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THE TAU LEPTON*

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1. INTRODUCTION

In the last few years there has been an important addition to the known elementary particles — the tau (τ) lepton. It is an important addition first because, to the best of our knowledge, the tau is a fundamental particle. That is, unlike most of the so-called elementary particles such as the proton or pion, the tau is not made up of simpler particles or constituents (see Section 1.1). A second reason for the importance of the tau is that all its measured properties agree with its designation as a lepton. Hence it joins the very small lepton family of particles; a family which previous to the tau's discovery had only four members: the electron (e), its associated neutron (ν_e), the muon (μ) and its associated neutrino (ν_μ). A third reason for the importance of the tau is that along with the discovery of the fifth quark, it appears to confirm some general theoretical ideas about the connection between leptons and quarks. A brief discussion on quarks and the lepton-quark connection is presented in Sections 1.1 and 2.2.

This review is on the experimental work which has been done on the tau, why we believe it is a lepton, the properties of the tau which have been measured, and the experimental work which is still to be done on the tau. I shall present just enough theory to provide a framework for discussing the experimental results. Correspondingly, I shall present a full set of experimental references (up to November, 1979), but only a few general theoretical references.

The history of the discovery of the tau has been reviewed by Feldman (1978a); I shall only outline it here. It is an old idea to look for leptons with masses greater than that of the electron or muon — the so-called heavy leptons. The first searches for a heavy charged lepton using electron-positron collisions were carried out by Bernardini et al (1973) and by Orioto et al (1974) at the ADONE e^+e^- storage ring. They looked for the electromagnetic production process

$$e^+ + e^- \rightarrow \ell^+ + \ell^- \qquad (1.1)$$

where ℓ represents the new lepton. The ADONE storage ring did not have enough energy to produce the tau.

The first evidence for the tau was obtained (Perl 1975, Perl et al 1975), in 1974 at the SPEAR e^+e^- storage ring using the reaction in Equation 1.1. Subsequent experiments at SPEAR, which is at the Stanford Linear Accelerator Center (SLAC), and at the DORIS e^+e^- storage ring at the Deutsches Elektromen-Synchrotron (DESY) confirmed this discovery and measured the properties of the tau. Recent reviews have been given by Kirkby (1979), Flügge (1979), Feldman (1978a) and Tsai (1980).

1.1 The Definition of a Lepton

The definition of a lepton is based upon our experience with the electron, muon, and their associated neutrinos. We classify a particle as a lepton (Perl, 1978) if it has the following properties:

1. The lepton does not interact through the strong interactions. Thus the lepton is differentiated from the hadron particle family, such as the pion, proton and ψ/J, all of which interact through the strong interaction.

2. The lepton has no internal structure or constituents. I shall call a particle without internal structure or constituents a point particle. This is of course always a provisional definition as we never know if by going to higher energy we will be able to detect the internal

structure of a particle or detect its constituents. However the requirement on a lepton is to be understood in contrast to the properties of hadrons. That is, hadronic properties are explained by the hadrons being made up of internal constituents — the quarks. The form factor concept provides a quantitative test of whether a particle has internal structure, and this is discussed in Section 3.2.

3. The lepton interacts through the weak interactions, and if charged through the electromagnetic interaction.

The leptons that we now know share two additional properties which may not be central to the definition of a lepton (Perl 1978).

4. The known leptons have spin 1/2. We can however conceive of particles which have properties one through three listed above and yet have other spins, zero for example (Farrar & Fayet 1979).

5. All the known leptons obey a lepton conservation law. This is defined formally in Section 2.1. I will give an intuitive definition here. A lepton, such as the e^-, possesses an intrinsic property called lepton number, which cannot disappear. This property can either be transferred to an associated neutrino (transferred from e^- to ν_e) or it can be cancelled by combining the lepton with its antilepton (e^- combined with e^+). As with the spin 1/2 we do not know if this is an intrinsic property of all leptons, or is only an accidental property of the known leptons.

1.2 The Tau Lepton

In this review we show that the tau lepton has the crucial lepton defining properties one through three listed in the previous section. It also has property four, namely spin 1/2; and very probably has property five, lepton conservation. It is easiest to get a general picture of the properties of the τ by comparing it with the e and μ (Table 1).

The astonishing property of the tau is its large mass of about 1782 MeV/c^2; 3600 times the electron mass and 17 times the muon mass. Until the tau was discovered many physicists held the vague idea that the simplicity and lack of structure of the leptons was associated with their relatively small mass. The masses of the electron, muon, and their associated neutrinos are all smaller than the mass of the smallest mass hadron, the neutral pion which has a mass of 135 MeV/c^2. Indeed, the word lepton comes from the greek lepto meaning fine, small, thin, or light. However this is certainly not descriptive of the tau whose mass is greater than that of many hadrons; almost twice the proton mass for example. Nevertheless the term lepton has been kept for the tau; often the oxymoron heavy lepton is used.

The relatively large mass of the tau allows it to decay to a variety of final states. Some of the decay modes which have been measured (Section 5) are:

$$\begin{aligned}
\tau^- &\to \nu_\tau + e^- + \bar{\nu}_e \\
\tau^- &\to \nu_\tau + \mu^- + \bar{\nu}_\mu \\
\tau^- &\to \nu_\tau + \pi^- \\
\tau^- &\to \nu_\tau + \rho^- \\
\tau^- &\to \nu_\tau + \pi^- + \pi^+ + \pi^- \\
\tau^- &\to \nu_\tau + \pi^- + \pi^+ + \pi^- + \pi^0
\end{aligned} \tag{1.2}$$

An analogous set of decay modes occurs for the τ^+. Note that in all measured τ decays a neutrino is produced, which indicates that the τ obeys a lepton conservation rule.

I now turn to the development of a theoretical framework for a more technical discussion of the properties of the tau.

2. THEORETICAL FRAMEWORK

I have defined the lepton as a particle which interacts through the weak and electromagnetic forces but not through the strong interactions; and which has no internal structure or constituents. To proceed further in the discussions it is now necessary to build a more restrictive theoretical framework. I shall impose on the lepton conventional weak interaction theory (Bailin 1978, Zipf 1978) and some sort of lepton conservation rule, since these are restrictions which the τ obeys. However the reader should keep in mind that there may exist leptons which do not obey these restrictions.

2.1 Weak Interactions and Lepton Conservation

Consider a charged and neutral lepton pair (L^-, L^o) with the same lepton number $n_L = +1$. Their antiparticles ($L^+, \bar{L}^o$) have lepton number $n_L = -1$. Lepton conservation means that in all reactions the sum of the n_L's of all the particles remains unchanged.

Assuming (a) conventional weak interaction theory, (b) that the L^- is heavier than the L^o, and (c) that there is sufficient mass difference between the L^- and the L^o, the following sorts of decays will occur (Fig. 1).

$$L^- \rightarrow L^o + e^- + \bar{\nu}_e \tag{2.1a}$$

$$L^- \rightarrow L^o + \mu^- + \bar{\nu}_\mu \tag{2.1b}$$

$$L^- \rightarrow L^o + (\text{hadrons})^- \tag{2.1c}$$

In Figure 1.c the quark-antiquark pair $d\bar{u}$ replaces the lepton-neutrino pair, and the quarks convert to hadrons. If the L^o is heavier than the L^- the reverse decays

$$L^o \rightarrow L^- + e^+ + \bar{\nu}_e \tag{2.2a}$$

$$L^o \rightarrow L^- + (\text{hadrons})^+ \tag{2.2b}$$

will occur. We shall assume that lepton-W and quark-W vertices have conventional Weinberg-Salam theory couplings (Bailin 1977, Zipf 1978).

The W propagator diagrams of Figures 1.a - 1.c have become the conventional way to represent weak decays. However when a lepton, such as the τ, has a mass much smaller than the proposed W mass (1.8 GeV/c^2 compared to roughly 100 GeV/c^2) the W propagator has no observable effect. Therefore for some of the discussions of the decays of the τ I shall use Figures 1.d - 1.e, which diagram the old four-fermion coupling of Fermi weak interaction theory (Bjorken & Drell 1964).

2.2 Simple Models for New Charged Leptons

2.2.1 SEQUENTIAL LEPTON MODEL In this model (Perl & Rapidis 1974) a sequence of charged leptons of increasing mass is assumed, each lepton type having a separately conserved lepton number and a unique associated neutrino of smaller, but not necessarily zero, mass. That is, there is a particle sequence:

Charged Lepton	Associated Neutrino
$e^\pm$	$\nu_e, \bar{\nu}_e$
$\mu^\pm$	$\nu_\mu, \bar{\nu}_\mu$
$\ell^\pm$	$\nu_\ell, \bar{\nu}_\ell$
$\vdots$	$\vdots$

(2.3)

Decays of the $\ell^\pm$ through the electromagnetic interaction such as $\ell^\pm \to e^\pm + \gamma$ or $\ell^\pm \to e^\pm + \gamma$ are forbidden. The $\ell^\pm$ can only decay through the weak interaction as described in Section 2.1, namely

$$\begin{aligned}
&\ell^- \to \nu_\ell + e^- + \bar{\nu}_e \\
&\ell^- \to \nu_\ell + \mu \ + \bar{\nu}_\mu \\
&\vdots \\
&\ell^- \to \nu_\ell + (\text{hadrons})^-
\end{aligned} \qquad (2.4)$$

The vertical dots in Equation 2.4 indicate decays to all associated lepton-neutrino pairs of sufficently small masses. In Equation 2.4 and in the remainder of this paper we only list the decay modes of the negatively charged lepton; the decay mode of the positively charged lepton is obtained by changing every particle to its antiparticle. The neutrinos in this model are stable because their associated charged lepton has a larger mass and their lepton number is conserved. The search for the τ was based on this model (Perl 1975) and to the best of our knowledge the τ conforms to this model.

2.2.2 ORTHOLEPTON MODEL In this model (Llewellyn Smith 1977) the new charged lepton, ℓ^-, has the same lepton number as a smaller mass, same sign charged lepton, such as the e^-. Let us use the e^- example. Then we expect that the dominant decay will occur through the electromagnetic interaction

$$\ell^- \to e^- + \gamma \qquad (2.5)$$

However current conservation forbids the ℓ-γ-e vertex from having the usual form $\bar{\psi}_\ell \gamma^\mu \psi_e$ (Low 1965, Perl 1978a); and this decay mode might be suppressed. Therefore decays through the weak interactions such as

$$\begin{aligned} \ell^- &\to e^- + e^+ + e^- \\ \ell^- &\to \nu_e + e^- + \bar{\nu}_e \\ \ell^- &\to e^- + (\text{hadrons})^0 \\ \ell^- &\to \nu_e + (\text{hadrons})^- \end{aligned} \qquad (2.5)$$

could in principle be detected.

2.2.3 PARALEPTON MODEL In this model (Llewellyn Smith 1977, Rosen 1978) the ℓ^- has the same lepton number as a smaller mass, opposite sign charged lepton, such as the e^+. Electromagnetic decays such as $\ell^- \to e^- + \gamma$ are now forbidden. The decay modes through the weak interaction are

$$\ell^- \rightarrow \bar{\nu}_e + e^- + \bar{\nu}_e \qquad (2.6.a)$$

$$\ell^- \rightarrow \bar{\nu}_e + \mu^- + \bar{\nu}_\mu \qquad (2.6b)$$

$$\ell^- \rightarrow \bar{\nu}_e + (\text{hadrons})^- \qquad (2.6c)$$

In this illustration the ℓ^- has the same lepton number as the e^+ and hence as the $\bar{\nu}_e$.

2.3 e - μ - τ Universality

A special case falling within the sequential heavy lepton model is the model in which the e, μ and τ only differ by having (a) different masses, and (b) different and separately conserved lepton numbers. In this model the e, μ and τ have the same spin 1/2, the same electromagnetic interactions, and the same weak interactions. They are all point particles and they are all associated with different massless, spin 1/2 neutrinos. Thus the comparative properties of the charged lepton depend only on the masses being different. We call this e - μ - τ universality.

2.4 Leptons and Quarks

The Weinberg-Salam theory of the unification of weak and electromagnetic interactions (Bailin 1977, Zifp 1978) provides a quantitative model for new leptons which is related to the sequential lepton model. In its current form Weinberg-Salam theory classifies the leptons and quarks into left handed doublets, containing at least

$$\begin{aligned} \text{Leptons} &= \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \\ \text{Quarks} &= \begin{pmatrix} \mu \\ d' \end{pmatrix}_L , \begin{pmatrix} c \\ s' \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L \end{aligned} \qquad (2.7)$$

and right handed singlets, containing at least

$$\begin{aligned} \text{Leptons} &= e_R,\ \mu_R,\ \tau_R \\ \text{Quarks} &= u_R,\ d'_R,\ c_R,\ s'_R,\ t_R,\ b_R \end{aligned} \qquad (2.8)$$

This classification assumes that the t quark exists and that the ν_τ is unique. The weak and electromagnetic interaction only connects particles to themselves or to the other member of the doublet. In the case of the leptons this is equivalent to lepton conservation. In the case of the first two quark doublets there is only approximate conservation because the d' and c' quarks are mixed by the Cabibbo angle θ_c. That is

$$\begin{aligned} d' &= d \cos \theta_c + s \sin \theta_c \\ s' &= -d \cos \theta_c + s \cos \theta_c \end{aligned} \qquad (2.9)$$

where d and c are pure quark states.

The τ plays an important role in this model, because with the τ there are three sets (usually called generations) of leptons and three sets of quarks (assuming the t quark exists). This theory does not require equal numbers of generations of leptons and quarks. But if it turns out that the numbers of generations are equal, that is certainly very significant with respect to the connection between leptons and quarks.

However our immediate need for this theory is more mundane. It predicts that the weak interactions between the members of a doublet are the same for all doublets. Hence from the $e - \nu_e$ or $\mu - \nu_\mu$ weak interactions we can predict the $\tau - \nu_\tau$ weak interactions if this theory is correct. Specifically, it predicts that (a) the $\tau - \nu_\tau$ coupling will be V—A and (b) the coupling constant will be the universal Fermi weak interaction constant $G_F \approx 1.02 \times 10^{-5}/M^2_{\text{proton}}$. We discuss these predictions in Sections 4.2 and 4.4.

3. THE IDENTIFICATION OF THE TAU AS A LEPTON

The identification of the tau as a lepton is intertwined with all the properties of the tau. Therefore in a general sense the subject of this entire review is the demonstration that the tau is a lepton. However it is useful to summarize this demonstration in one place, and that is the purpose of this section.

3.1 Decay Process Signatures

In this discussion the tau is treated as a sequential lepton. There is a possibility, discussed in Section 4.4, that the tau is an electron associated ortholepton with the decay $\tau^- \rightarrow e^- + \gamma$ strongly suppressed compared to the weak interaction decay modes. This possibility does not alter this discussion.

A crucial signature for identification of a particle as a sequential lepton is that it decays only via the weak interaction and that the various decay branching ratios are explained by the weak interactions. We can roughly calculate the weak interaction predictions for the τ decay by using Figure 1 and replacing the L,L^0 pair by the τ,ν_τ pair. Remembering that the quark decay mode, Figure 1.c, occurs in the different flavors, there are five diagrams of equal weight. Therefore, we expect that the leptonic decays $\nu_\tau e^-\bar{\nu}_e$ or $\nu_\tau\mu^-\bar{\nu}_\mu$ will each occur 20% of the time and the semi-leptonic decays via the quark mode will occur 60% of the time.

