+ + \nu_e + \bar{\nu}_\tau}{\tau^+} + \underset{\downarrow \; \text{hadrons} + \nu_\tau}{\tau^-} \; ; \qquad (14)$$

and more recently physicists using a very large solid angle Cerenkov detector at SPEAR, called DELCO[21], have found a very large sample of e-one-charged-hadron events. With the finding of these events, and the determination that their properties were consistent with heavy leptons as their source, the discovery stage of the work on the τ lepton ended. We are now in the stage of detailed study of the τ and measurement of its properties. This is the subject of the next section.

IV. PROPERTIES OF THE τ

A. Mass of the τ. The most recent measurement of the mass of the τ carried out by the DELCO collaboration[22] yields

$$m_\tau = 1782 \begin{smallmatrix} +\,2 \\ -\,7 \end{smallmatrix} \ \text{MeV}/c^2 \qquad (15)$$

This value was obtained by measuring the cross section, σ_{eh}, for the production of e-one-charged-hadron events as a function of the energy E_{total}. If the τ is a lepton, σ_{eh} should obey the equation

$$\sigma_{eh} = P_{eh} \frac{4\pi\alpha^2}{3E_{total}^2} \left[\frac{\beta(3 - \beta^2)}{2}\right] \tag{16a}$$

Here P_{eh} is the probability that a τ pair decays to an e-one-charged-hadron event; α is the fine structure constant; and $\beta = v/c$ where v is the velocity of the τ and c is the velocity of light. It is conventional in e^+e^- annihilation physics to remove the E_{total}^2 term in equation (16a) by defining the ratio

$$R_{eh} = \sigma_{eh}/\sigma_{e^+e^- \to \mu^+\mu^-} = P_{eh} \left[\frac{\beta\ (3 - \beta^2)}{2}\right] \tag{16b}$$

Here

$$\sigma_{e^+e^- \to \mu^+\mu^-} = \frac{4\pi\ \alpha^2}{3\ E_{total}^2} \tag{16c}$$

is the cross section for reaction (4). In equation (16b) as E_{total} increases, β approaches 1 and R_{eh} approaches a constant, namely P_{eh}. Figure 6a shows[22] R_{eh}. The E_{total} where R_{eh} begins to rise above zero is called the threshold energy, E_{thresh}, and m_τ is given by $E_{thresh}/2$. The behavior of R_{eh} in Fig. 6a and of $R_{e\mu}$ in Fig. 6b are consistent with equation (16b) and hence consistent with the τ being a lepton. ($R_{e\mu} = \sigma_{e\mu}/\sigma_{e^+e^- \to \mu^+\mu^-}$ where $\sigma_{e\mu}$ is the cross section for producing eμ events.)

An older value of m_τ obtained by the DASP collaboration[20] is

$$m_\tau = 1807 \pm 20\ \text{MeV}/c^2$$

B. Mass of the ν_τ. The DELCO collaboration[21] gives an upper limit of

$$m_{\nu_\tau} \leq 250 \text{ MeV}/c^2$$

with 90% confidence; m_{ν_τ} could be zero. The masses of the e and μ neutrinos may also be zero (Table I).

C. Lifetime of the τ. The PLUTO collaboration finds

$$\tau \text{ lifetime} \leq 3.5 \times 10^{-12} \text{ sec}$$

with 95% confidence. The theoretical prediction for this lifetime is 2.5×10^{-13} sec.

D. The Coupling of the τ to the ν_τ. The data favors[3,21] V-A coupling of the τ to the ν_τ. This, of course, is the coupling predicted by conventional weak interaction theory.

E. Spin of the τ. Measurement of the behavior of the cross section for $e^+ + e^- \rightarrow \tau^+ + \tau^-$ as a function of E_{total} strongly favor[3,21] the spin of the τ being 1/2. This has been discussed in detail by Tsai[23]. The spins of the e, μ, and their neutrinos are also 1/2, hence the τ on the basis of its spin is a conventional lepton, if we can call a heavy lepton conventional.

F. Decay Modes of the τ. Table IV lists the observed decay modes of the τ and compares the measured fractional decay rates with the theoretical predictions. These predictions are recent calculations of Y. S. Tsai[10] based on conventional weak interaction theory and V-A coupling. In all the measured modes the data and the theory agree; this is another reason for believing that the τ is a lepton.

G. Lepton Type of the τ. All measurements on the τ are consistent with its being a sequential heavy lepton with a unique and separately conserved lepton number. It has been shown[24,25] that the τ^- does <u>not</u> have the lepton number of the μ^+ or μ^-, nor does it have the lepton number of the e^+[26]. However, it is possible the τ^- could have the lepton number of the e^- -- we have not been able to rule out this possibility experimentally. But this leads to an ugly theory in which the decay

$$\tau^- \rightarrow e^- + \gamma ,$$

which has <u>not</u> been observed, must be prohibited or suppressed by means other than lepton conservation. My prejudice is that the sequential heavy lepton model, which has guided us so well, will in the end be the correct choice.

