~~10~~ 12/15/92 JS ①

SLAC-PUB--5937

DE93 004013

THE DISCOVERY OF THE TAU LEPTON*

Martin L. Perl
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

ABSTRACT

The discovery of the tau lepton and the third generation of fermions came from the convergence of three physics streams in the late 1960's and early 1970's. These streams were: the failed attempts by myself and others to understand the connection between the electron and the muon, the development of electron-positron storage rings, and the development of the theory of sequential leptons. In this paper I give the history of the discovery of the tau and the measurement of its major properties–the properties which established the tau as a sequential lepton.

Presented at the Third International Symposium on the History of Particle Physics:
The Rise of the Standard Model, Stanford, CA, June 24-27, 1992

---

* This work was supported by the Department of Energy, contract DE-AC03-76SF00515.

Conf-9206131--3

TABLE OF CONTENTS

A. Introduction

This paper begins with the period 1965–1974 when my colleagues and I worked experimentally on the $e - \mu$ problem and I became immersed in the then hypothetical world of heavy leptons. The paper goes on to describe the discovery, in the period 1974–1976, of the tau lepton by myself and my colleagues using the Mark I detector at the SPEAR e^+e^- storage ring. The next section of the paper recounts the verification of our discovery by ourselves and others, research which occupied the years 1976 through 1978. The final section describes the period 1978–1985 in which the transition was made in experiment and theory to the modern phase of tau research. I have told much of this history in a paper given at the first Workshop on Tau Lepton Physics (Perl 1990) and so I have repeated here quite a bit of material from that paper. A beautiful description of the discovery of the tau was given recently by Gary Feldman (1992).

The discovery of the tau was the subject of a doctoral thesis by Jonathan Treitel in the History of Science Program of Stanford University. The thesis is entitled "Confirmation with Technology: The Discovery of the Tau Lepton" (Treitel 1987).

B. Before the Tau: 1965–1974

B.1 The $e - \mu$ Problem

The history of the discovery of the tau lepton begins in the late 1960's when my colleagues and I and other experimenters worked on the problem of "how does the muon differ from the electron". In fact, that was the title of a paper I wrote for *Physics Today* in 1971 (Perl 1971). At SLAC my colleagues and I had been measuring for several years the differential cross sections for inelastic scattering of muons on protons, and then comparing (Toner *et al.* 1971, Braunstein *et al.* 1972) the $\mu - p$ cross sections with the corresponding $e - p$ cross sections. We hoped to find $e - \mu$ differences, particularly as we studied the differential cross sections at large momentum transfers. Some of our hopes, or at least of my hopes, were certainly naive by today's standards of knowledge of particle physics. For example, in my 1971 paper I speculated, Fig. 1, that the muon might have a special interaction with hadrons not possessed by the electron.

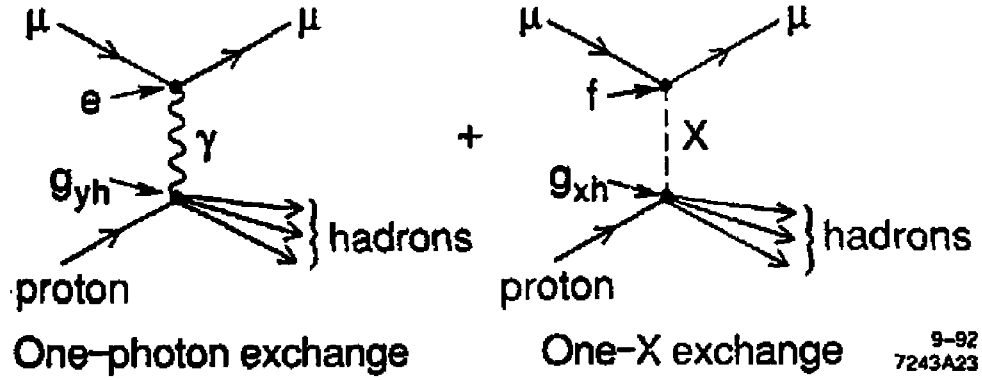


Fig. 1. From Perl (1971): the interaction of a muon with hadrons through exchange of a particle X, an example of the speculation that the muon has a special interaction with hadrons that is not possessed by the electron.

Other experimenters studied the differential cross section for $\mu - p$ elastic scattering and compared with $e - p$ elastic scattering (Ellsworth *et al.* 1968, Camelleri *et al.* 1969, Koustoulas *et al.* 1974). But statistically significant differences between $\mu - p$ and $e - p$ cross sections could not be found in either the elastic or inelastic case. Furthermore there were systematic errors of the order of 5 or 10% in comparing $\mu - p$ and $e - p$ cross sections because the techniques were so different.

Thus it became clear that this was not a fruitful direction and I began to speculate that if we could not find the origin of the $e - \mu$ difference, perhaps we could find another charged lepton, and then this new lepton might lead us back into understanding the origin of [illegible] differences.

B.2 Varieties of Leptons

In those naive days before the rise of the standard model, particle physicists thought about a large variety of types of leptons, and used or thought about using a variety of search methods. In 1972 I presented a paper (Perl 1972) in Moscow at the Seminar on the $\mu - e$ Problem entitled "Searches for Heavy Leptons and Anomalous Leptonic Behavior – the Past and the Future", and I revised it in 1974 with Petros Rapidis (Perl and Rapidis 1974). In these papers we discussed many possible types of leptons:

- sequential leptons
- excited leptons
- paraleptons
- ortholeptons
- long-lived leptons
- stable leptons

Incidentally, it was in these papers that we introduced the term sequential lepton to mean the sequence of pairs:

$$\begin{array}{ll} e^- & \nu_e \\ \mu^- & \nu_\mu \\ \mu'^- & \nu'_\mu \\ \mu''^- & \nu''_\mu \end{array}$$

and so forth, using the notation of those papers.