A more precise calculation of the branching ratios uses (a) conventional Weinberg-Salam theory; (b) the masses of the τ and the final state particles; (c) some theoretical concepts like CVC; and (d) some specific experimental parameters, for example the pion lifetime is required to calculate the decay rate for $\tau^- \rightarrow \pi^- \nu_\tau$. Many of these calculations were first made by Thacker and Sakurai (1971) and by Tsai (1971). Table 2 gives the branching ratios, based on these references and on the work of Gilman and Miller (1978), Kawamoto and Sanda (1978), Pham, Roiesnel and Truong (1978), and Tsai (1980). We assume a massless ν_τ, spin 1/2 for the τ and ν_τ, V—A coupling, Weinberg-Salam weak interaction theory; and they use the additional inputs listed in the third column of Table 2. Two of the branching ratios are uncertain. The decay rate of the three or more π's or K's decay mode, the multi-hadron decay mode, is difficult to calculate precisely (Section 5.3); and the A_1 decay mode calculation depends upon knowing for certain that the A_1 exists, and on knowing the properties of the A_1 (Section 5.2). Since the total of the branching fractions must be 1, any change in these decay rates will change all the branching fractions. In addition there is uncertainty in some of the calculations because they depend on experimental data such as the total cross section for $e^+ + e^- \rightarrow$ hadrons. Therefore a range of theoretical predictions is given for some of the branching fractions in Table 2.

Note that the crude prediction using Figure 1 is quite good, the individual leptonic branching ratios are calculated to be 16 to 18% rather than 20%, so that the total semi-leptonic branching ratio prediction increases to 64% - 68% from 60%.

As we show in detail in Section 5 all the decay modes listed in Table 2, except $\tau^- \rightarrow \nu_\tau + K^-$ have been seen; and their measured branching ratios agree with the calculations. It is of equal importance that τ decay modes which would occur through the strong or electromagnetic interactions have not been found (Section 5.3). Hence the τ decays only through the weak interactions; thus its decay processes are consistent with it being a lepton and inconsistent with it being a hadron.

G. Feldman has remarked that in the W exchange model of τ decay, Figures 1.a - 1.c, all the decay modes of the τ are decay modes of the W if the ν_τ is excluded. Hence the consistency of the measured with the predicted branching ratios may be thought of as (a) repeated proof that the τ acts as a lepton in the $\tau - W - \nu_\tau$ vertex and (b) studies of the decay modes of a virtual W.

3.2 e^+e^- Production Process Signatures

3.2.1 THEORY There are four general observations we can make about tau production in e^+e^- annihilation.

1. Taus should be produced in pairs via the one photon exchange process (Figure 2.a)

$$e^+ + e^- \rightarrow \gamma_{\text{virtual}} \rightarrow \tau^+ + \tau^- \tag{3.1}$$

once the total energy, $E_{c.m.}$, is greater than twice the τ mass (m_τ).

2. For spin-0 or 1/2 the production cross section for point particles is known precisely from quantum electrodynamics:

$$\text{spin-0:} \qquad \sigma_{\tau\tau} = \frac{\pi\alpha^2\beta^3}{3s} \tag{3.2}$$

$$\text{spin-1/2:} \qquad \sigma_{\tau\tau} = \frac{4\pi\alpha^2}{3s} \cdot \frac{\beta(3-\beta^2)}{2} \tag{3.3}$$

where $s = E^2_{c.m.}$ and $\beta = v/c$; v being the velocity of the τ and c being the velocity of light. α is the fine structure constant. $\sigma_{\tau\tau}$ for higher spins has been discussed by Tsai (1978), Kane and Raby (1978), and Alles (1979). I restrict further discussion in this section to spin 1/2, which is appropriate to the τ. It has become customary in e^+e^- annihilation physics to remove the $1/s$ dependence of cross sections (Equations 3.2 and 3.3) by defining

$$R = \sigma/\sigma_{e^+e^- \to \mu^+\mu^-} \tag{3.4a}$$

where

$$\sigma_{e^+e^- \to \mu^+\mu^-} = \frac{4\pi\alpha^2}{3s} \tag{3.4b}$$

Then for spin-1/2 we expect

$$R_\tau = \frac{\beta(3-\beta^2)}{2} \tag{3.5}$$

which has the simple property that $R_\tau \to 1$ as $\beta \to 1$; that is, as $E_{c.m.}$ rises above the τ threshold.

If the τ has internal structure than Equation 3.3 is modified by a form factor $F(s)$

$$\sigma_{\tau\tau} = \frac{4\pi\alpha^2}{3s} \cdot \frac{\beta(3-\beta^2)}{2} \cdot |F(s)|^2 \tag{3.6}$$

We expect that the internal structure will cause

$$|F(s)| << 1, \quad \text{when } E_{c.m.} >> 2m_\tau \ ; \tag{3.7}$$

This is what happens in pair production of hadrons such as $e^+e^- \to \pi^+\pi^-$ or $e^+e^- \to p\bar{p}$. A point particle has $F(s) = 1$ for all s.

3. The production process

$$e^+ + e^- \to \tau^+ + \tau^- + \text{hadrons} \tag{3.8}$$

should be very small compared to $e^+ + e^- \to \tau^+ + \tau^-$. This is because for a lepton the reaction in Equation 3.8 can only occur in a higher order process such as the one in Figure 2.b, where an extra power of α will appear in the cross section. On the other hand for hadrons the reaction in Equation 3.8 is the common one. For example: in the several GeV regions the cross section for $e^+ + e^- \to K^+ + K^- +$ hadrons is much larger than the cross section for $e^+ + e^- \to K^+ + K^-$.

4. At sufficiently high energy tau pairs should be produced in higher order electromagnetic processes (Figure 2.c) such as

$$e^+ + e^- \to \tau^+ + \tau^- + e^+ + e^- \tag{3.9}$$

and

$$e^+ + e^- \to \tau^+ + \tau^- + \gamma + \gamma \tag{3.10}$$

These production processes will be discussed in Section 6 in future studies of the τ because there is no published data on these reactions.

3.2.2. EXPERIMENTAL RESULTS BELOW 8 GeV Since the τ decays before detection, all production cross section measurements depend upon detection of some set of τ decay modes. Two sets have been used.

1. $e^\pm\mu^\mp$ events: the production and decay sequence

$$\begin{aligned} &e^+ + e^- \to \tau^+ + \tau^- \\ &\tau^+ \to e^+ + \nu_e + \bar{\nu}_\tau \\ &\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau \end{aligned} \tag{3.11}$$

leads to $e^\pm\mu^\mp$ pairs being the only detected particles in the event. These two-prong, total charge zero, $e\mu$ events constitute a very distinctive signature, hence such events led to the discovery of the tau (Perl 1975, Perl et al 1975). The SPEAR data (Perl 1977) on the energy dependence of the production of such events is shown in Figures 3 and 4. Figure 3 shows $R_{e\mu,\text{observed}}$, defined as

$$R_{e\mu,\text{observed}} = 2\,R_\tau\;B(\tau \to e\nu\text{'s})\;B(\tau \to \mu\nu\text{'s})\;A_{e\mu} \tag{3.12}$$

where the B's are branching fractions and $A_{e\mu}$ is the acceptance and efficiency of the apparatus. In the apparatus used for this data, the SLAC-LBL Mark I magnetic detector, $A_{e\mu}$ was almost independent of E_{cm}; hence the $R_{e\mu,\mathrm{observed}}$ values are proportional to R_τ. Note that the sharp threshold at about 3.7 GeV and the leveling out of the R value as $E_{c.m.}$ increases above 5 GeV is in agreement with Equation 3.5. This is shown explicitly in Figure 4 (Perl 1977) where R_τ has been calculated from Equation 3.12, and is in agreement with Equation 3.5 — the theoretical curve.

2. $e^\pm$ hadron$^\mp$ and $\mu^\pm$ hadron$^\mp$ events. The production and decay sequence

$$\begin{aligned} &e^+ + e^- \to \tau^+ + \tau^- \\ &\tau^+ \to e^+ + \nu_e + \bar{\nu}_\tau \qquad (3.13) \\ &\tau^- \to \mathrm{hadron}^- + \nu_\tau, \quad (\mathrm{hadron} = \pi \text{ or } K) \end{aligned}$$

leads to two-prong events consisting of one hadron and one opposite sign electron. The restriction to events with one hadron is necessary to reduce the background (Brandeli et al 1977, Kirkby 1979) from charm particle production and decay processes such as

$$\begin{aligned} &e^+ + e^- \to D^+ + D^- \\ &D^+ \to e^+ + \nu_e + K^0 \\ &D^- \to \mathrm{hadrons} \end{aligned}$$

since charm related events are predominantly multihadronic. Figure 5 shows early results from the DASP detector at DORIS (Brandelik et al 1977); and more recent results from the DELCO detector at SPEAR are given in Figure 6 (Kirkby 1979). The data in both figures are consistent with Equation 3.5.

If the τ decays to μ + neutrinos instead of e + neutrinos in Equation 3.13, then $\mu^{\pm}$ hadron$^{\mp}$ events are produced. These μ - single - hadron events can also be separated from charm particle related μ - multihadron events, and were very important in the early work on the τ (Cavalli-Sforza et al 1970, Feldman et al 1976, Burmester et al 1977a, and Burmester et al 1977b).

To summarize: the eμ, e-hadron and μ-hadron data discussed above, and all other published data on e-hadron and μ-hadron events (Barbaro-Galtieri et al 1977, Bartel et al 1977) are consistent with Equation 3.5 and hence with Equation 3.3. Therefore all the data is consistent with the τ being a point particle with spin-1/2. And of course the point particle property is required for a particle to be a lepton (Section 1.1). We can discuss this in a more quantitative way by inquiring as to the limits the data places on the deviation of the form factor $F_{\tau}(s)$ (Equation 3.6) from 1. There are two ways to answer this inquiry.

(a) We expect that the deviation of F(s) from one will be largest at high $E_{c.m.}$ Looking at the higher energy data in Figure 4 we see that R_{τ} is consistent with one within about ±20%. Therefore this data allows a maximum deviation of F(s) from one of about ±10% at these energies.

(b) An alternative method is to use a model for F(s); the usual choice is (Hofstadter 1977, Duinker 1979)

$$F(s) = 1 \mp \frac{s}{s - \Lambda_{\pm}^{2}} \qquad (3.14)$$

Note that the larger Λ is, the smaller is the deviation of F_{τ} from one. This model has recently been applied to very high energy data from the PETRA $e^{+}e^{-}$ colliding beams facility at DESY; and I turn next to that data.

3.2.3 EXPERIMENTAL RESULTS ABOVE 8 GeV As $E_{c.m.}$ increases in the PETRA and PEP energy range, roughly 10 to 40 GeV, τ pair events become increasingly distinctive for two reasons. (a) The increased energy of each τ causes their respective decay products to move in opposite and roughly collinear directions. (b) Since the τ decays predominantly to one or three charged particles, the total charged multiplicity of τ events is small compared to the average charged multiplicity of hadronic events of about 12 (Wolf 1979). Figure 7 from the PLUTO group at PETRA is an example. A particularly striking signature (Barber et al 1979) is

$$\begin{aligned} &e^+ + e^- \rightarrow \tau^+ + \tau^- \\ &\tau^+ \rightarrow \mu^+ + \text{neutrinos} \\ &\tau^- \rightarrow \text{hadrons}^- \text{ or } \nu^- \text{ or } e^- + \text{neutrinos} \end{aligned} \tag{3.15}$$

The restriction to single hadron decays used in Section 3.2.2 is no longer necessary.

Figure 8 from the Mark-J Collaboration at PETRA (Barber et al 1979) shows the production cross section for τ pairs using the signature in Equation 3.15. The application of Equation 3.14 to this data yields, with 95% confidence (Barber et al 1979)

$$\Lambda_- > 53 \text{ GeV}, \qquad \Lambda_+ > 47 \text{ GeV} \tag{3.16}$$

The meaning of these lower limits on Λ_τ is that the data shows no deviation from $F(s) = 1$; as we can see directly from Figure 8. Hence this new PETRA data is also consistent with the τ being a point particle.

4. PROPERTIES OF THE TAU

4.1 Mass

The τ mass (m_τ) is best determined by measuring the threshold for $e^+ + e^- \rightarrow \tau^+ + \tau^-$. Table 3 summarizes three recent measurements, all of which are consistent. The DELCO measurement is based on the largest statistics and this paper uses that value 1782^{+3}_{-4}.

4.2 Spins, $\tau-\nu_\tau$ Coupling and ν_τ Mass

The general form for the $\tau-\nu_\tau$ weak interaction four-current is

$$J^\lambda_{\tau\nu_\tau} = g_\tau \left\{\psi^\dagger_{\nu_\tau} \mathscr{O} \psi_\tau\right\}^\lambda , \quad \lambda = 1,\ 2,\ 3,\ 4 \tag{4.1}$$

where g is a coupling constant; ψ_{ν_τ} and ψ_τ are spin functions and $\mathscr{O}$ is an operator. The decay of the τ is dependent on the current. For example, in the decay $\tau^- \to \nu_\tau + e^- + \bar{\nu}_e$ the four-particle matrix element, Figure 1.d, is

$$T = J^\lambda_{\tau\nu_\tau}\ j_{\lambda,e\bar{\nu}_e} ; \tag{4.2}$$

where

$$j_{\lambda,e\bar{\nu}_e} = g\bar{u}_{\nu_e}\ \gamma_\lambda(1-\gamma_5)\ u_e \tag{4.3}$$

Here the u's are the usual Dirac spinors and the γ's are the usual Dirac γ matrices (Bjorken & Drell 1964). Equation 4.3 is of course the conventional V - A weak interaction current (Bjorken & Drell 1964). Also

$$\sqrt{2}\ g^2 = G_F = 1.02 \times 10^{-5} / M^2_{\text{proton}} \tag{4.4}$$

Hence the determination of $J^\lambda_{\tau\nu_\tau}$ involves the simultaneous determination of g_τ, the τ spin, the ν_τ spin, the form of the operator $\mathscr{O}$, and even the determination of the ν_τ mass.

Fortunately as discussed in Section 3.2.1, the τ pair production cross section depends upon the τ spin; and hence we have an independent way to determine that quantity. Equation 3.2 for spin 0 predicts a maximum R_τ

value of 0.25; however the measured maximum value is one, hence spin 0 is excluded. Spin 1 and higher integral spins predict a β^3 factor (Tsai 1978). The behavior of $\sigma_{\tau\tau}$ near threshold, Figure 9, excludes a β^3 behavior and hence spin 1 or higher integral spins.

If the τ is not a point particle, the case of spin 3/2 or higher half integral spins is at present indeterminate. One can always select the arbitrary, energy dependent, parameters which occur in the $\tau - \gamma - \tau$ vertex for spin 3/2, 5/2, ... , so that $\sigma_{\tau\tau}$ mimics the spin 1/2 case (Kane & Raby 1979). Such a model must also explain the $\tau^- \rightarrow \nu_\tau + \pi^-$ branching ratio which requires spin 1/2 for a point particle (Alles 1978, Kirkby 1979). Further tests of the higher half integral spin proposal can be made; however my strong instincts are to accept the spin 1/2 assignment.

The ν_τ spin is limited to half integral values by the existence of decay modes such as $\tau^- \rightarrow \nu_\tau + \pi^-$ and $\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e$. Furthermore, the measured value of the decay rate for $\tau^- \rightarrow \nu_\tau + \pi^-$ excludes spin 3/2 for a point-like τ or a point-like ν_τ (Alles 1978, Kirkby 1979). Higher half integral spins for the ν_τ have not been analyzed. Once again I use Ockham's razor and assign to the ν_τ a spin of 1/2 as the simplest hypothesis consistent with all observations on the ν_τ and τ.

Equation 4.1 now reduces to

$$J^\lambda_{\tau\nu_\tau} = g_\tau \, \bar{u}_{\bar{\nu}_\tau} \, \mathcal{O}^\lambda u_\tau \qquad (4.5)$$

where the u's are Dirac spinors and $\mathcal{O}$ is some combination of scalar, pseudoscalar, vector, axial vector and tensor current operators (Bjorken & Drell 1964, Rosen 1978). Insertion of Equation 4.5 in the matrix element, Equation 4.2, for

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e \tag{4.6a}$$

or

$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \tag{4.6b}$$

shows that the e^- or μ^- momentum spectrum will depend on the form of $\mathcal{O}$. A similar situation occurred in the determination of the matrix element in μ decay

$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e \tag{4.7}$$

(Marshak, Riazuddin and Ryan, 1969); except in that case the electron polarization was also measured, whereas in the τ case, Equations 4.6, the e^- or μ^- polarization has not been measured. As discussed by Marshak, Riazuddin and Ryan (1969) the measurement of the e^- or μ^- momentum spectrum does not completely determine $\mathcal{O}$ in Equation 4.5. This dilemma has been resolved by all experimenters who have worked on the τ by (a) assuming that only vector (V) and axial vector (A) currents occur in Equation 4.5, as is the case in all other weak interactions; and (b) allowing the relative strengths of the V and A currents to be fixed by measurement.