<u>H. Future Work on the τ.</u> Studies of the properties of the τ are continuing at SPEAR and DORIS and will also be undertaken at the three new, higher energy, electron-positron colliding beams facilities. These new facilities are PEP at SLAC and PETRA at DESY each with a maximum E_{total} of about 36 GeV, and CESR at Cornell with a maximum E_{total} of about 18 GeV. One direction of these new studies will be to learn more about the τ's decay mode. For example: do decay modes such as $\tau^- \rightarrow K^- + \nu_\tau$ exist at the predicted 1% decay rate? Or does the decay mode $\tau^- \rightarrow e^- + e^+ + e^-$, forbidden by the sequential lepton model, but predicted by other models, exist?

At the higher energy e^+e^- facilities, we can test in more detail our present conclusion that the τ is a lepton. We have come to this conclusion by using Occam's razor and asserting that a charged particle is <u>either</u> a lepton or a hadron. But suppose the τ is some very strange new kind of particle which is 90% leptonic and 10% hadronic in nature. We might expect that the 10% hadronic component would show itself at very high energies through the reaction

$$e^+ + e^- \rightarrow \tau^+ + \tau^- + \text{hadrons}$$

If, however, the reaction

$$e^+ + e^- \rightarrow \tau^+ + \tau^-$$

continues to behave at very high energies as it does at the presently available energies, then we shall have additional proof that the τ is a pure lepton.

V. LEPTONS AND QUARKS

I will conclude this paper with two remarks on the possible impact of the discovery of the τ on elementary particle physics. First a short remark. We have never understood how to calculate the masses of elementary particles. For example, we do not have the least idea why the mass of the electrons is 0.51 MeV/c^2. Perhaps the discovery of the τ will provide a clue as to how to calculate masses because now for the first time we know the masses of <u>three</u> truly elementary particles: the e, μ, and τ. (The neutrinos appear to have zero mass which is not much of a help to calculations.)

My second and longer remark is that, as I noted in Section I, it has become customary to regard the hadrons as composite particles made up of more elementary particles -- the quarks. One then regards the quarks and leptons as two different but similar families of truly elementary particles.

Furthermore, in some theories the numbers of leptons are equal to the numbers of quarks. For example, before the discovery of the τ there seemed to be four leptons and four quarks:

$$\text{Leptons:}\quad e,\ \mu,\ \nu_e,\ \nu_\mu$$

$$\text{Quarks:}\quad u,\ d,\ s,\ c$$

The discovery of the τ upset this equality. However, it may be restored as follows: If the τ is a sequential heavy lepton, its neutrino, ν_τ, is unique and constitutes a sixth lepton. The discovery of the upsilon particle indicates the existence of a fifth quark called b. If we are then willing to believe that a sixth quark, usually called t, also exists, there is again lepton-quark numerical equality:

$$\begin{array}{ll}\text{Leptons:} & e,\ \mu,\ \tau,\ \nu_e,\ \nu_\mu,\ \nu_\tau \\ \text{Quarks:} & u,\ d,\ s,\ c,\ b,\ t\end{array} \tag{17}$$

Many elementary particle physicists would like to see this closed system of twelve elementary particles, with the addition of the intermediate bosons $W^\pm$, Z^o, constitute the fundamental nature of matter[27]. After all, such closed systems of elementary constituents have played crucial roles in physics up to now. We explain the long series of atoms as being made of different combinations of electrons around a nucleus; and we explain the hundreds of different kinds of nuclei by different combinations of neutrons and protons. If the system of truly elementary particles is closed as in equation (17), then we will also be able to explain the hundred or more kinds of hadrons as various combinations of quarks. And the lepton will remain a relatively simple and sparse family with the τ being the only heavy lepton.

There is an alternative possibility which intrigues me. Perhaps the τ is the beginning of a long, or even infinite, series of heavy leptons; and perhaps these leptons are truly elementary, as the e, μ, and τ appear to be. Then the elementary particle physicist will face a situation unique in physics: a large number of related entities whose properties cannot be explained in terms of a much smaller number of more fundamental entities. Then our present ways of theorizing about elementary particles will not work and we will need some radically new ideas. Of course, this is speculation; and for experimenters, there is an obvious task which precedes this speculation. We must find out whether the τ is the first and last of the heavy leptons, or whether it is only the beginning of a sequence of heavy leptons.

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27. I am simplifying here. Most theories also require other particles, such as the gluons, which are supposed to carry the forces between the quarks.