The list of search methods included:

- searches in particle beams
- production of new leptons by e^+e^- annihilation
- photoproduction of new leptons
- production of new leptons in $p-p$ collisions
- searches in lepton bremsstrahlung
- searches in charged lepton-proton inelastic scattering
- searches in neutrino-nucleon inelastic scattering

Of all these methods the search for new charged leptons using e^+e^- annihilation was most appealing to me. The idea was to look for

$$e^+ + e^- \rightarrow \ell^+ + \ell^-$$

with

$$\ell^+ \rightarrow e^+ + \text{undetected neutrinos carrying off energy}$$

$$\ell^- \rightarrow \mu^- + \text{undetected neutrinos carrying off energy} \qquad (1)$$

or

$$\ell^+ \rightarrow \mu^+ + \text{undetected neutrinos carrying off energy}$$

$$\ell^- \rightarrow e^- + \text{undetected neutrinos carrying off energy}$$

This search method had many attractive features:

- If the ℓ was a point particle, I could search up to an ℓ mass (m_ℓ) almost equal to the beam energy, given enough luminosity.
- The appearance of an $e^+\mu^-$ or $e^-\mu^+$ event with missing energy would be dramatic.
- The apparatus I proposed to use to detect the reactions in Eq. 1 was very poor in identifying types of charged particles, certainly by today's standards, but the easiest particles to identify were the e and the μ.
- There was little theory involved in predicting that the ℓ would have the weak decays

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

  with corresponding decays for the ℓ^+. One simply could argue by analogy from the known decay

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

I incorporated the e^+e^- search method summarized by Eq. 1 in our 1971 Mark I proposal (Larsen *et al.*) to use the not-yet-completed SPEAR e^+e^- storage ring.

B.3 Sequential Lepton Theory

My thinking about sequential leptons and the use of the method of Eq. 1 to search for them was greatly helped and influenced by the seminal work of my long-term friend and colleague, Paul Tsai. His 1971 paper (Tsai 1971) entitled "Decay Correlations of Heavy Leptons in $e + e \rightarrow \ell^+ + \ell^-$" provided the theory for my work in sequential lepton searches from the beginning. The reader might look back at Table II from Tsai's paper. This table gives the decay modes and their branching ratios for various lepton masses, branching ratios which we are still trying to precisely measure today. Tsai's work was incorporated in the heavy lepton search part of the Mark I detector proposal for SPEAR (Larsen *et al.* 1971).

In 1971 Thacker and Sakurai also published a paper on the theory of sequential lepton decays (Thacker and Sakurai 1971) but it is not as comprehensive as the work of Tsai. The 1971 paper of Tsai was the bible for my work on sequential heavy leptons, and in many ways it still is my bible in heavy lepton physics. A more general paper "Spontaneously Broken Gauge Theories of Weak Interactions and Heavy Leptons" by James Bjorken and Chris Llewellyn Smith (1973) was also very important in my thinking.

B.4 The Mark I Proposal

My thoughts in the late 1960's and 1970–1971 about heavy lepton searches using e^+e^- annihilation coincided with the beginning of the building of the SPEAR e^+e^- storage ring by a group led by Burton Richter and John Rees. Gary Feldman and I, and our Group E, joined with their Group C and a Lawrence Berkeley Laboratory Group led by William Chinowsky, Gerson Goldhaber, and George Trilling. Incidentally, at that time, we in Group E were also working with physicists from the Massachusetts Institute of Technology on a SLAC experiment in the electroproduction of hadrons (Dakin *et al.* 1972, Martin *et al.* 1976). I had given up on investigating the $\mu - e$ puzzle through studying inelastic charged lepton scattering but I still hoped that anomalous lepton properties could be found in the interaction of leptons and hadrons.

Returning to the Mark I experiment at SPEAR, we submitted the proposal (Larsen *et al.* 1971) in 1971. Figure 1 of Perl (1990) shows the title page. The contents consisted of five sections and a supplement as follows:

A.	Introduction	Page 1
B.	Boson Form Factors	Page 2
C.	Baryon Form Factors	Page 6
D.	Inelastic Reactions	Page 12
E.	Search for Heavy Leptons	Page 16
	Figure Captions	Page 19
	References	Page 20
	Supplement	

Thus the heavy lepton search was left for last and allotted just three pages because it seemed to be a remote dream. But the three pages contained the essential idea of searching for heavy leptons using $e\mu$ events, Eq. 1.

I wanted to include a lot more about heavy leptons and the $e - \mu$ problem but my colleagues thought that would unbalance the proposal. We compromised on a 10 page supplement entitled "Supplement to Proposal SP-2 on Searches for Heavy Leptons and Anomalous Lepton-Hadron Interactions". The supplement began as follows.

> "1. <u>Introduction</u>
>
> While the detector is being used to study hadronic production processes it is possible to simultaneously collect data relevant to the following questions:
>
> (1) Are there charged leptons with masses greater than that of the muon?
>
> We normally think of the charged heavy leptons as having spin $\frac{1}{2}$ but the search method is not sensitive to the spin of the particle. This search for charged heavy leptons automatically includes a search for the intermediate vector boson which has been postulated to explain the weak interactions. This is discussed in Section 8.
>
> (2) Are there anomalous interactions between the charged leptons and the hadrons?

> In this part of the proposal we show that using the detector we can gather definitive information on the first question within the available mass range. We can obtain preliminary information on the second question - information which will be very valuable in designing further experiments relative to that question. We can gather all this information while the detector is being used to study hadronic production processes. Additional running will be requested if the existence of a heavy lepton, found in this search, needs to be confirmed. This is discussed in Section 5."

My heart was in heavy lepton searches, but I continued to investigate the idea that an unknown $e-\mu$ difference could be revealed by an anomalous interaction of the e or μ with hadrons; a carry-over from our old comparisons of $e-p$ and $\mu-p$ inelastic scattering.

B.5 Heavy Lepton Searches at ADONE

While SPEAR and the Mark I detector were being built heavy lepton searches (Zichichi, 1992) were being carried out at the ADONE e^+e^- storage ring by two groups of pioneer experimenters in electron-positron annihilation physics: One group led by Antonino Zichichi reported in 1970 and 1973 (Alles-Borelli *et al.* 1970, Bernardini *et al.* 1973). Figure 2 is taken from their 1973 paper entitled "Limits of the Mass of Heavy Leptons". It is interesting to quote the first two paragraphs of that paper.