With these assumptions, Equation 4.5 reduces to

$$J^\lambda_{\tau\nu_\tau} = g_\tau \, \bar{u}_{\nu_\tau} \gamma^\lambda (v - a\gamma_5) \, u_\tau \quad ; \tag{4.8}$$

$$v, a \text{ real}, \qquad v^2 + a^2 = 1$$

Table 4 gives the special values of v and a. Then in the τ rest system the normalized momentum distribution of the e or μ in Equations 4.6 is

$$dP/dy = y^2 \left[6(v-a)^2(1-y) + (v+a)^2(3-2y) \right] \tag{4.9}$$

where y = e or μ momentum/maximum e or μ momentum, and the e or μ mass and all neutrino masses are set to zero (Bjorken & Drell 1964).

Of course the e or τ momentum is measured in the laboratory system where the τ is in motion, and Equation 4.9 must be transformed properly.

Early studies of the v and a parameters were carried out using e-μ events (Perl et al 1976, Barbaro-Galtieri et al 1977), e-hadron events (Yamada 1977, Brandelik et al 1977, Barbaro-Galtieri et al 1977), and μ-hadron events (Feldman et al 1976, Burmester et al 1977a, Burmester et al 1977b). All these studies were consistent with V - A; Figure 11 from the PLUTO group is an example; and where the statistics were sufficient they excluded V + A, Figure 12.

The most definitive study has been carried out by the DELCO group (Kirkby 1979), Figure 13. They use the ρ Michel parameter (Michel 1950). With this parameter Equation 4.9 becomes

$$dP/dy = 4y^2\left[3(1-y) + (8\rho/3)(4y-3)\right] \tag{4.10}$$

and

$$\rho = 3(v+a)^2 / 8 \tag{4.11}$$

they find $\rho = 0.72 \pm 0.15$, assuming the ν_τ mass is zero, which is in excellent agreement with V - A and in disagreement with V, A, or V + A (Table 4). Kirkby (1979) presents other evidence for V - A using $\langle p_e \rangle / E_{cm}$.

The effect of a non-zero ν_τ mass on the e or μ momentum spectrum is shown in Figure 12; the larger the ν_τ mass the fewer are the events with very energetic e's or μ's. Thus the ν_τ mass determination interacts with the V - A test. It has been shown that V + A is excluded for any value of the ν_τ mass (Bacino et al 1978, Kirkby 1979). However the limited statistics of all the momentum spectrum measurements allow some deviation from V - A combined with some deviation of the ν_τ mass from zero. No study of the combined deviations has been done. Indeed, it has

Become conventional to assume that the $\tau - \nu_\tau$ current is precisely V - A and then to set an upper limit on the ν_τ mass. Table 5 gives three such determinations in historical order; all are consistent with a zero mass.

To summarize this section: all measurements are consistent with

$$\begin{aligned} \tau \text{ spin} &= 1/2 \\ \nu_\tau \text{ spin} &= 1/2 \\ \tau - \nu_\tau \text{ current} &= V - A \\ \nu_\tau \text{ mass} &= 0.0 \end{aligned} \tag{4.12}$$

Those are the standard set of parameters of the τ (Tsai 1980). They are, of course, compatible with $e - \mu - \tau$ universality. As I have noted in this section, there has been a liberal use of Ockham's razor; and measurements should continue on questions such as better limits on the ν_τ mass.

4.3 Lifetime

Thus we have reduced the $\tau - \nu_\tau$ current to

$$J^\lambda_{\tau\nu_\tau} = g_\tau \, \bar{u}_{\bar{\nu}_\tau} \gamma^\lambda (1-\gamma_5) \, u_\tau \tag{4.13}$$

but the value of g_τ is still undetermined. It cannot be determined by measurement of branching ratios or decay mode distributions because it appears as a constant multiplier in all decay mode matrix elements. One way to determine it is to measure the τ lifetime T_τ; other ways are discussed in Section 6. A specific example is helpful here. The decay rate for $\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e$ (Tsai 1971, Thacker & Sakurai 1971) is

$$\Gamma(\nu_\tau e^- \bar{\nu}_e) = \frac{2g_e^2 g_\tau^2 m_\tau^5}{192\pi^3} \tag{4.14}$$

note the analogy to the $\mu \to \nu_\mu + e^- + \bar{\nu}_e$ decay rate

$$\Gamma(\nu_\mu e^- \bar{\nu}_e) = \frac{G_F^2 m_\mu^5}{192\pi^3} \tag{4.15}$$

where $G_F^2 = 2g^4$. Then

$$T_\tau = \frac{B(\nu_\tau e^- \bar{\nu}_e)}{\Gamma(\nu_\tau e^- \bar{\nu}_e)} = B(\nu_\tau e^- \bar{\nu}_e) \left(\frac{g^2}{g_\tau^2}\right) \left(\frac{m_\mu^5}{m_\tau^5}\right) T_\mu \tag{4.16}$$

where $B(\nu_\tau e^- \bar{\nu}_e)$ is the $\tau^- \to \nu_\tau + e^- + \bar{\nu}_e$ branching ratio and T_μ is the μ lifetime. Using $B(\nu_\tau e^- \bar{\nu}_e) = .17$ (Section 5.1), Equation 4.16 predicts

$$T_\tau = 2.7 \times 10^{-13} \text{ sec, for } g_\tau = g \tag{4.17a}$$

The measurement of T_τ requires a study of the average decay length of the τ's produced in $e^+ + e^- \to \tau^+ + \tau^-$; however so far experiments have only been able to put an upper limit on this decay length. The smallest upper limit (Kirkby 1979, Bacino et al 1977a) is

$$T_\tau < 2.3 \times 10^{-12} \text{ sec, 95\% confidence limit} \tag{4.17b}$$

Hence from Equation 4.16

$$g_\tau^2 / g^2 > 0.12, \text{ 95\% confidence limit} \tag{4.18a}$$

Or defining $\sqrt{2}\, G_\tau = g_\tau^2$

$$G_\tau / G_F > 0.12, \text{ 95\% confidence limit} \tag{4.18b}$$

This is consistent with $G_\tau = G_F$, and hence is consistent with $e - \mu - \tau$ universality and with Weinberg-Salam theory; but $G_\tau = G_F$ has not yet been proven.

4.4 Lepton Type and Associated Neutrino

I turn next to the question of whether the τ is a sequential lepton with a unique lepton number, or whether the τ shares lepton number with the μ or e. Consider the μ first. If the τ were a μ-related ortholepton (Section 2.2.2) the reaction

$$\nu_\mu + \text{nucleus} \rightarrow \tau^- + \text{anything} \tag{4.19a}$$

should occur. Analogously if the τ were a μ-related paralepton (Section 2.2.3)

$$\nu_\mu + \text{nucleus} \rightarrow \tau^+ + \text{anything} \tag{4.19b}$$

would occur. Chops et al (1978) have looked for the reactions in Equations 4.19 by using a neon-hydrogen filled bubble chamber exposed to a ν_μ beam. They found no events; their upper limit on $G_{\tau-\nu_\mu}$ is $G_{\tau-\nu_\mu}/G_F < 0.025$ with 90% confidence. However in these μ-related models $G_{\tau-\nu_\mu}$ is identical with what I call G_τ in Equation 4.18b, and must have the value $G_{\tau-\nu_\mu}/G_F > 0.12$. This excludes the μ-related ortholepton and paralepton models.

The equivalent tests for e-related models have not been done because ν_e beams have not been built. Heile et al (1978) have excluded the e-related paralepton model using an argument of Ali and Yang (1976). If the τ were an e-related paralepton its leptonic decay modes would be

$$\tau^- \rightarrow \bar{\nu}_e + e^- + \bar{\nu}_e \tag{4.20a}$$

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

The two identical $\bar{\nu}_e$'s in Equation 4.20 constructively interfer leading to the decay width ratio (Ali & Yang 1976)

$$\Gamma(\tau^- \rightarrow e^- + \text{neutrinos}) / \Gamma(\tau^- \rightarrow \mu^- + \text{neutrinos}) \approx 2 \tag{4.21}$$

The measurements of Heile et al (1978) show this ratio to be close to one; hence this model is wrong.

There is no way, using present data, to exclude the e-related ortholepton model for the τ. That is, it is possible that the τ^- and e^- have the same lepton number. The decay mode

$$\tau^- \to e^- + \gamma \tag{4.22}$$

is then allowed. It has not been seen; the upper limit is 2.6% (Section 5.3). However this does not exclude this model because the $\tau-\gamma-e$ vertex can be suppressed (Section 2.2.2)

More complicated models (Altarelli et al 1977, Horn & Ross 1977) such as the τ decaying into a mixture of ν_e and ν_μ have been considered and excluded. They have been reviewed by Gilman (1978) and Feldman (1978). However one can always devise a complicated model that cannot be excluded. For example, suppose the τ shares its neutrino with a heavier τ'. That model cannot be excluded using present data, and if true the τ would not be a sequential lepton.

As we have done before we select the simplest model consistent with all the data; that is the sequential model. It is, of course, consistent with $e-\mu-\tau$ universality and with Weinberg-Salam theory.

5. DECAY MODES OF THE TAU

5.1 Purely Leptonic Decay Modes

Conventional weak interaction theory (Bjorken & Drell 1964) predicts that the decay width for

$$\tau^- \to \nu_\tau + \ell^- + \bar{\nu}_\ell \,, \qquad \ell = e \text{ or } \mu$$

is

$$\Gamma(\nu_\tau \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_\tau^2}{192\pi^3} \tag{5.1}$$

where the mass of the ℓ is neglected. This is a very basic and simple calculation and the only parameter is G_F; hence, the measurement of the purely leptonic branching fractions is crucial.

Feldman (1978) has reviewed all the data on B_e and B_μ the branching fractions for

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e \tag{5.1a}$$

and

$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \tag{5.1b}$$

respectively. All measurements are consistent and their average values, Table 6, agree with the theoretical predictions from Table 2. In Table 6 two sets of values of B_e and B_μ are given. One set assumes they are unrelated; the other set assumes they are connected via

$$\Gamma(\nu_\tau \mu^- \bar{\nu}_\mu)/\Gamma(\nu_\tau e^- \bar{\nu}_e) = 1 - 8y + 8y^3 - y^4 - 12y^2 \ell n\, y = .972 \tag{5.2}$$

where $y = (m_\mu/m_\tau)^2$ (Tsai 1971).

5.2 Single Hadron or Hadronic Resonance Decay Modes

In this section I consider the decay modes

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

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

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

$\tau^- \rightarrow \nu_\tau + K^*(890)^-$

$\tau^- \rightarrow \nu_\tau + A_1^-$

1. $\tau^- \rightarrow \nu_\tau + \pi^-$ This mode has the decay width (Tsai 1971)

$$\gamma(\nu_\tau \pi^-) = \frac{G_F^2 f_\pi^2 \cos^2\theta_c m_\tau^3}{8\pi} \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 \tag{5.3a}$$

Here in comparison to Equation 5.1 two more parameters have appeared: θ_c, the Cabibbo angle; and f_π, the coupling constant which appears in the μ decay width (Tsai 1971)

$$\Gamma(\pi^- \to \bar{\nu}_\mu + \mu^-) = \frac{G_F^2\, f_\pi^2 \cos^2\theta_c}{8\pi}\; m_\pi\, m_\mu^2 \left[1 - \frac{m_\mu^2}{m_\pi^2}\right]^2 \tag{5.3b}$$

However $f_\pi^2 \cos^2\theta_c$ can be evaluated from Equation 5.3b; therefore, the calculation of $\Gamma(\nu_\tau \pi^-)$ is firm.

Table 7 gives four published measurements of this decay mode. They are consistent with each other and the theoretical prediction of 9.8% to 10.6% (Table 2). Dorfan (1979) has recently given a preliminary value of 10.7 ± 2.1% based on a new analysis of SLAC-LBL Mark II data.

2. $\tau^- \to \nu_\tau + K^-$ This is a Cabibbo suppressed decay mode and weak interaction theory predicts (Tsai 1971)

$$\Gamma(\nu_\tau K^-)/\Gamma(\nu_\tau \pi^-) = \tan^2\theta_c \frac{\left(1 - m_K^2/m_\tau^2\right)^2}{\left(1 - m_\pi^2/m_\tau^2\right)^2} \tag{5.4}$$

The smallness of this branching fraction, $\tan^2\theta_c \approx 0.05$, and the difficulty of separating K's from the much larger π background has so far prevented the measurement of this mode.

3. $\tau^- \to \nu_\tau + \rho^-$ The two measurements of this mode give

$$\begin{aligned} B(\tau^- \to \nu_\tau + \rho^-) &= 20.5 \pm 4.1\% \quad \text{(Abrams et al 1979, Dorfan 1979)} \\ B(\tau^- \to \nu_\tau + \rho^-) &= 24. \pm 9.\ \% \quad \text{(Brandelik et al 1979)} \end{aligned} \tag{5.5}$$

These values are consistent with theoretical predictions of 20.% 23.% (Table 2). Figure 14 shows the ρ momentum spectrum which is consistent with the flat spectrum expected for this two-body decay.

4. $\tau^- \to \nu_\tau + K^*(890)^-$ This, like $\tau^- \to \nu_\tau + K^-$, is a Cabibbo suppressed decay mode and will be suppressed relative to $\tau^- \to \nu_\tau + \rho^-$

by a factor of $\tan^2\theta_c \approx 0.05$. Hence a branching fraction of about 1% is expected. The first measurement of this mode has recently been reported by Dorfan (1979) using SLAC-LBL Mark II data. The value

$$B[\tau^- \rightarrow \nu_\tau + K^*(890)^-] = 1.3 \pm 0.4 \pm 0.3\% \tag{5.6}$$

is found, in good agreement with theory. In Equation 5.6 the first error is statistical and the second is systematic.

5. $\tau^- \rightarrow \nu_\tau + A_1^-$ The search for this decay mode is important (Sakurai 1975) because it may be the only way to establish the existence of the A_1 resonance which is assumed to have: mass ≈ 1100 MeV/c^2, $I^G = 1^-$, $J^P = 1^+$ (Bricman et al 1978). It is because of this importance that I consider the present data suggestive of the A_1's existence but not yet conclusive. The experimental analysis is difficult for two reasons: (a) The mode is found via

$$\tau^- \rightarrow \nu_\tau + A_1^-, \quad A_1^- \rightarrow \pi^- + \pi^+ + \pi^- \quad : \tag{5.7}$$

and this has to be separated from higher multiplicity $\pi^\pm$ and π^o decay modes in which some π's are undetected. (b) After the $\pi^- \pi^+ \pi^-$ mode is separated out, one has to show that it contains a reasonance with the expected properties (Basdevant & Berger 1978).

I will only summarize the experimental situation here. The PLUTO group has published two papers giving evidence for the A_1 (Alexander et al 1978b, Wagner et al 1979). Figure 15 shows their recent analysis (Wagner et al 1979) using

$$\tau^- \rightarrow \nu_\tau + \rho^o + \pi^- \rightarrow \nu_\tau + \pi^- + \pi^+ + \pi^- \tag{5.8}$$

The SLAC-LBL group has also studied this decay mode (Jaros et al 1978); Figure 16 shows their data on Equation 5.7.