TABLE I

The Lepton Particle Family

Name	Electron	Muon	Tau
Charged lepton	$e^{\pm}$	$\mu^{\pm}$	$\tau^{\pm}$
Charged lepton mass (MeV/c^2)	0.51	105.7	$1782\ ^{+\ 2}_{-\ 7}$
Charged lepton life-time (sec)	stable	2.20×10^{-6}	$< 3.5 \times 10^{-12}$
Associated neutrino	ν_e, $\bar{\nu}_e$	ν_μ, $\bar{\nu}_\mu$	ν_τ, $\bar{\nu}_\tau$
Associated neutrino mass	$< 60\ eV/c^2$ (may be 0.0)	$< 0.57\ MeV/c^2$ (may be 0.0)	$< 250\ MeV/c^2$ (may be 0.0)

TABLE II

Comparison of Leptons and Hadrons

Family	Lepton	Hadron
Structure	Simple particle, no structure or constituents found by experiments.	Composite particle, constituents are quarks
Interacts through strong interactions	No	Yes
Interacts through electromagnetic interaction	Only if charged	Yes, in all cases
Interacts through weak interactions	Yes	Yes
Interacts through gravitational interaction	Yes	Yes
Number of types found so far	6 if ν_τ is unique	More than 100

TABLE III

Values of lepton numbers for various particles. This table assumes the τ is a sequential heavy lepton with its own lepton number η_τ.

Particle	Electron lepton number, η_e	Muon lepton number, η_μ	Tau lepton number, η_τ
e^-, ν_e	+1	0	0
e^+, $\bar{\nu}_e$	-1	0	0
μ^-, ν_μ	0	+1	0
μ^+, $\bar{\nu}_\mu$	0	-1	0
τ^-, ν_τ	0	0	+1
τ^+, $\bar{\nu}_\tau$	0	0	-1
All hadrons	0	0	0

TABLE IV

Comparison of predicted and measured fractional decay rates for the τ. Where several measurements have been made, the range of values is given. Numbers are rounded off to the nearest percent. See Ref. 3 and 21 for details and references.

Decay Mode	Predicted Fractional Decay Rates	Measured Fractional Decay Rates	Groups Making Measurements
$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e$ or $\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu$	16%	16 to 19%	DASP DELCO SLAC-LBL
$\tau^- \to \nu_\tau + \pi^-$	10%	6 to 11%	DELCO SLAC-LBL PLUTO
$\tau^- \to \nu_\tau + \rho^-$	23%	24 ± 9%	DASP
$\tau^- \to \nu_\tau +$ $\geq$ 3 charged hadrons	28%	16 to 32%	DELCO MPP PLUTO SLAC-LBL

FIGURE CAPTIONS

1. Theoretical prediction for the lifetime of a sequential heavy lepton with V-A coupling and conventional weak interactions.