> "Great interest in heavy leptons has recently been revived by the gauge theories of weak interactions. These theoretically wanted heavy leptons would be of two types, electronlike and muonlike, and would have the leptonic number opposite to that of the same charge state of the ordinary lepton. So (E^+, ν_e, e^-) would be a triplet with leptonic number of the ordinary electron, and (M^+, ν_μ, μ^-) another triplet with leptonic number of the ordinary muon. Heavy leptons of a different type, each one with its own associated neutrino–and therefore with a leptonic number different from that of the ordinary leptons–were advocated a long time ago in the hope of understanding why the chain of leptons is short with respect to the long chain of hadrons.
>
> All these types of heavy leptons can be produced via timelike photons in the reaction

$$e^+ + e^- \rightarrow \begin{array}{l} \rightarrow E^+ + E^- \quad , \\ \rightarrow M^+ + M^- \quad , \\ \rightarrow L^+ + L^- \quad ." \end{array}$$

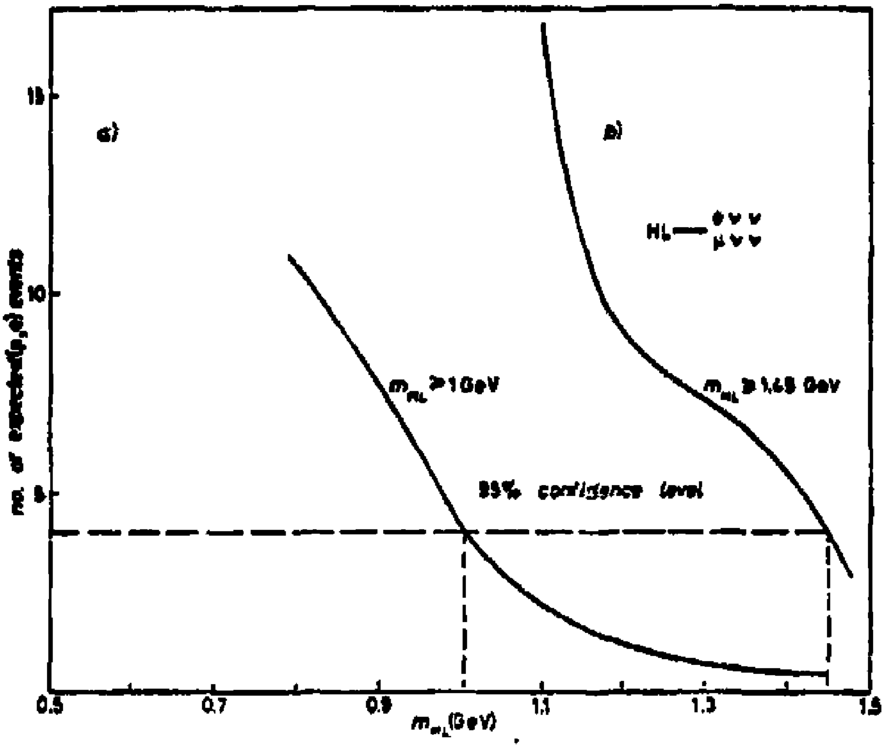


Fig. 2. From Bernardini *et al.* (1973) the caption reads:
"The expected number of $(\mu^{\pm} e^{\mp})$ pairs *vs.* m_{HL} for two types of universal weak couplings of the heavy leptons. The dashed lines indicate the 95% confidence levels for m_{HL}. a) HL universally coupled with ordinary leptons and hadrons, b) HL universally coupled with ordinary leptons."

Returning to Fig. 2 (Bernardini *et al.* 1973), the experiment covered two search regions, the mass reach depending upon the leptonic decay assumptions.

The other group of pioneer experimenters in electron-positron annihilation physics was led by Shuji Orito and Marcello Conversi. Their search region (Orito *et al.* 1974) also extended to masses of about 1 GeV/c^2.

C. Discovery of the Tau in the Mark I Experiment: 1974–1976

C.1 SPEAR and the Mark I Detector

The SPEAR e^+e^- collider began operation in 1973. Eventually SPEAR obtained a total energy of about 8 GeV, but in the first few years the maximum energy with useful luminosity was 4.8 GeV.

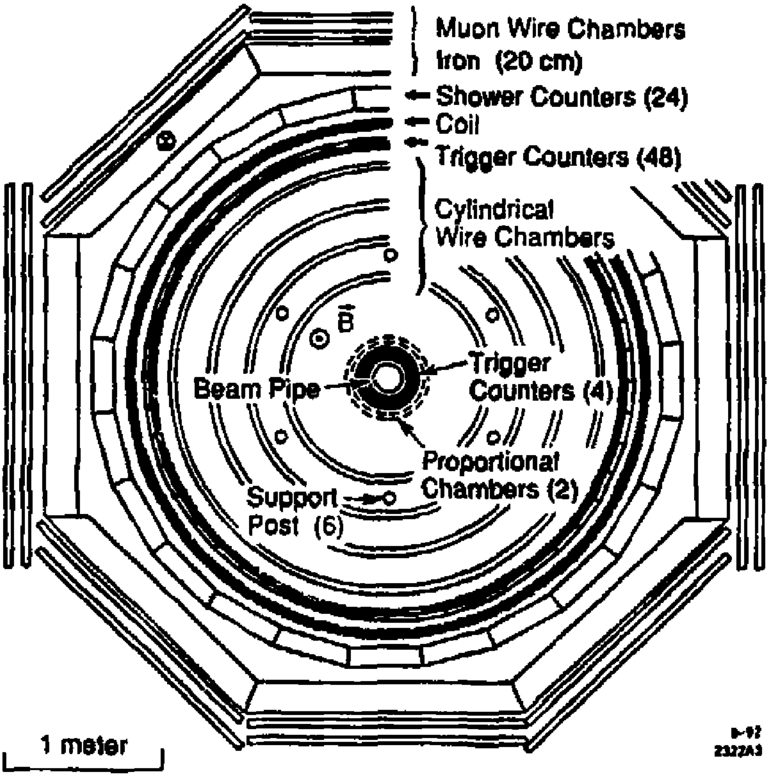


Fig. 3. The initial form of the Mark I detector.