5.3 Multi-Hadron Decay Modes

The multi-hadron decay modes are

$$\tau^- \rightarrow \nu_\tau + (n_\pi \pi + n_K K)^- \qquad n_\pi + n_K \geq 2 \tag{5.9}$$

where the hadrons do not come from a single resonance such as the ρ or A_1. There is no general method for calculating the decay width $\Gamma(\nu_\tau + n_\pi \pi + n_K K)$; because that would require us to know how a W with a small virtual mass converts into hadrons; and of course we don't know this at present. Instead several special methods have been used. Decay modes with even numbers of pions have been studied by Gilman and Miller (1978). They used CVC to connect the vector hadronic weak interaction current to the vector hadronic electromagnetic current. We have experimental information on the latter since we know the multi-hadron cross sections for

$$e^+ + e^- \rightarrow \gamma_{\text{virtual}} \rightarrow \text{hadrons} \tag{5.10a}$$

That is, Equation 5.10a is used to predict some of the rates for

$$W_{\text{virtual}} \rightarrow \text{hadrons} \tag{5.10b}$$

Pham, Roiesnel and Truong (1978) have used current algebra and PCAC to calculate rates for the axial vector hadronic current; that is for the decay modes with odd numbers of pions.

Unfortunately we do not yet have the required measurements to compare in detail with these calculations. This is because the experimental separation of the various multi-hadron modes is obscured by (a) the great difficulty of detecting π^0's in multi-hadron events; and by (b) the possibility of some charged π's escaping detection. Therefore, it is premature to attempt a precise comparison of theory and measurement of the multi-hadron decay modes. Table 8 lists existing measurements. All of them are compatible with calculations, given the large errors in the measurements and the uncertainties in the calculations. A final remark; the branching fraction of 28 ± 6% for modes with ≥ 2 charged hadrons should be compared with the A_1 + multi-hadron subtotal in Table 2 of 31 to 35%. The latter are expected to be larger because they include some modes with one charged π and two or more π^0's.

5.4 Sequential Model Forbidden Decay Modes

If the τ lepton number were not perfectly conserved, or if the τ, e and μ lepton numbers were slightly mixed the τ might decay electromagnetically into modes such as

$$\begin{aligned} &\tau^- \to e^- + \gamma \\ &\tau^- \to \mu^- + \gamma \\ &\tau^- \to e^- + e^+ + e^- \\ &\tau^- \to e^- + \mu^+ + \mu^- \\ &\tau^- \to \mu^- + \mu^+ + \mu^- \end{aligned} \tag{5.11}$$

none of these decay modes have been found. Branching fraction upper limits are given in Table 9, along with upper limits on some other modes forbidden by the sequential model. The limits in Table 9 were obtained several years ago; increased statistics obtained since will allow searches which are five to ten times more sensitive.

6. FUTURE STUDIES OF THE TAU

6.1 Future Studies of the Properties of the Tau

As I have indicated at several places in this review, there is more experimental work to be done on the properties of the τ for two reasons:

(a) Just as we continue to test the leptonic nature of the e and μ and the validity of the laws of lepton conservation, so we should continue to test these properties of the τ. It is possible that the relatively large mass of the τ might be associated with deviation from $e-\mu-\tau$ universality. (b) Measurement of the properties of the τ can teach us about other areas of elementary particle physics such as the existence of the A_1.

The main τ studies to be done are the following:

1. high energy, high statistics measurement of $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$;
2. better determination of the limits on the ν_τ mass;
3. measurement of the τ lifetime and determination of G_τ;
4. finding and measuring $\tau^- \rightarrow \nu_\tau + K^-$;
5. elucidation of $\tau^- \rightarrow \nu_\tau + A_1$ and study of A_1 properties if it exists.
6. detailed study of multi-hadron decay modes of τ; and
7. better limits on sequential model forbidden decay modes.

6.2 The Tau as a Decay Product

Several known or proposed very heavy hadrons should decay to one or more τ's, Table 10. The measurement of these decay modes has three purposes: (a) Some provide a separate measurement of G_τ, (b) Some test our standard model for the τ, such as the spin being 1/2. (c) Some provide information about the heavy hadron.

6.3 Tau Production in Photon-Hadron Collisions

We should be able to produce pairs of heavy charged leptons, such as τ pairs, by the very high energy Bethe-Heitler process (Kim & Tsai 1973, Tsai 1974, Smith et al 1977)

$$\gamma \pm \text{nucleus} \rightarrow \tau^{+} + \tau^{-} + \text{anything} \qquad (6.1a)$$

I don't think we can learn much about the τ from this process, if our standard model of the τ is correct. However, this is a test of that model which should be done. An alternative method would use very high energy μ's via

$$\begin{aligned} &\mu + \text{nucleus} \rightarrow \mu + \text{anything} + \gamma_{\text{virtual}} \\ &\gamma_{\text{virtual}} \rightarrow \tau^{+} + \tau^{-} \end{aligned} \qquad (6.1b)$$

The detection of the τ pairs in the reactions of Equations 6.1 is difficult because the τ decay products are immersed in an enormous background of hadrons, e's and μ's. The most promising signature appears to be $e^{\pm}\mu^{\mp}$ pairs.

6.4 Tau Production in Hadron-Hadron Collisions

Taus can be produced in hadron-hadron collisions in two types of processes:

1. Virtual photons from quark-antiquark annihiliations can produce $\tau^{+}\tau^{-}$ pairs (Chu & Gunion 1975; Bhattacharya et al. 1976).

2. Heavy hadrons such as those in Table 10 can be produced, and subsequently decay to $\tau\nu_{\tau}$ or $\tau^{+}\tau^{-}$ pairs.

Unfortunately the detection of the τ's looks like a very difficult task because of the overwhelming background from e, μ and hadron production. However process two can be used to produce ν_{τ}'s in sufficient quantity to permit their detection, and I turn next to that subject.

6.5 Future Studies of the Tau Neutrino

The production and decay sequence

$$\text{proton} + \text{nucleon} \rightarrow F^- + \text{hadrons} \qquad (6.2a)$$

$$F^- \rightarrow \tau^- + \bar{\nu}_\tau \qquad (6.2b)$$

$$\tau^- \rightarrow \nu_\tau^- + \text{charged particles} \qquad (6.2c)$$

can produce a ν_τ beam (Barger & Phillips 1978; Albright & Schrock 1979, Scuilli 1978). However the neutrinos from π and K decay would overwhelm the ν_τ signal unless the majority of the π's and K's interact before they decay. Therefore the entire proton beam must be dumped in a thick target. There is still some problem with ν_e's and ν_μ's from D meson and other charmed particle semi-leptonic decays, but the detection of the ν_τ appears feasible.

The detection of the ν_τ and the study of its interactions can provide the following information. (a) We can check that the ν_τ is a unique lepton and is not a ν_e; hence we test the electron-related ortholepton model (Section 4.4). (b) More generally we can test if the ν_τ behaves conventionally with conventional weak interactions. (c) We can measure the product of the cross section for Reaction 6.2a and the branching ratio for Reaction 6.2b.

7. SUMMARY

All published studies of the τ are consistent with it being a point-like, spin 1/2, sequential charged lepton. These studies are consistent with $e - \mu - \tau$ universality, and they are consistent with conventional Weinberg-Salam theory. There is more experimental work to be done on measuring the properties of the tau; and on using the tau to study other particles.

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Literature Cited

Abrams, G. S. et al. 1979. Phys. Rev. Lett. 43:1555

Albright, C. H., Schrock, R. E. 1979. Phys. Lett. 84B:123

Alexander, G. et al. 1978a. Phys. Lett. 78B:162

Alexander, G. et al. 1978b. Phys. Lett. 73B:99

Ali, A., Yang, T. C. 1976. Phys. Rev. D14:3052

Alles, W. 1978. Lett. Nuovo Cimento 25:404

Altarelli, G. et al. 1977. Phys. Lett. 67B:463

Bacino, W. et al. 1978. Phys. Rev. Lett. 41:13

Bacino, W. et al. 1979a. Phys. Rev. Lett. 42:749

Bacino, W. et al. 1979b. Phys. Rev. Lett. 42:6

Bailin, David 1977. Weak Interactions. London, England:Sussex University Press, pp. 406

Barbaro-Galtieri, A. et al. 1977. Phys. Rev. Lett. 39:1058

Barber, D. P. et al. 1979. Phys. Rev. Lett. 43:1915

Barger, V., Phillips, R. 1978. Phys. Lett. 74B:393

Bartel, W. et al. 1978. Phys. Lett. 77B:331

Basdevant, J. L., Berger, E. L. 1978. Phys. Rev. Lett. 40:994

Bernardini, M. et al. 1973. Nuovo Cimento 17:383

Bhattacharya, R., Smith, J., Soni, A. 1976. Phys. Rev. D13:2150

Bjorken, J. D., Drell, S. D. 1964. Relativistic Quantum Mechanics, New York, NY:McGraw Hill, pp. 414

Brandelik, R. et al. 1977. Phys. Lett. 73B:109

Brandelik, R. et al. 1979. Zeit. Phys. C1:233

Bricman, C. et al. 1978. Phys. Lett. 75B:1. This is the Particle Data Group's Review of Particle Properties.

Burmester, J. et al. 1977a. Phys. Lett. 68B:297

Burmester, J. et al. 1977b. Phys. Lett. 68B:301

Cavalli-Sforza, M. et al. 1976. Phys. Rev. Lett. 36:558

Chu, G., Gunion, J. F. 1975. Phys. Rev. D11:73

Cnops, A. M. et al. 1978. Phys. Rev. Lett. 40:144

Dorfan, J. 1979. Proc. of Annual Meeting of Division of Particles and Fields, McGill University, Montreal, Canada. In press.

Eichten, E., Gottfried, K. 1977. Phys. Lett. 66B:286

Ellis, J., Gaillard, M. K., Nanopoulos, D. V., Rudaz, S. 1977. Nucl. Phys. B131:285

Farrar, G. R., Fayet, P. 1979. Searching for the Spin-0 Leptons of Supersymmetry. Rutgers/Caltech RU-79-160.

Feldman, G. J. et al. 1976. Phys. Lett. 63B:466

Feldman, G. J. 1978a. Proc. Int. Meeting on Frontier of Physics, Singapore. In press. Also issued as Stanford Linear Accelerator Center SLAC-PUB-2230.

Feldman, G. J. 1978b. Proc. of Neutrinos-78, Purdue University, West Lafayette, Indianna.

Flügge, G. 1977. Proc. of 1977 Experimental Meson Spectroscopy Conference, Northeastern University, Boston, Mass.

Flügge, G. 1979. Zeit. Phys. C1:121

Gilman, F. J. 1978. Stanford Linear Accelerator Center SLAC-PUB-2226.

Gilman, F. J., Miller, David, H. 1978. Phys. Rev. D17:1846.

Heile, F. J. et al. 1978. Nuc. Phys. B138:189

Hitlin, D. 1978. Proc. of XIX Int. Conf. on High Energy Physics, Tokyo, Japan.

Hofstadter, R. 1975. Proc. of 1975 Int. Symp. on Lepton and Photon Interactions at High Energies, Stanford Linear Accelerator Center, Stanford University, Stanford, California.

Horn, D., Ross, G. G. 1977. Phys. Lett. 67B:460

Jaros, J. A. et al. 1978. Phys. Rev. Lett. 40:1120

Kane, G., Raby, S. 1979. University of Michigan UHME 79-26.

Kawamoto, N., Sanda, A. I. 1978. Phys. Lett. 76B:446

Kim, K. J., Tsai, Y. S. 1973. Phys. Rev. D8:3109

Kirkby, J. 1978. Proc. of Neutrinos-78, Purdue University, West Lafayette, Indianna, p. 631.

Kirkby, J. 1979, Proc. of 1979 Int. Sym. on Lepton and Photon Interactions at High Energy, Fermi National Laboratory, Batavia, Illinois. In press.

Knies, G. 1977. Proc. of 1977 Int. Sym. on Lepton and Photon Interactions at High Energies, Duetsches Elektronen-Synchrotron, Hamburg, Germany

Llewellyn Smith, C. H. 1977. Proc. Royal Society (London) A355:585

Low, F. E. 1965. Phys. Rev. Lett. 14:238

Marshak, R. E., Riazuddin, Ryan, C.P. 1969. Theory of Weak Interactions in Particle Physics, New York, NY:Wiley-Interacience. 761pp.

Michel, L. 1950. Proc. Phys. Soc. (London) A63:514

Orioto, S. et al. 1974. Phys. Lett. 48B:165

Perl, M. L., Rapidis, P. 1974. Stanford Linear Accelerator Center SLAC-PUB-1499.

Perl, M. L. 1975. Proc. of Summer Institute on Particle Physics, SLAC-191, Stanford Linear Accelerator Center, Stanford University, Stanford, California, p. 333.

Perl, M. L. et al. 1975. Phys. Rev. Lett. 35:1489

Perl, M. L. et al. 1976. Phys. Lett. 63B:466

Perl, M. L. 1977a. Proc. of 1977 Int. Symp. on Lepton and Photon Interactions at High Energies, Deutsches Elektronen-Synchrotron, Hamburg, Germany, p. 145

Perl, M. L. et al. 1977b. Phys. Lett. 70B:487

Perl, M. L. 1978. New Phenomena in Lepton-Hadron Physics, New York, NY:Plenum Press, ed. Fries, D. E. C. and Wess, J., p. 115. Also issued as Stanford Linear Accelerator Center SLAC-PUB-2219 (1978). This reference discusses broader definitions of a lepton.

Pham, T. N., Roiesnel, C., Truong, T. N. 1978. Phys. Lett. 78B:623

Rosen, S. P. 1978. Phys. Rev. Lett. 40:1057

Sakurai, J. J. 1975. Proc. of the 1975 Int. Sym. on Lepton and Photon Interactions at High Energies, Stanford Linear Accelerator Center, Stanford University, Stanford, California.

Sciulli, F. 1978. Proc. of Neutrino-78, Purdue University, West Lafayette, Indiana.

Smith, J., Soni, A., Vermaseren, J. A. M. 1977. Phys. Rev. D15:648

Smith, J. G. et al. 1978. Phys. Rev. D18:1

Thacker, H. B., Sakurai, J. J. 1971. Phys. Lett. 36B:103

Tsai, Y. S. 1971. Phys. Rev. D4:2821

Tsai, Y. S. 1974. Rev. Mod. Phys. 46:815

Tsai, Y. S. 1978. Stanford Linear Accelerator Center SLAC-PUB-2105.

Tsai, Y. S. 1980. Stanford Linear Accelerator Center SLAC-PUB-2403.

Wagner, W. et al. 1979. Zeit. Phys. In press.

Wolf, G. 1979. Proc. of 1979 Int. Sym. on Lepton and Photon Interactions at High Energies, Fermi National Laboratory, Batavia, Illinois. In press. Also issued by DESY as DESY 79/61.

Yamada, S. 1977. Proc. of 1977 Int. Sym. on Lepton and Photon Interactions at High Energies, Deutsches Elecktronen-Synchrotron, Hamburg, Germany.

Zipf, M. C., ed. 1978. Proc. of Summer Inst. on Particle Physics, SLAC-215, Stanford Linear Accelerator Center, Stanford University, Stanford, California.

Table 1 The known leptons

Name	Electron	Muon	Tau
Charged lepton symbol	$e^{\pm}$	$\mu^{\pm}$	$\tau^{\pm}$
Charged lepton mass in MeV/c^2	0.51	105.7	1782^{+3}_{-4} [a]
Charged lepton lifetime in seconds	stable	2.20×10^{-6}	$<2.3 \times 10^{-12}$ [a]
Charged lepton spin	1/2	1/2	1/2
Associated neutrino	$\nu_e, \bar{\nu}_e$	$\nu_\mu, \bar{\nu}_\mu$	$\nu_\tau, \bar{\nu}_\tau$ [b]
Associated neutrino mass	<60 eV/c^2 [c]	<0.57 MeV/c^2 [c]	<250 MeV/c^2 [a,c]

[a] The detailed discussion of these measurements appears in Section 4.

[b] All measured properties of the τ are consistent with it having a unique neutrino, ν_τ; however, more experimental work needs to be done on these properties as discussed in Section 4.4.