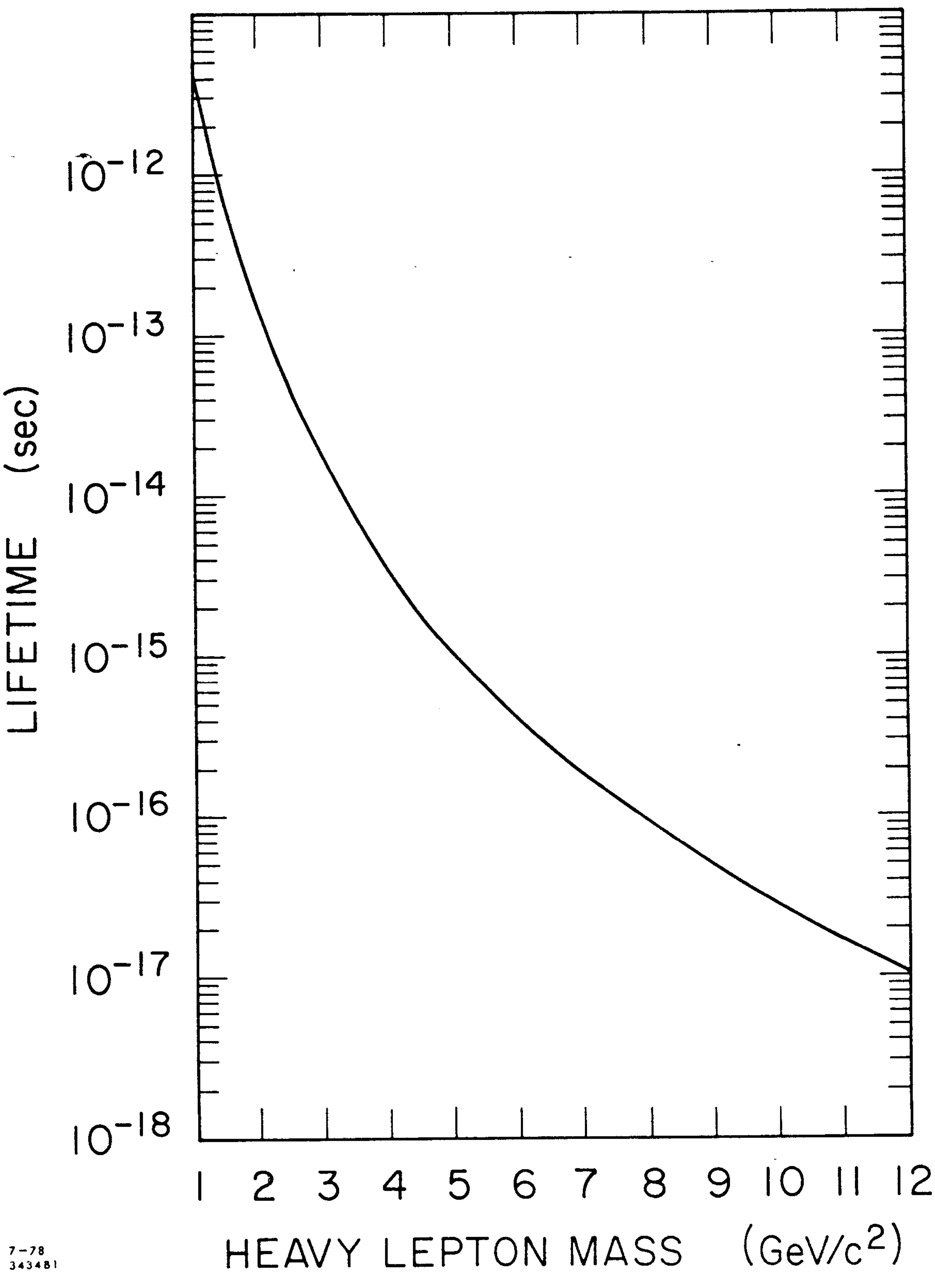
2. A cross-sectional view of the SLAC-LBL magnetic detector. The e^- and e^+ beams move along an axis (perpendicular to the paper) inside the beam pipe. The concrete absorber was an addition to the detector used to detect μ-hadron events from tau decays.

3. A schematic diagram of how eμ events are produced. The τ's are produced at point (a) where the e^+ and e^- beams collide. They decay close to point (a) at points (b) and (c) while still inside the beam pipe (see Fig. 2). Therefore only the decay products reach the detector. However, the neutrinos, indicated by dashed lines, cannot be observed in the detector; only the e and μ are observed.

4. (a) The solid curve is the theoretical momentum spectrum of the e or μ coming from the three-body decay $\tau \rightarrow e$ (or μ) + ν + ν of a moving τ. The dashed curve is the theoretical momentum spectrum of the e or μ from a two-body decay $\tau \rightarrow e$ (or μ) + ν. The comparison of the three-body decay curve with the data is made in (b) for the SLAC-LBL magnetic detector results (Ref. 14) and in (c) for the PLUTO detector results (Ref. 15). The curves in (b) and (c) are corrected for apparatus acceptance and the spread in E_{total}; hence they differ slightly from the curve in (a).