We also began operating the Mark I experiment in 1973 in the form shown in Fig. 3. The Mark I was one of the first large-solid-angle, general purpose detectors built for colliding beams. The use of large-solid-angle particle tracking and the use of large-solid-angle particle identification systems is obvious now, but it was not obvious twenty years ago. The electron detection system used lead-scintillator sandwich counters built by our Berkeley colleagues. The muon detection system was also crude using the iron flux return which was only 1.7 absorption lengths thick.

C.2 Discovery of the $e - \mu$ events

However, both detection systems worked well enough, and in 1974 I began to find $e\mu$ events, that is events with an e, an opposite sign μ, no other charged particles, and no visible photons.

By early 1975 we had seen dozens of $e\mu$ events, but those of us who believed we had found a heavy lepton faced two problems: how to convince the rest of our collaboration and how to convince the physics world. The main focus of this early skepticism was the γ, e and μ identification systems: Had we underestimated hadron misidentification into leptons? Since our γ and e system only covered about half of 4π, what about undetected photons? What about inefficiencies and cracks in these systems?

I worked through this skepticism by gradually expanding the geographic range of the talks I gave. And in those talks, I answered objections if I could. If new objections were raised, I simply said that I had no answer then. I then worked on the new objections before the next talk.

In June, 1975 I gave the first international talk on the $e\mu$ events (Perl 1975) at the 1975 Summer School of the Canadian Institute for Particle Physics. The contents of the talk are shown here.

Table of Contents - Part II

The talk had two purposes. First, to discuss possible sources of $e\mu$ events: heavy leptons, heavy mesons and intermediate bosons. And second, to demonstrate that we had some good evidence for $e\mu$ events. The largest single energy data sample, Table 1, was at 4.8 GeV, the highest energy at which we could then run SPEAR. The 24 $e\mu$ events in the total charge=0, number photons=0 column was our strongest claim.

One of the cornerstones of this claim was an informal analysis carried out by Jasper Kirkby who was then at Stanford University and SLAC. He showed me that just using the numbers in the 0 charge, 0 photons columns of Table 1, we could calculate the probabilities for hadron misidentification in this class of events. There were not enough eh, μh, and hh events to explain away the 24 $e\mu$ events.

Table I. From Perl (1975). A table of 2-charged-particle events collected at 4.8 GeV in the Mark I detector. The table, containing 24 $e\mu$ events with zero total charge and no photons, was the strongest evidence at that time for the τ. The caption read:

> "Distribution of 513, 4.8 GeV, 2-prong, events which meet the criteria: $p_e > 0.65$ GeV/c, $p_\mu > 0.65$ GeV/c, $\theta_{copl} > 20^\circ$."

	Total Charge = 0			Total Charge = ±2		
Number photons =	0	1	> 1	0	1	> 1
ee	40	111	55	0	1	0
$e\mu$	24	8	8	0	0	3
$\mu\mu$	16	15	6	0	0	0
eh	18	23	32	2	3	3
μh	15	16	31	4	0	5
hh	13	11	30	10	4	6
Sum	126	184	162	16	8	17

The misidentification probabilities determined from three-or-more prong hadronic events and other considerations are given in Table II (Perl 1975). Compared to present experimental techniques the $P_{h\to e}$ and $P_{h\to\mu}$ misidentification probabilities of about 0.2 are enormous, but I could still show that the 24 $e\mu$ events could not be explained away.

Table II. From Perl (1975). The caption read:
"Misidentification probabilities for 4.8 GeV sample"

Momentum range (GeV/c)	$P_{h\to e}$	$P_{h\to\mu}$	$P_{h\to h}$
0.6 - 0.9	.130 ± .005	.161 ± .006	.709 ± .012
0.9 - 1.2	.160 ± .009	.213 ± .011	.627 ± .020
1.2 - 1.6	.206 ± .016	.216 ± .017	.578 ± .029
1.6 - 2.4	.269 ± .031	.211 ± .027	.520 ± .043
weighted average using hh, μh, and $e\mu$ events	.183± .007	.198 ± .007	.619 ± .012

This Montreal paper ended with these conclusions:

"1) No conventional explanation for the signature $e\mu$ events has been found.

2) The hypothesis that the signature $e\mu$ events come from the production of a pair of new particles – each of mass about 2 GeV – fits almost all the data. Only the θ_{coll} distribution is somewhat puzzling.

3) The assumption that we are also detecting ee and $\mu\mu$ events coming from these new particles is still being tested."

I was still not able to specify the source of the μe events: leptons, mesons or bosons. But I remember that I felt strongly that the source was heavy leptons. It would take almost two more years to prove that.

A remark on the θ_{coll} distribution, Fig. 5 of Perl (1975). I was worried that there were no events with $\theta_{coll} > 80°$. I knew that in small data sets it is unlikely for all distributions to fit predictions, but I was worried.