[c] could be 0.0

Table 2 Predictions for τ^- branching ratios

Mode	Branching ratio (%)	Additional input to calculation
$e^-\bar{\nu}_e\nu_\tau$	16.4 - 18.0	none
$\mu^-\bar{\nu}_\mu\nu_\tau$	16.0 - 17.5	none
$\pi^-\nu_\tau$	9.8 - 10.6	π^- lifetime
$K^-\nu_\tau$	≈ 0.5	θ_{Cabibbo}
$\rho^-\nu_\tau$	20. - 23.	CVC plus e^+e^- annihilation cross sections
$K^{*-}\nu_\tau$	0.8 - 1.5	Das-Mathur-Okubo sum rules plus θ_{Cabibbo}
$A_1^-\nu_\tau$	8. - 10.	Weinberg sum rules
(2 or more π's,K's)$^-\nu_\tau$	23. - 25.	quark model, CVC, $\sigma(e^+e^- \to \text{hadrons})$, etc.
$A_1^-\nu$ + (2 or more π's,K's)$^-\nu_\tau$ subtotal[a]	31. - 35.	

[a] Does not included the ρ, K^* or A_1 modes.

Table 3 Measurements of the τ mass using the production threshold

Experiment	Mass (MeV/c^2)	Figure	Reference
DELCO	1782^{+3}_{-4}	9	Bacino 1978, Kirkby 1979
DASP	1807±20	5	Brandelik 1978
DESY-HEIDELBERG	1787^{+10}_{-18}	10	Bartel 1978

Table 4 Parameters for the $\tau - \nu_\tau$ current

Type	v	a	ρ
V - A	1	1	3/4
pure V	1	0	3/8
pure A	0	1	3/8
V + A	1	-1	0

Table 5 Upper limits on ν_τ mass

Group	Upper limit on ν_τ mass (MeV/c^2)	Confidence (%)	Reference
SLAC-LBL	600	95%	Perl et al 1977b
PLUTO	540	90%	Knies 1977
DELCO	250	95%	Kirkby 1979

Table 6 Purely leptonic decay mode branching fractions (Feldman 1978)[a]

	B_e and B_μ free	$B_\mu = 0.972B_e$	Theory
B_e	16.5 ± 1.5	17.5 ± 1.2	16.4 - 18.0
B_μ	18.6 ± 1.9	17.1 ± 1.2	16.0 - 17.5

[a] in percent.

Table 7 Branching fractions for $\tau^- \rightarrow \nu_\tau + \pi$

Experiment	Mode	Branching Fraction [a] (%)	Reference
SLAC-LBL	$x\pi$	$9.3 \pm 1.0 \pm 3.8$	Feldman 1978b
PLUTO	$x\pi$	$9.0 \pm 2.9 \pm 2.5$	Alexander et al 1978a
DELCO	$e\pi$	$8.0 \pm 3.2 \pm 1.3$	Bacino et al 1979b
SLAC-LBL	$x\pi$ $e\pi$	$8.0 \pm 1.1 \pm 1.5$ $8.2 \pm 2.0 \pm 1.5$	Hitlin 1978
Average		8.3 ± 1.4	

[a] The first error is statistical, the second systematic.

Table 8 Some measurements of multi-hadron decay modes[a]

Mode for τ^-	Branching fraction (%)	Reference
$\nu_\tau + \pi^- + \pi^+ + \pi^- + \geq 0\pi^0$	18 ± 6.5	Jaros et al 1978
$\nu_\tau + \pi^- + \pi^+ + \pi^-$	7 ± 5	Jaros et al 1978
$\nu_\tau + \pi^- + \pi^+ + \pi^- + \pi^0$	11 ± 7	Jaros et al 1978
$\nu_\tau + \rho^0 + \pi^-$	5.4 ± 1.7	Wagner et al 1979
$\nu_\tau + \geq 3$ charged particles $\pm \geq 0\pi^0$	28 ± 6	Kirkby 1979

[a] Including the A_1 resonance if it exists.

Table 9 Upper limits on branching fractions for decay modes forbidden by the sequential model

Mode	Upper limit on branching fraction (%)	C.L. (%)	Experimental group or detector	Ref.
$\tau^- \to e^- + \gamma$ $\tau^- \to \mu^- + \gamma$	12	90	PLUTO Group	()[a]
$\tau^- \to e^- + \gamma$	2.6	90	LBL-SLAC lead glass wall	()[b]
$\tau^- \to \mu^- + \gamma$	1.3	90	LBL-SLAC lead glass wall	()[b]
$\tau^- \to$ (3 charged leptons)$^-$	1.	95	PLUTO Group	()[a]
$\tau^- \to$ (3 charged leptons)$^-$	0.6	90	SLAC-LBL magnetic detector	()[b]
$\tau^- \to$ (3 charged particles)$^-$	1.0	95	PLUTO Group	()[a]
$\tau^- \to \rho^- + \pi^0$	2.4	90	SLAC-LBL magnetic detector	()[b]

[a] Flugge 1977

[b] Perl 1977a

Table 10 Some predicted decay modes of heavy hadrons to one or two τ's

Hadron	Quark composition	Predicted decay mode	Predicted branching fraction (%)	Reference
F	$c\bar{s}$	$F^+ \to \tau^+ + \nu_\tau$	≈ 3	Albright and Schrock 1979
B [a]	$b\bar{u}, b\bar{d}$	$B^+ \to \tau^+ + \nu_\tau$	0.5 - 1.	Ellis et al 1977
Υ	$b\bar{b}$	$\Upsilon \to \tau^+ + \tau^-$	≈ 3.5	Eichten and Gottfried 1977 Ellis et al 1977
T [b]	$t\bar{t}$	$T \to \tau^+ + \tau^-$	$\approx 8.$	Ellis et al 1977

[a] The evidence for the existence of the B is scanty at present.

[b] This is a proposed particle; there is no evidence for its existence at present.

Figure Legends

Figure 1 Diagrams for the decay of the τ into quarks or leptons: (a - c) intermediate boson view, (d - e) four-fermion coupling view.

Figure 2 Diagrams for: (a) $e^+e^- \to \tau^+\tau^-$ via one photon exchange, (b) higher order production of a τ pair with hadrons, and (c) $e^+e^- \to e^+e^-\tau^+\tau^-$ via a two-virtual photon process.

Figure 3 $R_{e\mu,\text{observed}}$ for (a) $3.6 \le E_{c.m.} \le 4.8$ GeV and (b) $3.6 \le E_{c.m.} \le 7.8$ GeV (Perl 1977a).

Figure 4 R_τ compared to theoretical curves for point-like, spin 1/2 particles for two τ masses (Perl 1977a). This older data indicated a τ mass between 1825 and 1900 MeV/c^2; the presently accepted value is 1782 MeV/c^2.

Figure 5 Cross section for e-hadron events from DASP (Brandelik et al 1977) compared to theoretical curve for point-like, spin 1/2 particles.

Figure 6 R_τ from DELCO (Kirkby, 1979) compared to theoretical curves for point-like particles with spin 0, 1/2, 1 or 3/2.

Figure 7 An example of a τ pair event at $E_{c.m.} = 22$ GeV obtained by the PLUTO group at PETRA. The single track is an electron, and the three tracks going in the other direction are pions.

Figure 8 Comparison of the cross section for τ pair production with the theoretical curve for a point-like spin 1/2 particle. The data is from the Mark J detector at PETRA (Barber et al 1979), except for the point marked PLUTO obtained by the PLUTO group at DORIS.

Figure 9 The threshold behavior of R_{ex} for e-hadron and eμ events from DELCO (Kirkby 1979).

Figure 10 The threshold behavior of the cross section for e-hadron and μ-hadron events measured by the DESY-Heidelberg group (Bartel 1978). The theoretical curve is for a point-like spin 1/2 particle.

Figure 11 The momentum spectrum for muons in μ-hadron events obtained by the PLUTO group (Burmester et al 1977a). Muons with momenta less than the vertical dashed line could not be identified in the detector. The theoretical curve is for the decay $\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu$ with V - A coupling, all spins 1/2 and a massless ν_τ.

Figure 12 The momentum spectrum of e's or μ's in eμ events from the SLAC-LBL magnetic detector group (Perl et al 1976). $r = (p - .65)/(p_{max} - .65)$ where p is the momentum of the e or μ in GeV/c and p_{max} is its maximum value. The .65 constant is the lowest momentum at which e's and μ's could be identified in this detector. The solid theoretical curves are for the decays $\tau^- \to \nu_\tau + e^- + \bar{\nu}_e$ or $\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu$ with V - A coupling, all spins 1/2, and a mass for the ν_τ indicated by the attached number in GeV/c^2. The dashed theoretical curve is for V + A coupling and a massless ν_τ.

Figure 13 The normalized momentum spectrum for electrons from e-hadron and eμ events from DELCO (Kirkby 1979). The theoretical curves are for the decays $\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e$ with all spins 1/2, a massless neutrino and the indicated coupling. The fits to V - A (solid) and V + A (dashed) give χ^2/dof of 15.9/17 and 53.7/17, respectively.

Figure 14 The distribution $X_p = (E_\rho - E_{min})/(E_{max} - E_{min})$ where E_ρ is the ρ energy and E_{max} and E_{min} are its maximum and mimimum values from the SLAC-LBL magnetic detector (Abrams et al 1979). The theoretical curve is for $\tau^- \rightarrow \nu_\tau + \rho^-$ corrected for detector acceptance and measurement errors. Without these corrections the curve would be flat for $X_\rho = 0$ to 1 and zero above $X_\rho = 1$

Figure 15 Invariant $\rho^0\pi$ mass distribution from the PLUTO group (Wagner et al 1979), compared to an s-wave without and with an imposed A_1 resonance of mass = 1.0 GeV/c^2 and width = 0.475 GeV/c (dashed curve), added to the expected background (solid curve).

Figure 16 Invariant $(3\pi)^\pm$ mass distribution from four-prong events $\mu^\mp(3\pi)^\pm$ obtained by the SLAC-LBL magnetic detector (Jaros 1978). The number of photons accompanying the event is n_γ; hence (a) contains the possible $A^\pm \rightarrow (3\pi)^\pm$ signal, and (b) and (c) are measures of the possible feed down background from events with π^0's.

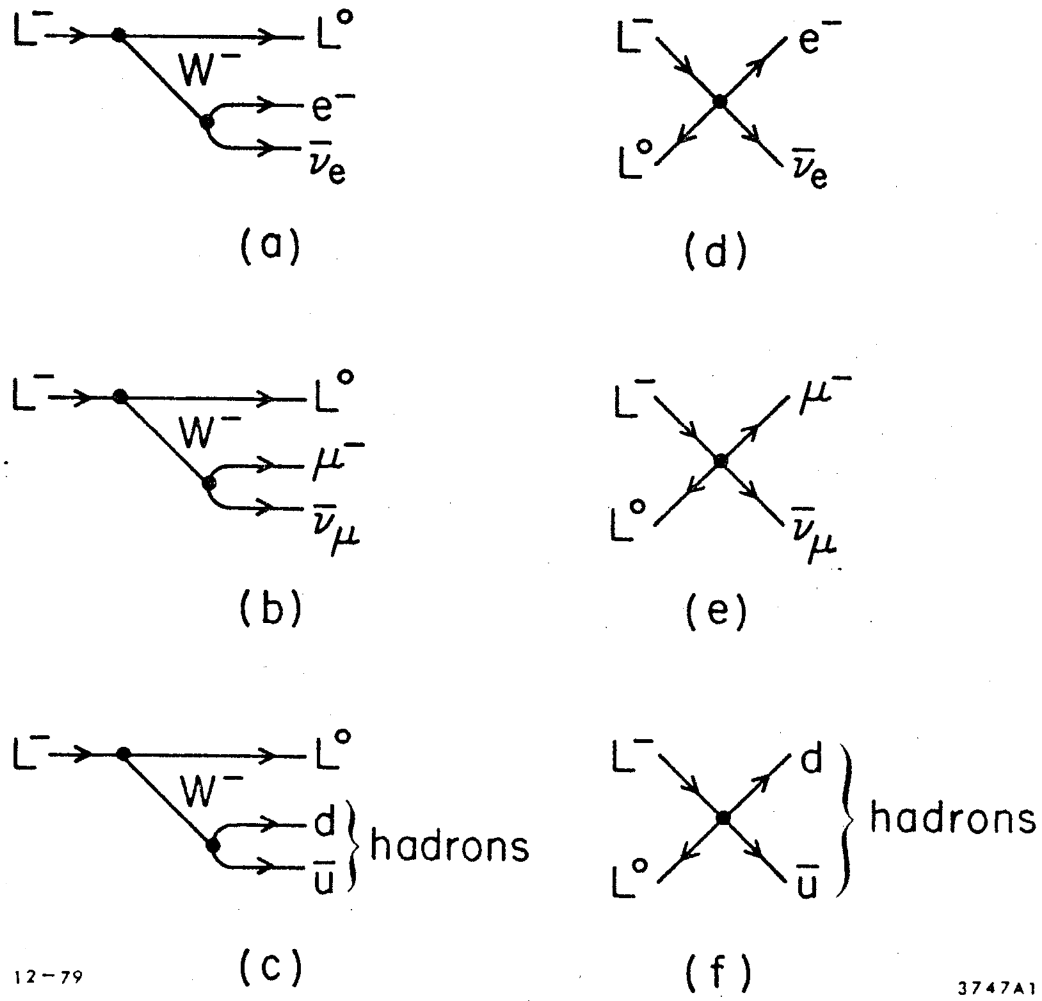
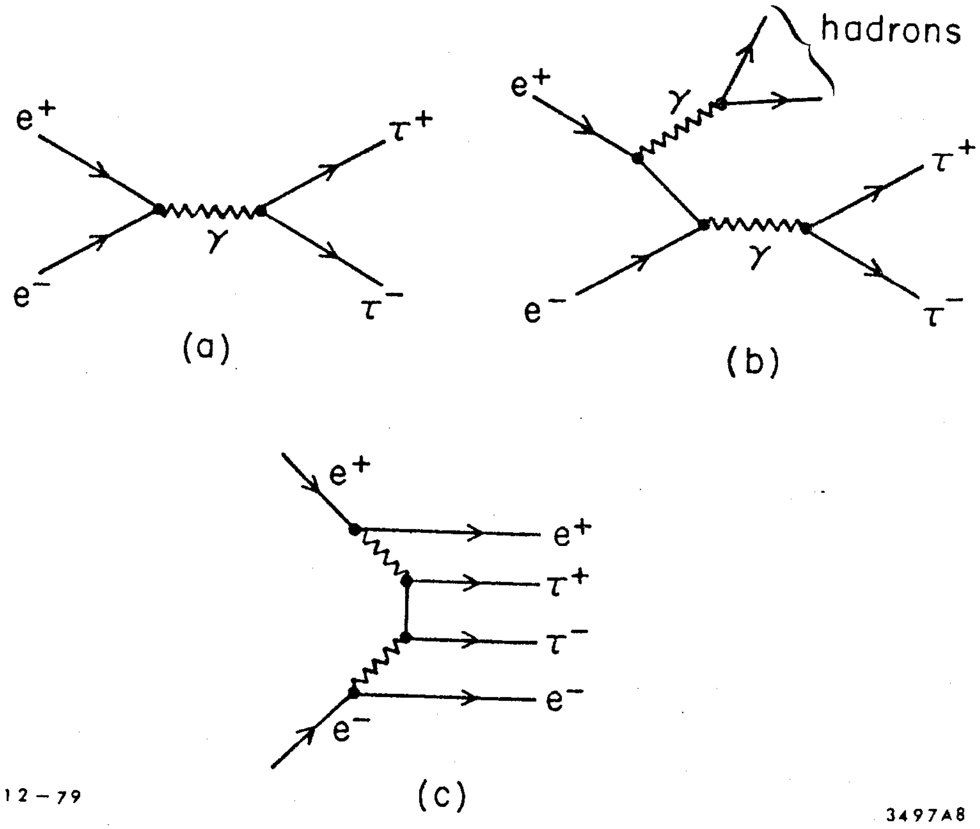
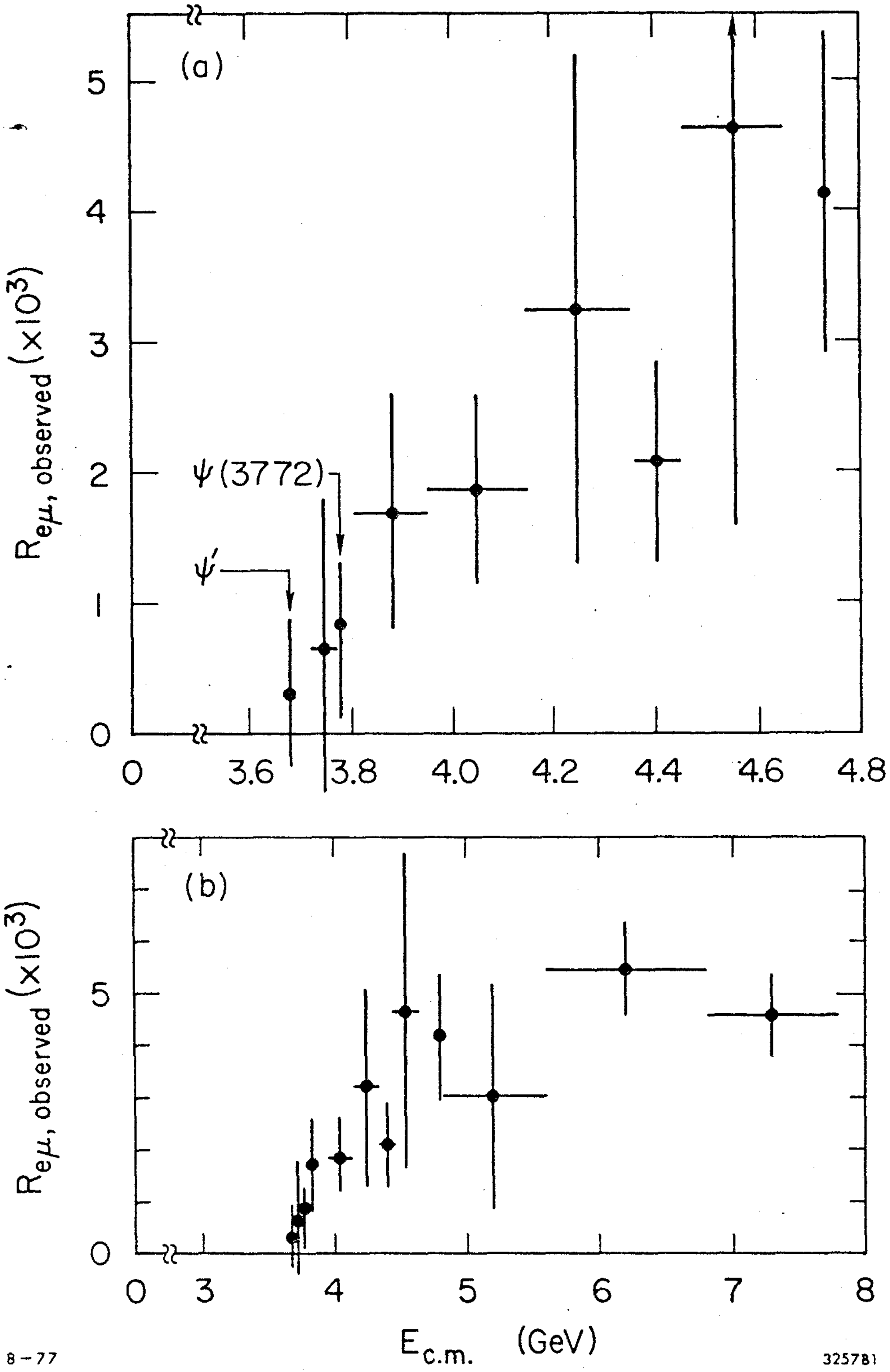