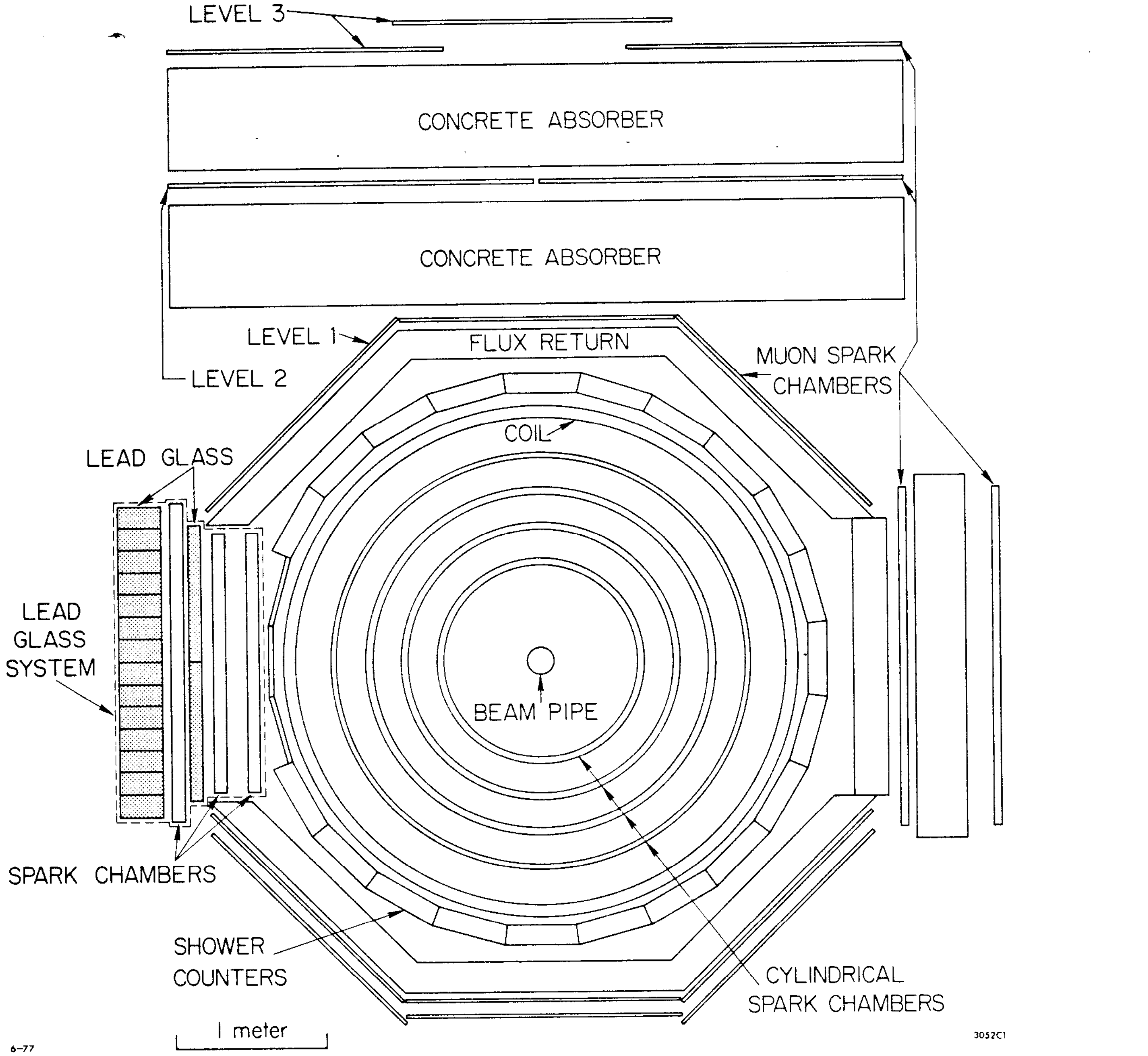
5. A section of the DASP detector slowing the Cerenkov counter. Redrawn from Ref. 19.

6. Behavior of (a) $R_{eh} = \sigma_{eh}/\sigma_{e^+e^- \rightarrow \mu^+\mu^-}$ from DELCO[22]; and of (b) $R_{e\mu} = \sigma_{e\mu}/\sigma_{e^+e^- \rightarrow \mu^+\mu^-}$ from the SLAC-LBL magnetic detector collaboration[3].