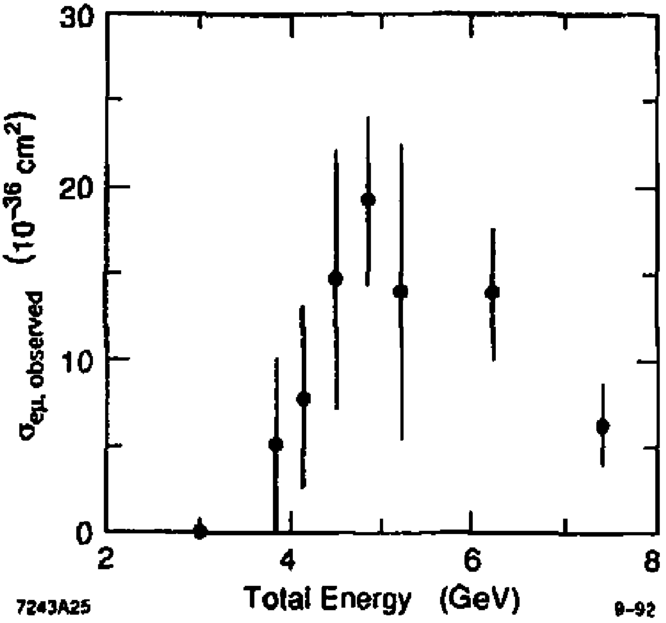
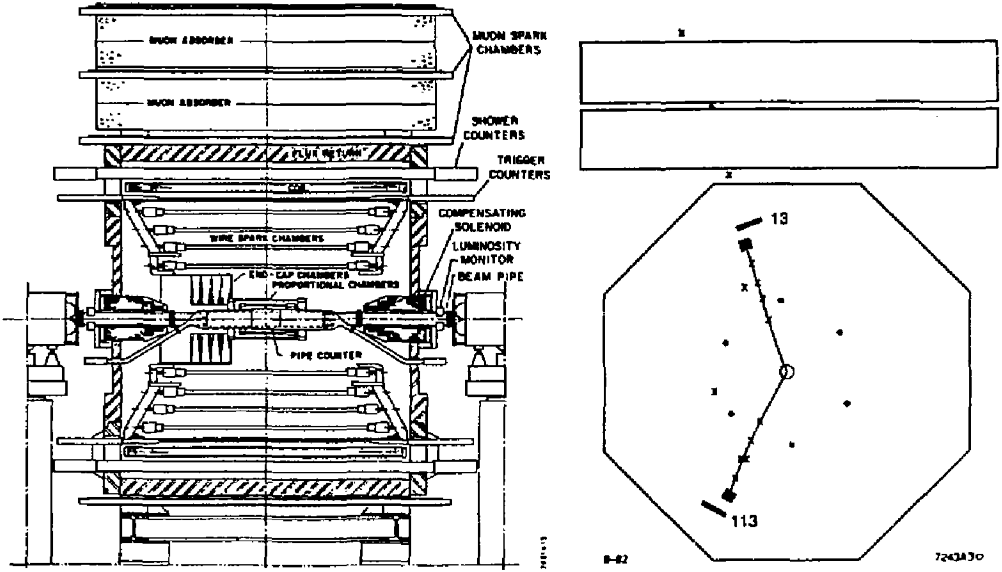


Fig. 4. From Perl *et al.* (1975): the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.



(a) (b)

Fig. 5. (a) The Mark I detector with the muon tower; (b) one of the first $e\mu$ events using the muon tower. The μ moves upward through the muon detector tower and the e moves downward. The numbers 13 and 113 give the relative amounts of electromagnetic shower energy deposited by the μ and e. The six square dots show the positions of longitudinal support posts of the magnetostrictive spark chamber used for tracking.

C.3 First Publication

As 1974 passed we acquired e^+e^- annihilation data at more and more energies, and at each of these energies there was an anomalous $e\mu$ event signal, Fig. 4. Thus, I and my colleagues in the Mark I experiment became more and more concerned of the reality of the $e\mu$ events and the absence of a conventional explanation.

An important factor in this growing conviction was the addition of a special muon detection system to the detector, Fig. 5a, called the muon tower. This addition was conceived and built by G. Feldman. Although we did not use events such as that in Fig. 5b in our first publication, seeing a few events like this was enormously comforting.

Finally in December 1975, the Mark I experimenters published a paper by Perl *et al.* (1975) entitled " Evidence for Anomalous Lepton Production in $e^+ - e^-$ Annihilation". The final paragraph read:

> "We conclude that the signature $e - \mu$ events cannot be explained either by the production and decay of any presently known particles or as coming from any of the well-understood interactions which can conventionally lead to an e and a μ in the final state. A possible explanation for these events is the production and decay of a pair of new particles, each having a mass in the range of 1.6 to 2.0 GeV/c^2."

We were not yet prepared to claim that we had found a new charged lepton, but we were prepared to claim that we had found something new. To accentuate our uncertainty I denoted the new particle by U for unknown in some of our 1975–1977 papers. The name τ came later. Incidentally, τ was suggested by P. Rapidis who was then a graduate student and worked with me in the early 1970's on the $e - \mu$ problem (Perl and Rapidis 1974). The letter τ is from Greek $\tau\rho\iota\tau o\nu$ for third – the third charged lepton.

D. Is it a Lepton: From Uncertainty and Controversy to Confirmation: 1976–1978

D.1 Uncertainty

Our first publication was followed by several years of confusion and uncertainty about the validity of our data and its interpretation. It is hard to explain this confusion a decade later when we know that τ pair production is 20% of the e^+e^- annihilation cross section below the Z^0, and when τ pair events stand out so clearly at the Z^0.

There were several reasons for the uncertainties of that period. It was hard to believe that both a new quark, charm, and a new lepton, tau, would be found in the same narrow range of energies. And, while the existence of a fourth quark was required by theory, there was no such requirement for a third charged lepton. So there were claims that the $e\mu$ events were the complicated result of the decays of charm quarks. There were claims that the other predicted decay modes of tau pairs such as e–hadron and μ–hadron events could not be found. Indeed finding such events was just at the limit of the particle identification capability of the detectors of the mid-1970's.

It was a difficult time. Rumors kept arriving of definitive evidence against the τ: $e\mu$ events *not* seen, the $\tau \rightarrow \pi\nu$ decay *not* seen, theoretical problems with momentum spectra or angular distribution. With colleagues such as G. Feldman I kept going over our data again and again. Had we gone wrong somewhere in our data analysis?

An illustration of the confusion about the tau is provided by two editions of a 1976-1977 popular book on particle physics by Nigel Calder entitled "The Key to the Universe". In the first edition (Calder 1977a) Calder wrote:

> "Martin Perl and his colleagues detected peculiar events occurring in SPEAR. From the scene of collision an electron and a heavy electron (the well-known muon) carrying opposite electric charges were ejected at the same moment without

any other detectable particles coming out. No conventional process, involving conventional particles, could account for such events."