L⁻
W⁻
L°
e⁻
ν̄e
(a)
L⁻
W⁻
L°
μ⁻
ν̄μ
(b)
L⁻
W⁻
L°
d
ū
hadrons
(c)
L⁻
e⁻
L°
ν̄e
(d)
L⁻
μ⁻
L°
ν̄μ
(e)
L⁻
d
L°
ū
hadrons
(f)
12-79
3747A1

Fig. 1



e$^+$
e$^-$
γ
τ^+
τ^-
(a)
hadrons
e$^+$
γ
τ^+
e$^-$
γ
τ^-
(b)
e$^+$
e$^+$
τ^+
τ^-
e$^-$
e$^-$
12-79
(c)
3497A8

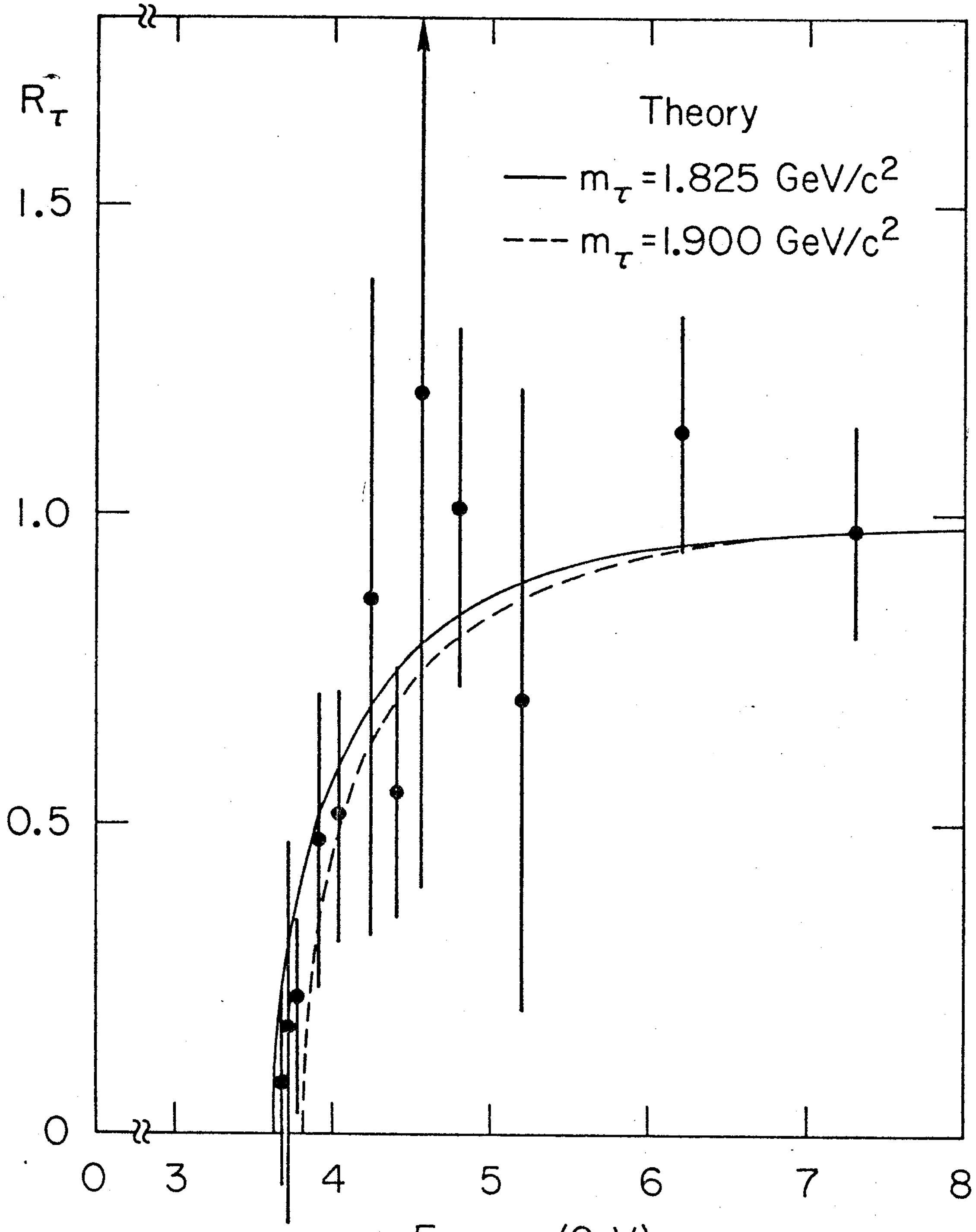
Fig. 2



8-77

3257B1

Fig. 3



11-77

325786

Fig. 4

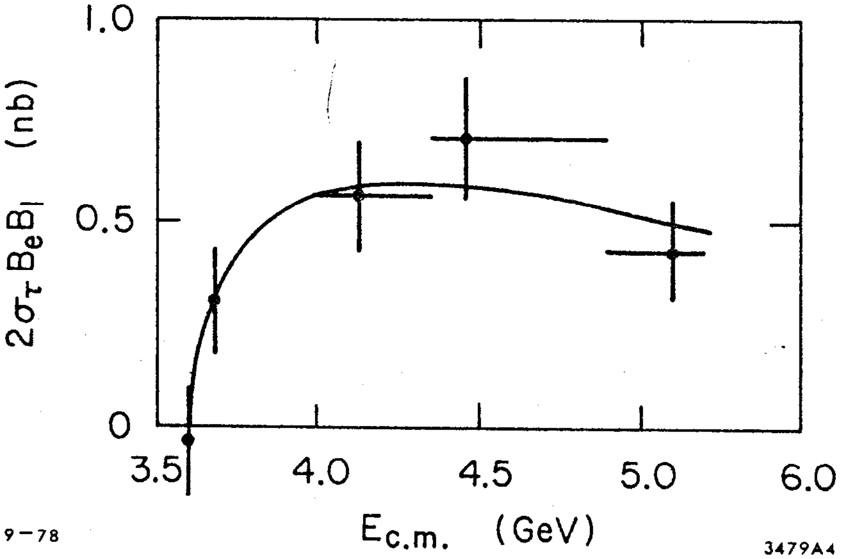
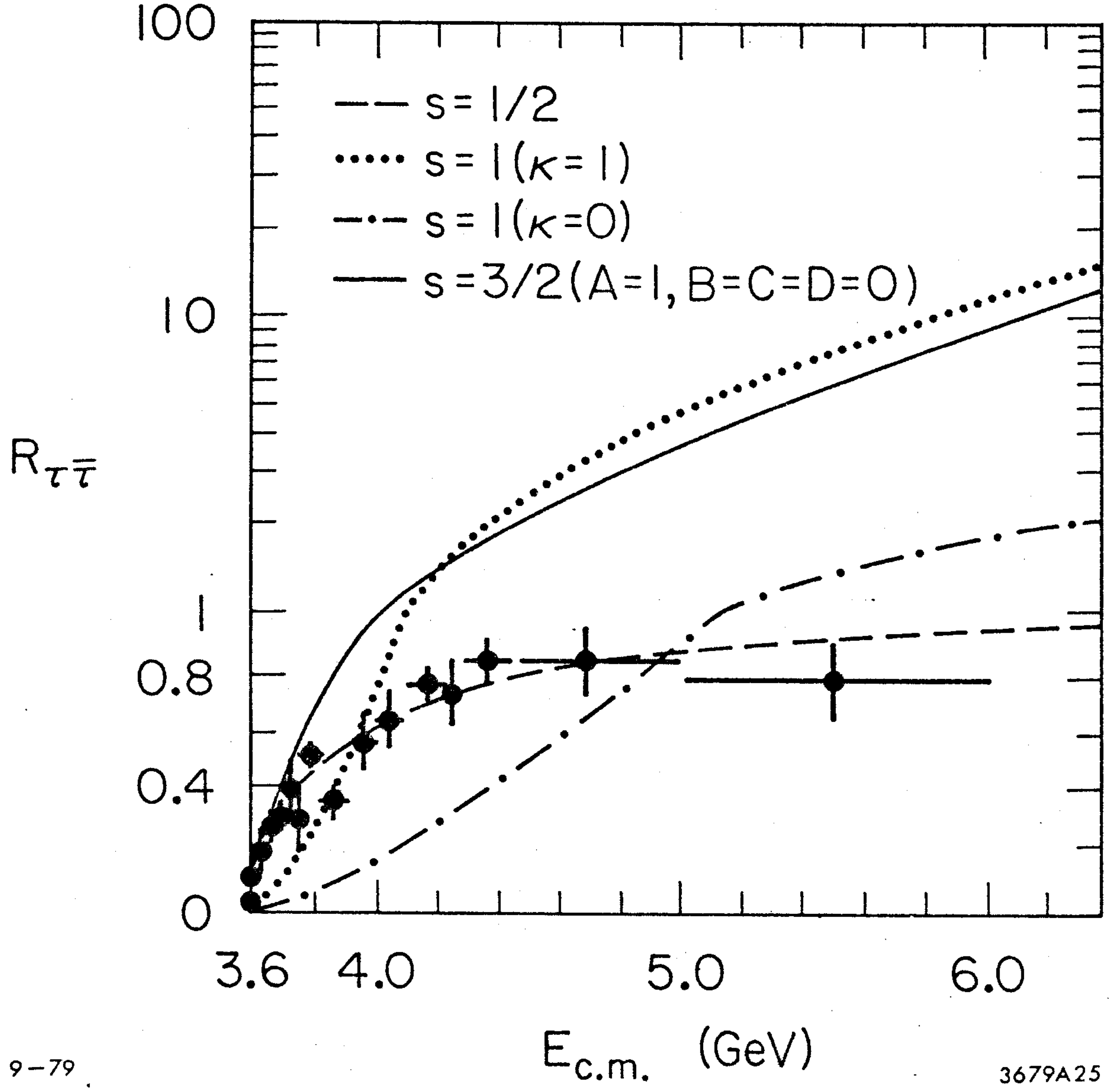
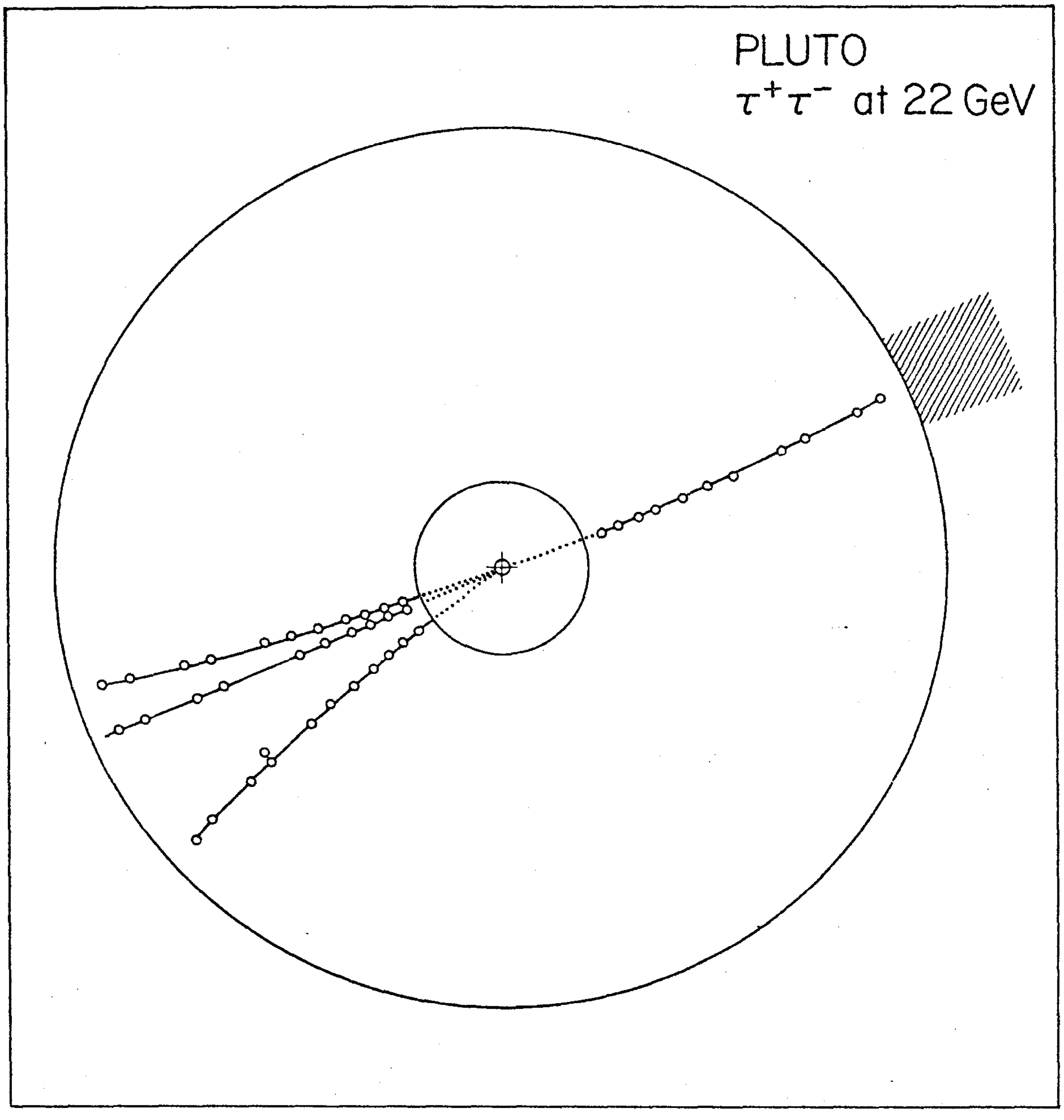