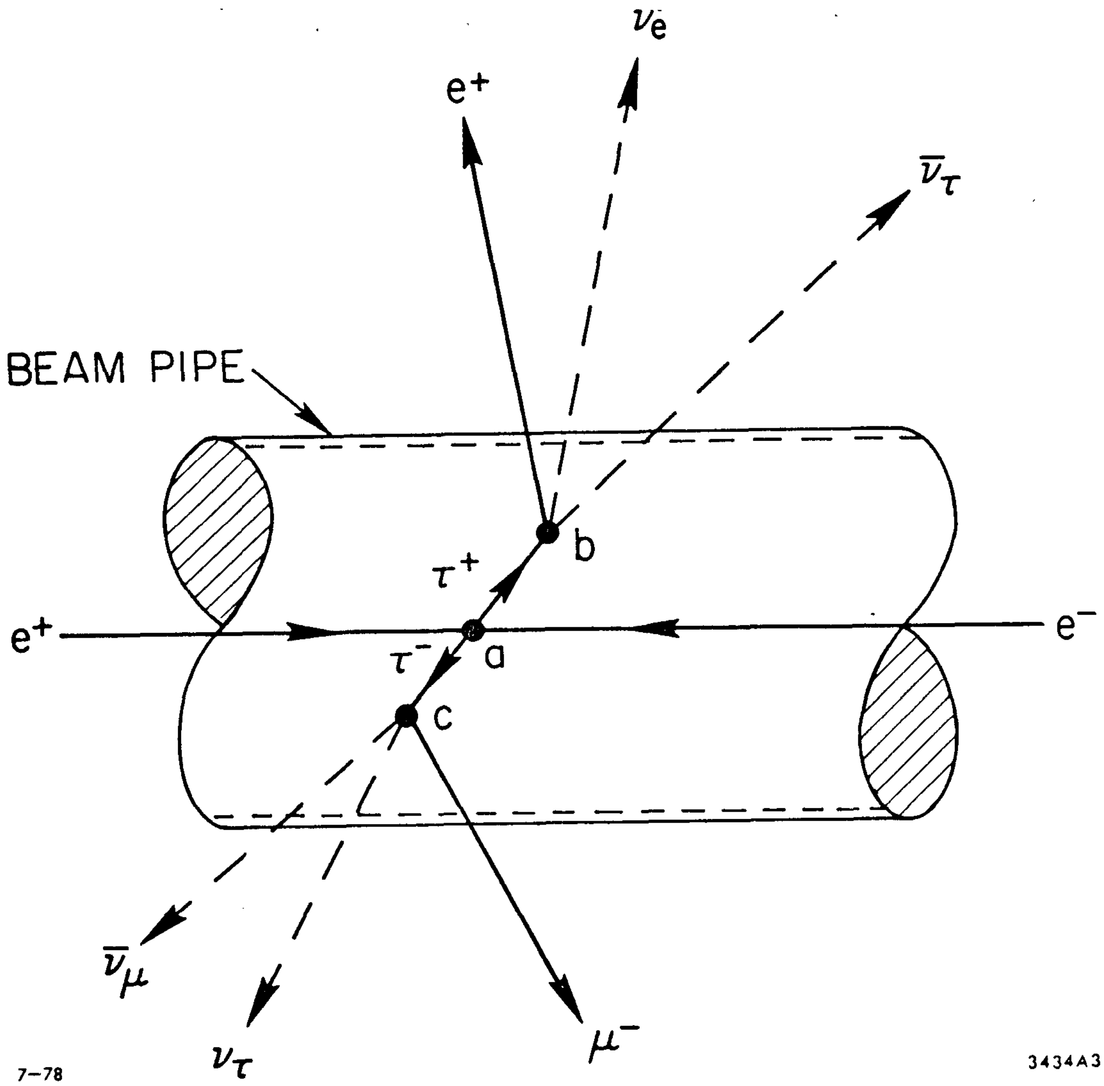
LIFETIME (sec)
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
1 2 3 4 5 6 7 8 9 10 11 12
HEAVY LEPTON MASS (GeV/c^2)
7-78
3434B1

Fig. 1



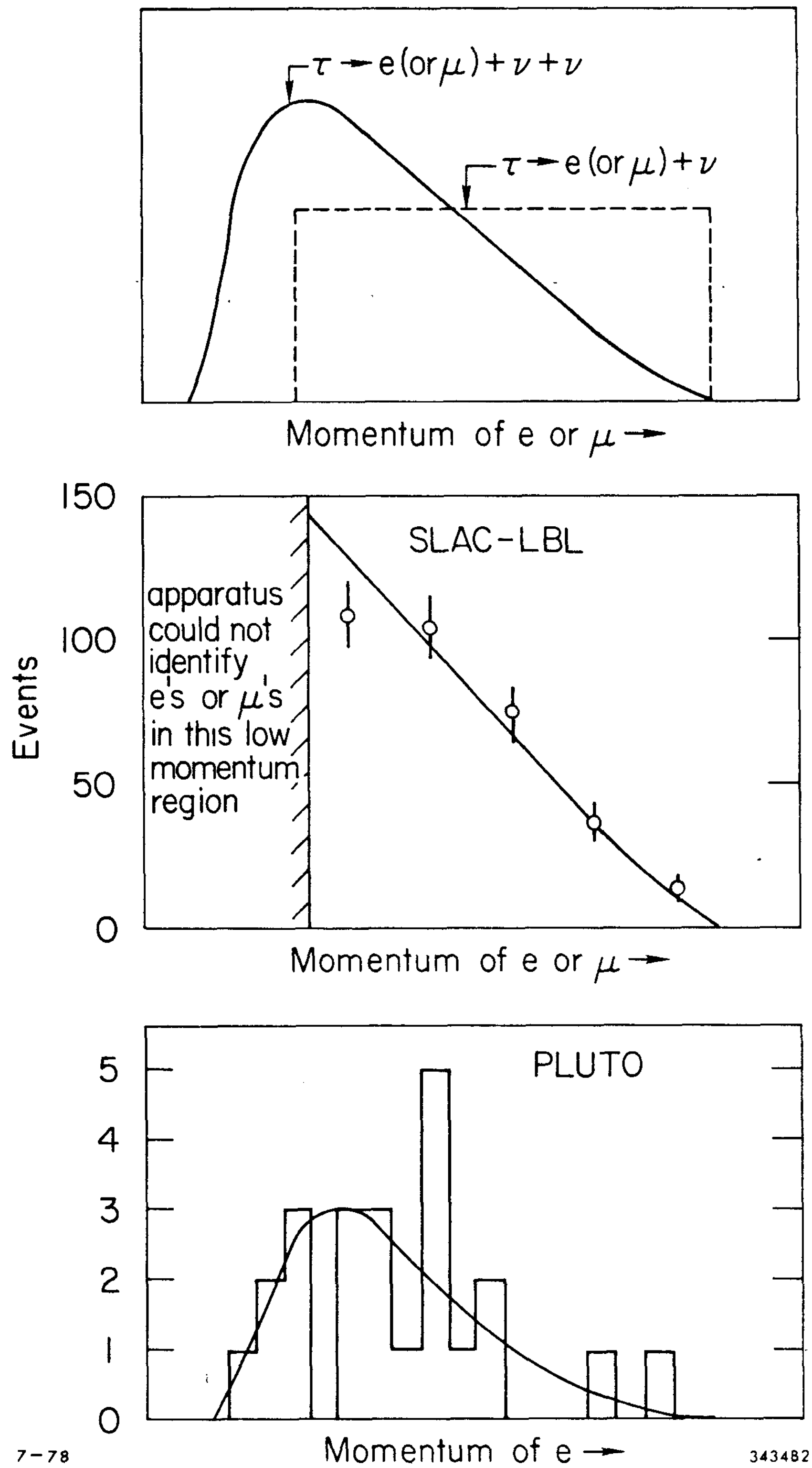
LEVEL 3
CONCRETE ABSORBER
CONCRETE ABSORBER
LEVEL 1
FLUX RETURN
LEVEL 2
MUON SPARK
CHAMBERS
COIL
LEAD GLASS
LEAD
GLASS
SYSTEM
BEAM PIPE
SPARK CHAMBERS
SHOWER
COUNTERS
CYLINDRICAL
SPARK CHAMBERS
1 meter
6-77
3052C1