> "The particle called U was grotesquely weighty for an electron. Theorists had been asking one another for many years why the muon, a heavy electron of 105 mass-energy units, was two hundred times heavier than the ordinary electron (0.5 units). They had no answer even to that. And the U particle was estimated to be 1800 mass-energy units, twice as heavy as a hydrogen atom!"
>
> "Doubts also overtook Stanford's heavy lepton, the U particle. There were suggestions, notably from the DORIS experiments in Hamburg, that it was an illusion – perhaps a misinterpretation of the decay of the charmed particles. At the time of writing these doubts have not been resolved and they illustrate again the difficulties and tensions of high-energy physics. A fair summary of the situation may be that there is no very compelling evidence so far for nature deploying more than four types of quarks and four members of the electron family."

But in the second edition (Calder 1977b) he wrote:

> "The particle U was grotesquely weighty for an electron. Theorists had been asking for one another for many years why the muon, a heavy electron of 105 mass-energy units, was two hundred times heavier than the ordinary electron (0.5 units). They had no answer even to that. And the U particle was estimated to be 1800 mass-energy units, twice as heavy as a hydrogen atom! Experiments with DORIS in Hamburg confirmed the discovery."

D.2 Anomalous Muon Events

The first advance beyond the $e\mu$ events came with three different demonstrations of the existence of anomalous μ−hadron events from

$$\begin{aligned} &e^+ + e^- \rightarrow \tau^+ + \tau^- \\ &\tau^+ \rightarrow \bar{\nu}_\tau + \mu^+ + \nu_\mu \\ &\tau^- \rightarrow \nu_\tau + \text{hadrons} \end{aligned} \tag{4}$$

I have in my files a June 3, 1976 Mark I note by G. Feldman discussing μ events using the muon identification tower of the Mark I detector, Fig. 5a. For data acquired above 5.8 GeV he found the following:

> "Correcting for particle misidentification, this data sample contains 8 μe events and 17 μ–hadron events. Thus, if the acceptance for hadrons is about the same as the acceptance for electrons, and these two anomalous signals come from the same source, then with large errors, the branching ratio into one observed charged hadron is about twice the branching ratio into an electron. This is almost exactly what one would expect for the decay of a heavy lepton."

This conclusion was published (Feldman *et al.* 1977) in a paper entitled "Inclusive Anomalous Muon Production in e^+e^- Annihilation".

The first and very welcome outside confirmation of anomalous muon events came from another SPEAR experiment by Cavalli-Sforza *et al.* (1976).

The most welcomed confirmation, because it came from an experiment at the DORIS e^+e^- storage ring, was from the PLUTO experiment. In 1977 the PLUTO Collaboration published (Burmester *et al.* 1977) A paper entitled "Anomalous Muon Production in e^+e^- Annihilation as Evidence for Heavy Leptons". PLUTO was also a large-solid-angle detector and so for the first time we could fully discuss the art and technology of τ research with an independent set of experimenters, with our friends Hinrich Meyer and Eric Lohrman of the PLUTO Collaboration.

With the finding of μ–hadron events I was convinced I was right about the existence of the τ as a sequential heavy lepton. Yet there was much to disentangle: it was still difficult to demonstrate the existence of anomalous e–hadron events and there were still rumors that the $\tau \rightarrow \pi\nu$ decay mode could not be found.

D.3 Anomalous Electron Events

The demonstration of the existence of e–hadron events

$$\begin{aligned} &e^+ + e^- \rightarrow \tau^+ + \tau^- \\ &\tau^+ \rightarrow \bar{\nu}_\tau + e^+ + \nu_e \\ &\tau^- \rightarrow \nu_\tau + \text{hadrons} \end{aligned} \qquad (5)$$

required improved electron identification in the detectors. A substantial step forward was made by the new DELCO detector at SPEAR (Kirkby 1977) which I will discuss in connection with the determination of the mass of the τ.

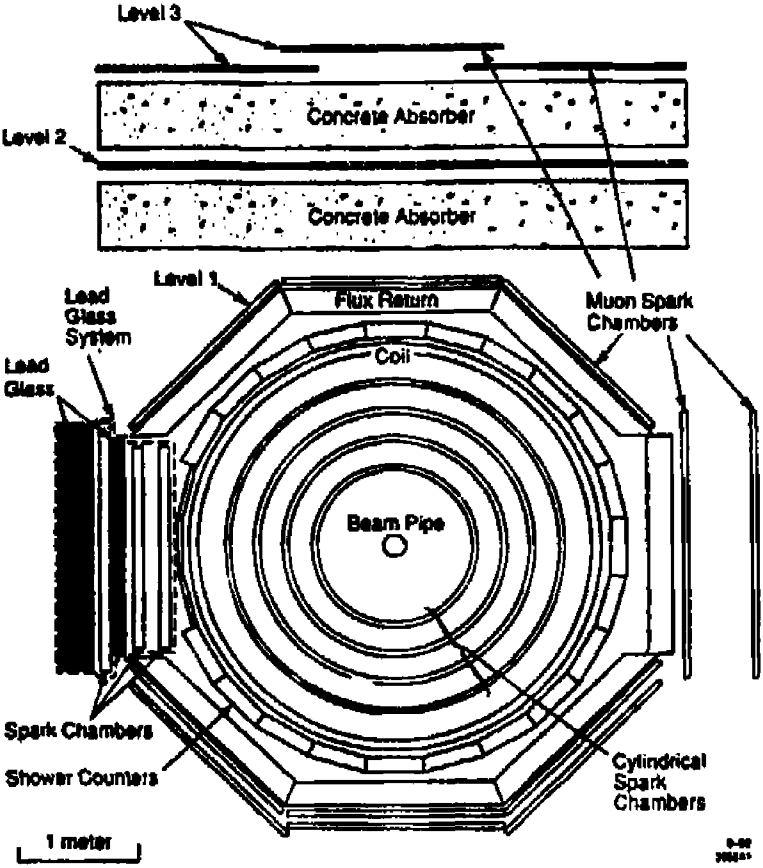


Fig. 6. The "lead glass wall" modification of the Mark I detector used at SPEAR to find anomalous $e-$ hadron events (Barbaro-Galtieri *et al.* 1977).