Fig. 5



100
10
1
0.8
0.4
0
$R_{\tau\bar{\tau}}$
s = 1/2
s = 1 (κ = 1)
s = 1 (κ = 0)
s = 3/2 (A = 1, B = C = D = 0)
3.6
4.0
5.0
6.0
$E_{c.m.}$ (GeV)
9–79
3679A25

Fig. 6



12–79

3747A7

Fig. 7

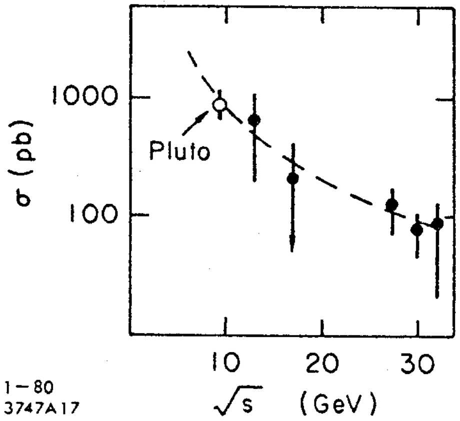
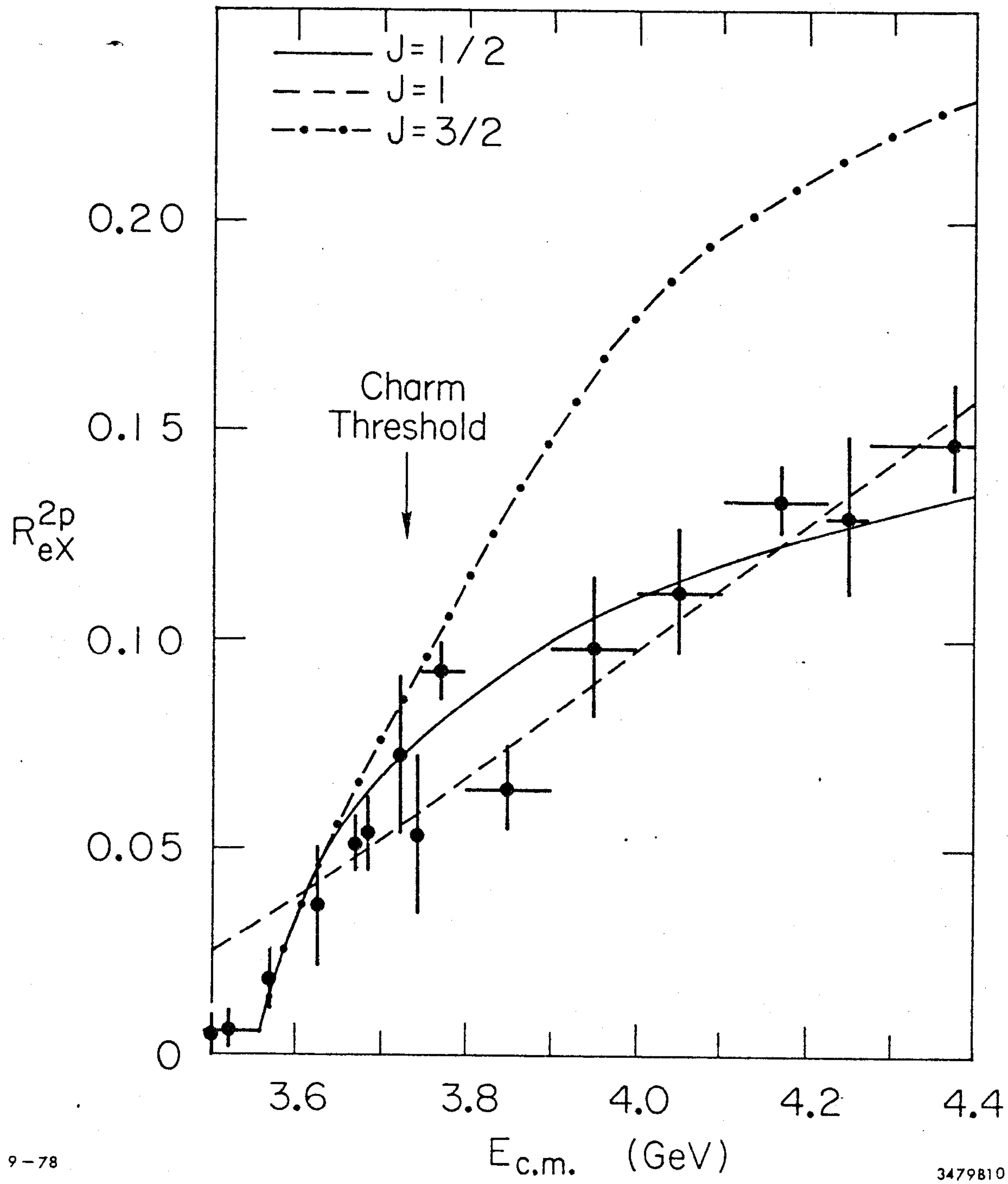


Fig. 8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J = 3/2
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0.15
0.10
0.05
0
R_{eX}^{2p}
Charm Threshold
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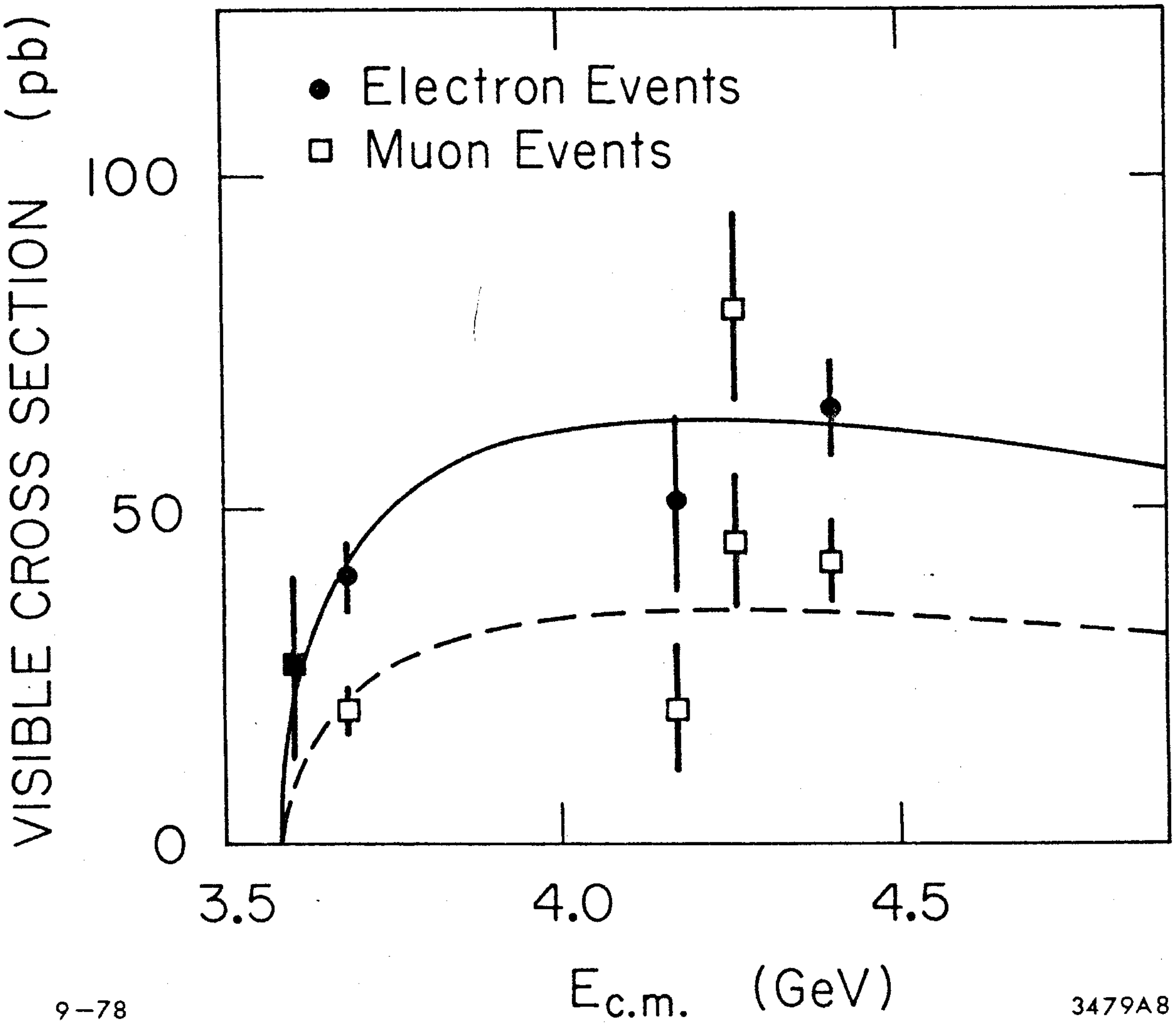
3.8
4.0
4.2
4.4
$E_{c.m.}$ (GeV)
9-78
3479810

Fig. 9


● Electron Events
□ Muon Events
VISIBLE CROSS SECTION (pb)
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50
100
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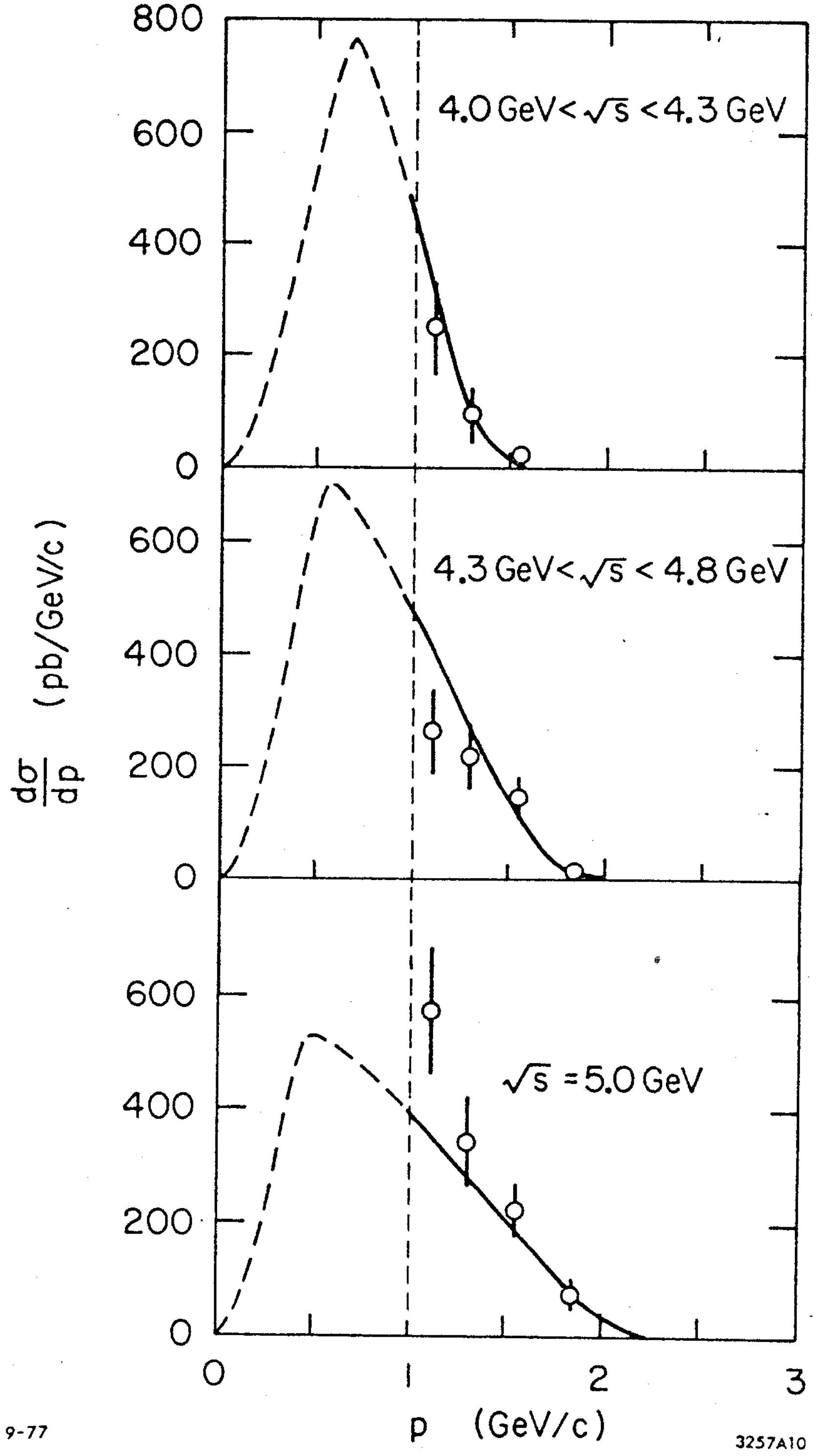
4.0
4.5
Ec.m. (GeV)
9-78
3479A8

Fig. 10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600
400
200
0
4.0 GeV< $\sqrt{s}$ <4.3 GeV
600
400
200
0
4.3 GeV< $\sqrt{s}$ < 4.8 GeV
600
400
200
0
$\sqrt{s}$ =5.0 GeV
$\frac{d\sigma}{dp}$ (pb/GeV/c)
0
1
2
3
p (GeV/c)
9-77
3257A10