Fig 2



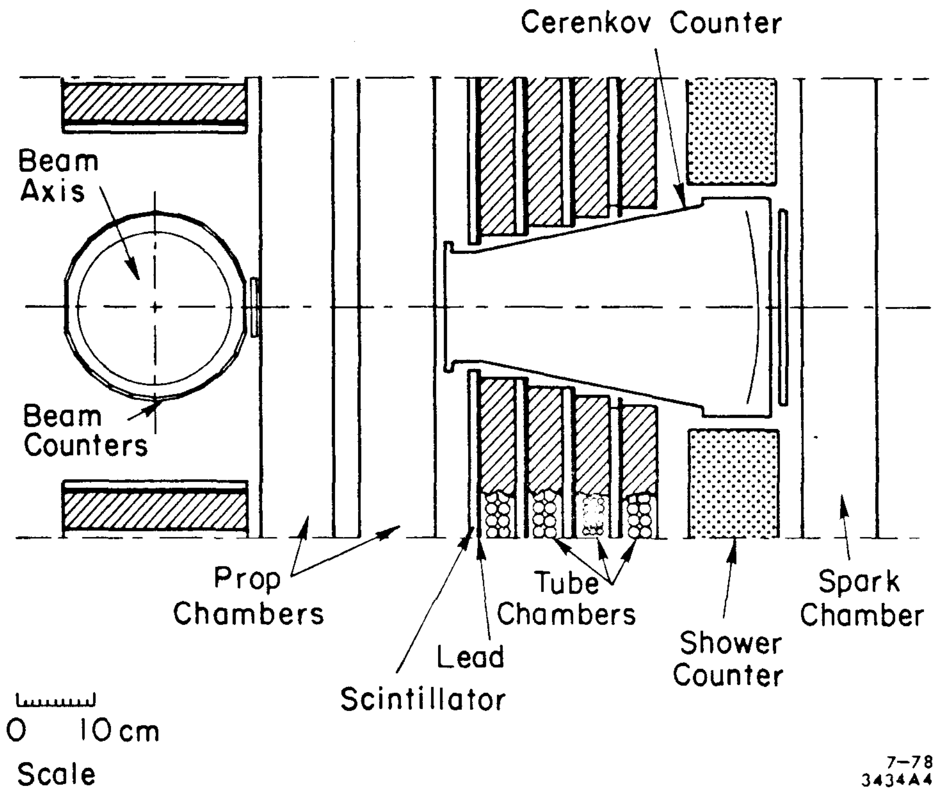
ν_e
e^+
$\bar{\nu}_\tau$
BEAM PIPE
b
τ^+
e^+
e^-
τ^-
a
c
$\bar{\nu}_\mu$
ν_τ
μ^-
7–78
3434A3