The Mark I detector was also improved by Group E from SLAC and a Lawrence Berkeley Laboratory Group led by Angela Barbaro-Galtieri; some of the original Mark I experimenters had gone off to begin to build the Mark II detector. We installed a wall of lead glass electromagnetic shower detectors in the Mark I, Fig. 6. This led to the important paper (Barbaro-Galtieri *et al.* 1977) entitled "Electron-Muon and Electron-Hadron Production in e^+e^- Collisions". The abstract read:

> "We observe anomalous $e\mu$ and $e-$hadron events in e^+e^- collisions at SPEAR in an experiment that uses a lead-glass counter system to identify electrons. The anomalous events are observed in the two-charged-prong topology. Their properties are consistent with the production of a pair of heavy leptons in the reaction $e^+e^- \rightarrow \tau^+\tau^-$ with subsequent decays of $\tau^\pm$ into leptons and hadrons. Under the assumption that they come only from this source, we measure the branching ratios $B(\tau \rightarrow e\nu_e\nu_\tau) = (22.4 \pm 5.5)\%$ and $B(\tau \rightarrow h + \text{neutrals}) = (45 \pm 19)\%$."

D.4 The 1977 Photon-Lepton Conference at Hamburg

At the 1977 International Symposium on Lepton and Photon Interactions at High Energies there were three review papers which portrayed the then current state of knowledge of the τ.

A paper from the DASP experiment at DORIS (Yamada 1977) with the title "Recent Results from DASP" described their measurements of $\mu-$hadron and $e-$hadron events, Eqs. 4 and 5, which confirm the sequential lepton nature of the τ. But Yamada reported that they could not find the pion decay mode

$$\tau^- \rightarrow \nu_\tau + \pi^- \quad , \tag{6}$$

setting an upper limit on the branching fraction of (2. ± 2.5)% while theory predicts about 10%.

The second review paper (Kirkby 1977) was entitled "Direct Electron Production Measurement by DELCO at SPEAR". The abstract reads in part

> "A comparison of the events having only two visible prongs (of which only one is an electron) with the heavy lepton hypothesis shows no disagreement. Alternative hypotheses have not yet been investigated."

Finally, in my paper (Perl 1977) entitled "Review of Heavy Lepton Production in e^+e^- Annihilation", I concluded

> "*a.* All data on anomalous $e\mu$, ex, ee and $\mu\mu$ events produced in e^+e^- annihilation is consistent with the existence of a mass 1.9 ± 0.1 GeV/c^2 charged lepton, the τ.
>
> *b.* This data cannot be explained as coming from charmed particle decays.
>
> *c.* Many of the expected decay modes of the τ have been seen. A very important problem is the existence of the $\tau^- \rightarrow \nu_\tau \pi^-$ decay mode."

D.5 The Search for $\tau^- \rightarrow \nu_\tau + \pi^-$

Thus in the summer of 1977 the major problem in fully establishing the nature of the τ was the uncertainty in the branching ratio, $B(\tau \rightarrow \pi\nu)$. This was a serious problem because from $B(\pi \rightarrow \mu\nu)$ and $B(\tau \rightarrow e\nu\nu)$ it follows directly that $B(\tau \rightarrow \pi\nu)$ should be about 10%. I can't explain now why experimenters, including ourselves, had difficulty with this mode, but we did have difficulty.

In the Mark I collaboration the first demonstration that $B(\tau \rightarrow \pi\nu)$ was substantial came from Gail Hanson in an internal note dated March 7, 1978. She looked at a sample of 2-prong, 0-photon events with one high-momentum prong. Figure 11 in Perl (1979) taken from her internal note shows an excess of events, particularly at large x, if $B(\tau \rightarrow \pi\nu)$ is taken as zero.

By the middle of 1978 there was no longer a problem with $\tau \rightarrow \pi\nu$, the clouds of confusion parted and the sun shone on a $B(\tau \rightarrow \pi\nu)$ close to the expected 10%. Table III from Feldman (1978) shows the late-1978 measurements.

Table III. From Feldman (1978), the various measured branching fractions for $\tau^- \rightarrow \pi^- \nu_\tau$ in late 1978.

Experiment	Mode	Events	Background	$B(\tau \rightarrow \pi\nu)$ (%)
SLAC-LBL	$x\pi$	≈ 200	≈ 70	$9.3 \pm 1.0 \pm 3.8$
PLUTO	$x\pi$	32	9	$9.0 \pm 2.9 \pm 2.5$
DELCO	$e\pi$	18	7	$8.0 \pm 3.2 \pm \pm 1.3$
Mark II	$x\pi$	142	46	$8.0 \pm 1.1 \pm 1.5$
	$e\pi$	27	10	$8.2 \pm 2.0 \pm 1.5$
Average				8.3 ± 1.4

Thus by the end of 1978 all confirmed measurements agreed with the hypothesis that the τ was a lepton which was produced by a known electromagnetic interaction and, at least in its main modes, decayed through the conventional weak interaction. I think of 1978 as the year when the first phase of research on the τ ended.

E. Nailing Down the Tau: 1978–1985

In the final section of this paper I sketch the history of τ research in the years 1978 to 1985 when that research made the transition from the verification of the existence of the tau to the present period of detailed studies of tau properties; studies which may lead to the discovery of new particle physics.

E.1 The Tau Mass

The initial history of measurements of the τ mass, m_τ, is brief. The first estimate $m_\tau = 1.6$ to 2.0 GeV/c was made along with the initial evidence for the τ (Perl *et al.* 1975). By the beginning of 1978 the DASP experiment (Brandelik *et al.* 1978) at the DORIS e^+e^- storage ring showed $m_\tau = 1807 \pm 20$ MeV/c^2.