Fig. 11

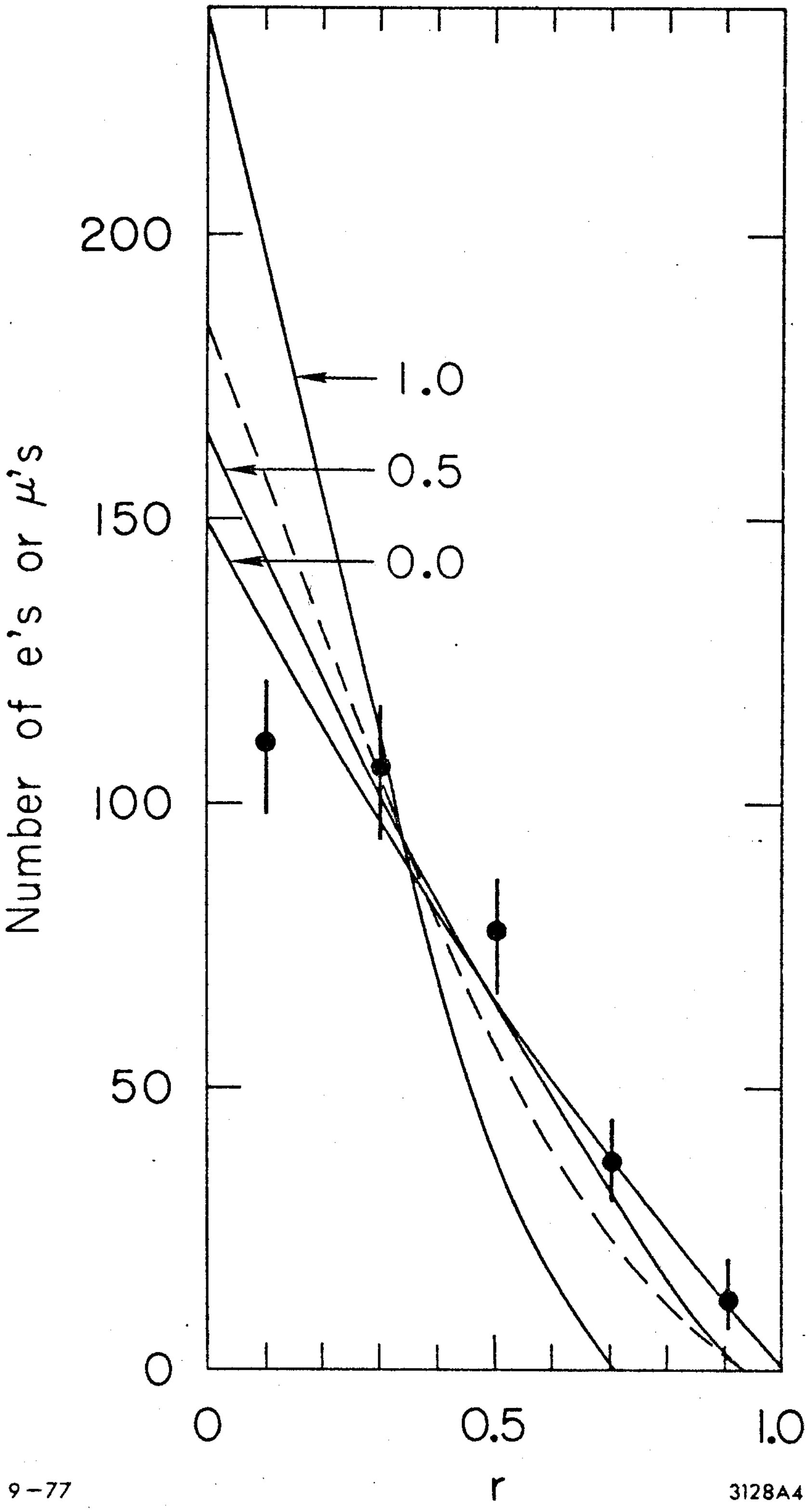


Fig. 12

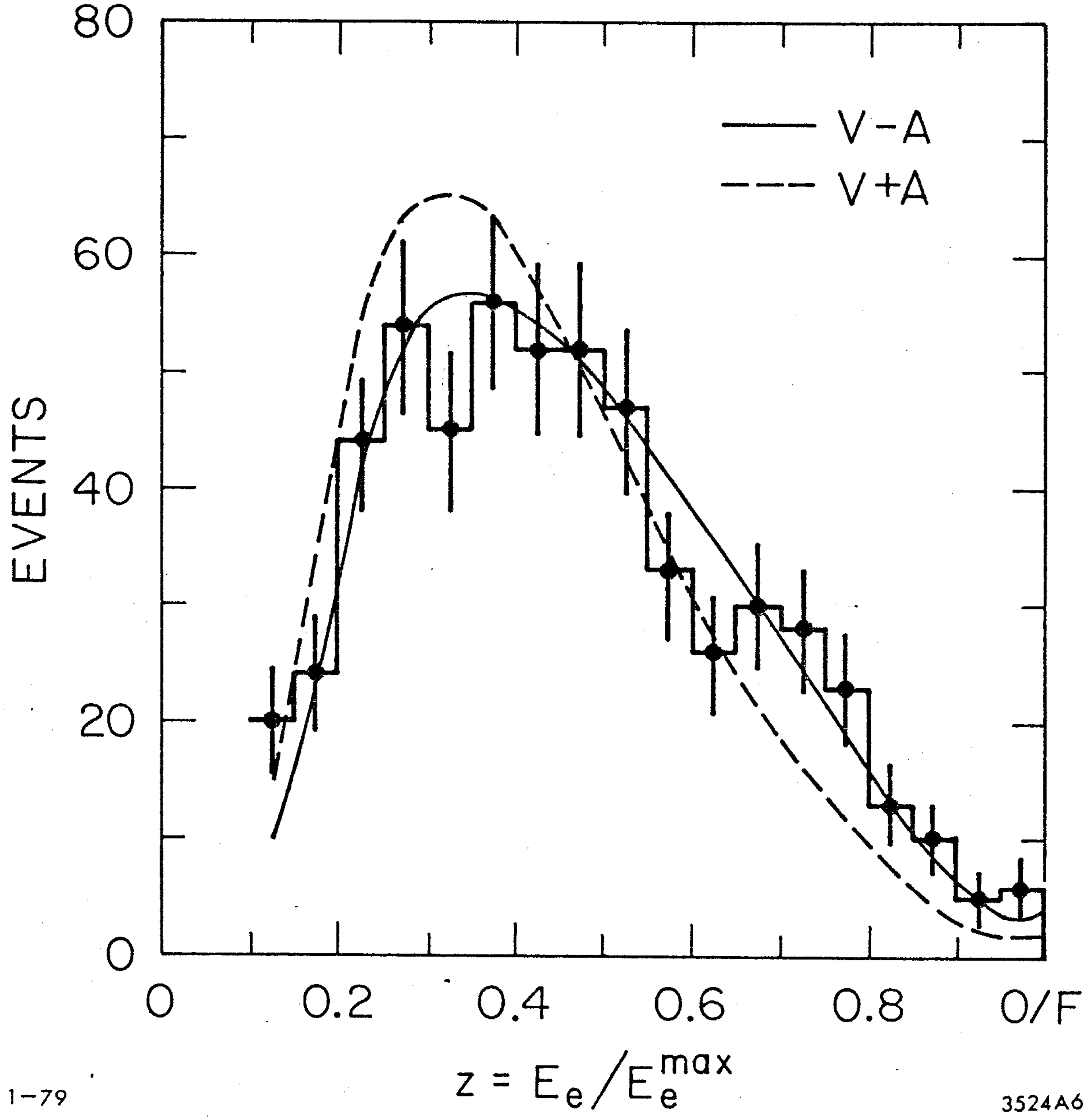


Fig. 13

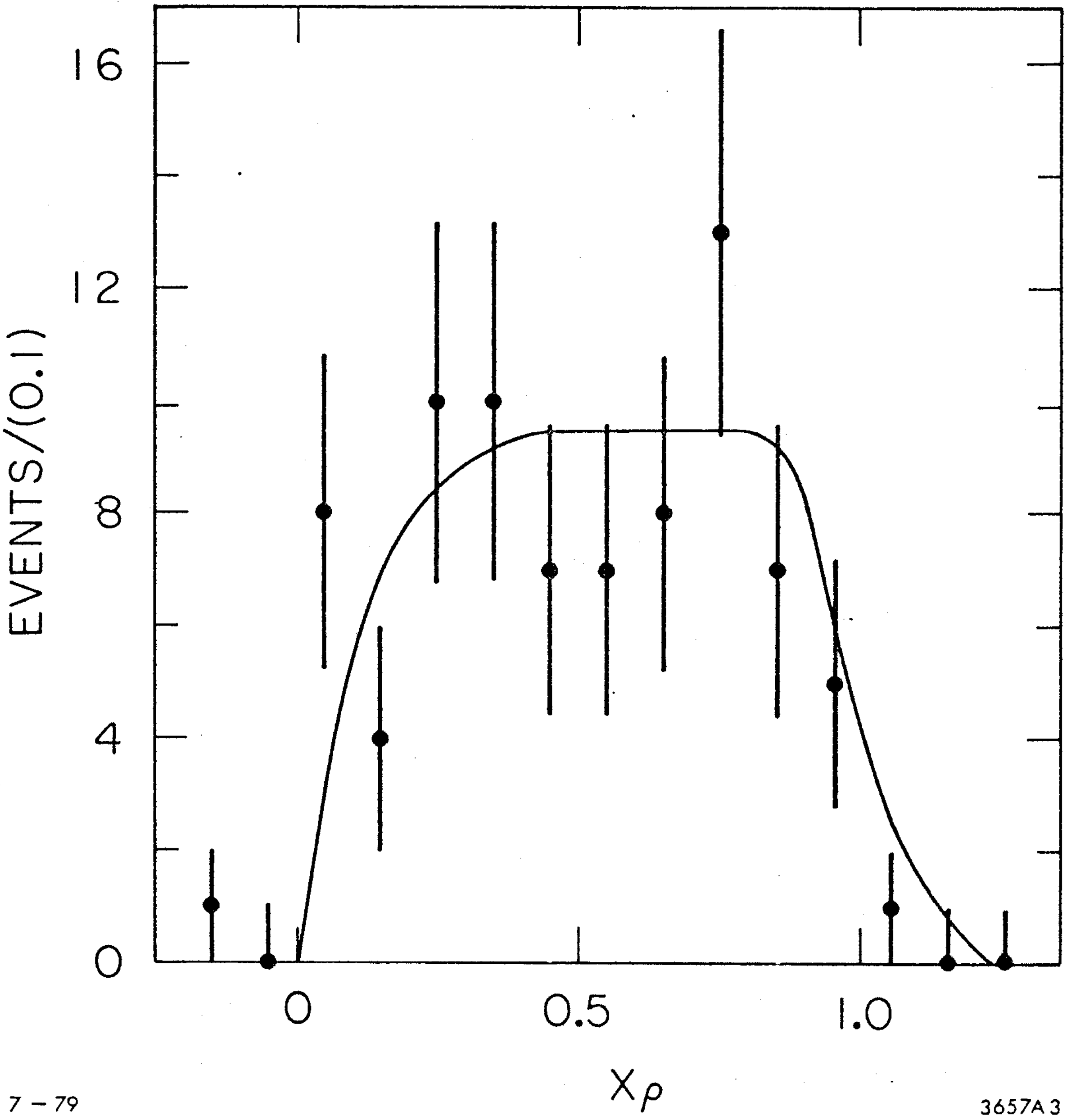
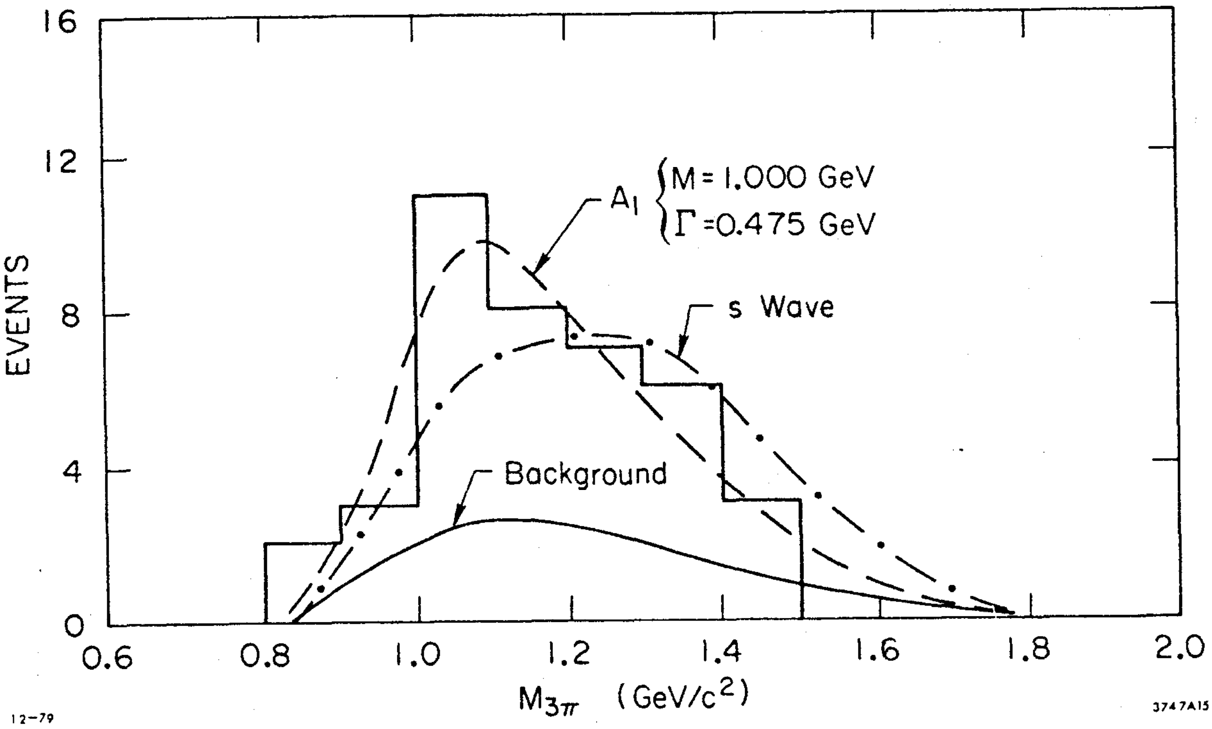


Fig. 14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4
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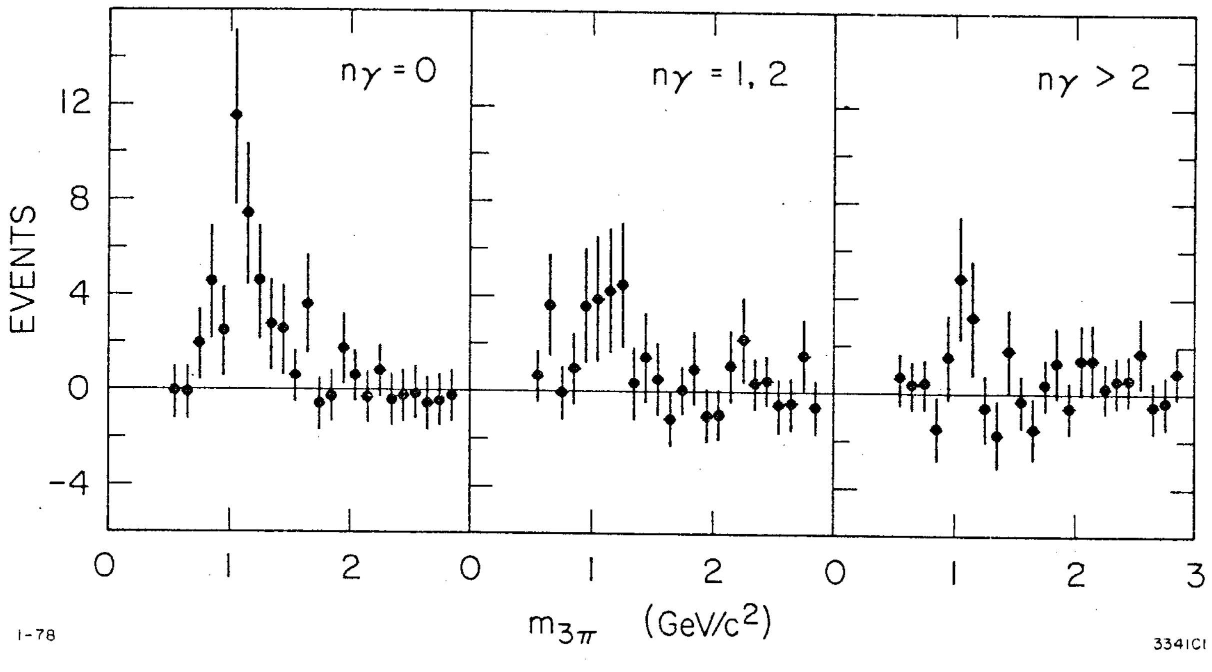
0.8
1.0
1.2
1.4
1.6
1.8
2.0
$M_{3\pi}$ (GeV/c^2)
A_1 M = 1.000 GeV
Γ = 0.475 GeV
s Wave
Background
12-79
3747A15

Fig. 15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nγ = 1, 2
nγ > 2
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4
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-4
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1
2
0
1
2
0
1
2
3
$m_{3\pi}$ (GeV/c^2)
1-78
3341C1

Fig. 16