Fig. 3



τ → e(or μ) + ν + ν
τ → e (or μ) + ν
Momentum of e or μ →
150
100
50
0
Events
SLAC-LBL
apparatus could not identify e's or μ's in this low momentum region
Momentum of e or μ →
PLUTO
5
4
3
2
1
0
Momentum of e →
7-78
343482

Fig. 4



Cerenkov Counter
Beam
Axis
Beam
Counters
Prop
Chambers
Lead
Scintillator
Tube
Chambers
Shower
Counter
Spark
Chamber
0 10 cm
Scale
7-78
3434A4

Fig. 5

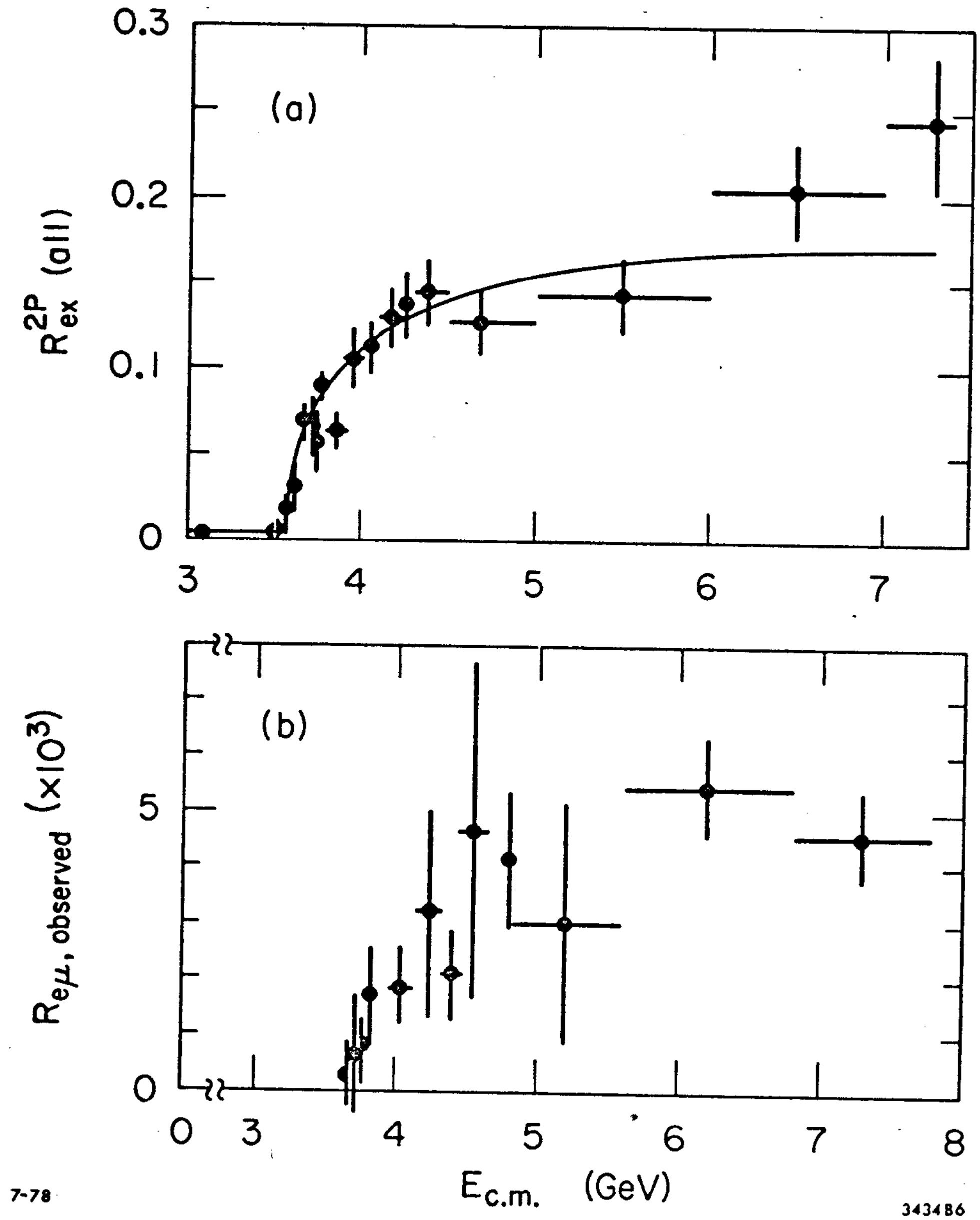

(a)
0.3
0.2
0.1
0
R_{ex}^{2P} (all)
3
4
5
6
7
(b)
5
0
$R_{e\mu}$, observed ($\times 10^3$)
0
3
4
5
6
7
8
$E_{c.m.}$ (GeV)
7-78
3434B6

Fig. 6