By the middle of 1978 the DELCO experiment at SPEAR (Bacino *et al.* 1978) had made the best measurement $m_\tau = 1784^{+3}_{-7}$ MeV/c^2 as reported in a paper entitled "Measurement of the Threshold Behavior of $\tau^+\tau^-$ Production in e^+e^- Annihilation".

It is only in 1992, fourteen years later, that there has been an improvement in the measurement of m_τ, the BES Collaboration using the BEPC e^+e^- collider has just reported (Bai *et al.* 1992) $m_\tau = 1776.9 \pm 0.5$ MeV/c^2.

E.2 The Tau at High Energies – PETRA and PEP

As the 1970's ended, τ research began to be carried out at higher energies, first at the new PETRA e^+e^- collider at DESY, then at the new PEP collider at SLAC. Two of the earlier high energy papers are from the TASSO and CELLO experiments. "Production and Properties of the τ Lepton in e^+e^- Annihilation at C.M. Energies from 12 to 31.6 GeV" (Brandelik *et al.* 1980), and "Measurement of $e^+e^- \to \tau^+\tau^-$ at High Energies and Properties of the τ Lepton" (Behrend *et al.* 1982). This was the beginning of a tremendous amount of research in the 1980's on the tau by the CELLO, JADE, MARK-J, PLUTO, and TASSO experiments at PETRA; and by the DELCO, HRS, MAC, MARK II, and TPC experiments at PEP. The papers on the tau from these experiments number close to one hundred.

Although they do not fall within the historical period under discussion, it is important to point out the many contributions to tau research beginning in the 1980's: by the ARGUS and Crystal Ball experiments at DORIS II, by the MARK III experiment at SPEAR, by the CLEO and CLEO II experiments at CESR, by the AMY, TOPAZ, and VENUS experiments at TRISTAN, by the ALEPH, DELPHI, L3, and OPAL experiments at LEP, and by the MARK II and SLD experiments at the SLC. And in the last year the BES experimenters at the BEPC have begun τ research.

E.3 The Tau Lifetime

Measurements of the τ lifetime, τ_τ, could not be made at the energies at which SPEAR and DORIS usually operated below 7 GeV; the first measurement of τ_τ required the higher energies of PETRA and PEP. The best measurements required, in addition, secondary-vertex detectors. Actually the first published measurement (Feldman *et al.* 1982) used a primative secondary-vertex detector built by Walter Innes and myself to improve the triggering efficiency of the Mark II detector. Led by G.J. Feldman and G.H. Trilling we measured $\tau_\tau = (4.6 \pm 1.9) \times 10^{-13}$ sec.

Another early measurement was from the MAC experiment at PEP (Ford *et al.* 1982) with $\tau_\tau = (4.9 \pm 2.0) \times 10^{-13}$ sec.

The modern era in τ lifetime measurements began with the pioneering work of John Jaros on precision vertex detectors (Jaros 1982). Table IV taken from that paper shows the status of τ lifetime measurements at the end of 1982.

Table IV. From Jaros (1982), the status of τ lifetime measurements in 1982.

Experiment	Number of Decays	Average Decay Length Error (mm)	$\tau_\tau (10^{-13}$ s)
TASSO	599	10	0.8 ± 2.2
MARK II	126	4	4.6 ± 1.9
MAC	280	4	$4.1 \pm 1.2 \pm 1.1$
CELLO	78	6	$4.7 \pm^{3.9}_{2.9}$
MARK II Vertex Detector	71	0.9	$3.31 \pm .57 \pm .60$

Today's average value of τ_τ is in the range of (2.95 to 3.04) $\times 10^{-13}$ sec so these measurements were remarkably good for the detector technology of the early 1980's. Thus by the beginning of 1984 a decade of τ research had ended with a value of the lifetime in agreement with conventional weak interaction decay theory and, although not discussed here, many measurements on decay modes and branching ratios. It seemed as though τ research was ready to settle down into a comfortable second decade.

E.4 Precise Calculations on Tau Decays: 1984–1985

But comfort and ease did not appear. In 1984–1985 two papers appeared which carefully applied accepted decay theory to the many measurements on τ branching. One paper by Truong (1984) was entitled "Hadronic τ Decay, Pion Radiative Decay, and Pion Polarizability". The other was by Gilman and Rie (1985) and was entitled "Calculation of Exclusive Decay Modes of the Tau". As you know, these papers showed that there was something wrong in the theory or in the measurements of the one-charged decay modes of the τ. We did not understand the τ at the 5–10% level in 1985.

F. The Future of the Tau

Seven years has passed since 1985 but the question still remains (Perl 1992a, 1992b):

> ***Is the tau simply a standard model lepton, or will the physics of the tau lead us outside of the standard model?***

For me, the remark of Francis Bacon is my guide:

> ***......they are ill discoverers that think there is no land when they can see nothing but sea.***

The standard model is the sea of particle physics, what does it conceal in particle physics that is new and more fundamental? In 1975 the discovery of the tau was new land in the sea of two generations. Perhaps the tau will lead us out of the sea of the standard model.

References

Alles-Borelli V *et al.* 1970, *Limits on the Electromagnetic Production of Heavy Leptons, Lett. Nuovo Cimento* **IV** 1156

Bacino W *et al.* 1978, *Measurement of the Threshold Behavior of $\tau^+\tau^-$ Production in e^+e^- Annihilation, Phys. Rev. Lett.* **41** 13

Bai J Z *et al.* 1992, *Measurement of the Mass of the Tau Lepton*, submitted to *Phys. Rev. Lett.* , also SLAC-PUB-5870

Barbaro-Galtieri A *et al.* 1977, *Electron-Muon and Electron-Hadron Production in e^+e^- Collisions, Phys. Rev. Lett.* **39** 1058

Behrend H J *et al.* 1982, *Measurement of $e^+e^- \to \tau^+\tau^-$ at High Energies and Properties of the τ Lepton, Phys. Lett.* **114B** 282

Bernardini M *et al.* 1973, *Limits of the Mass of Heavy Leptons*, Nuovo Cimento **17A** 383

Bjorken J D and Llewellyn Smith C H 1973, *Spontaneously Broken Gauge Theories of Weak Interactions and Heavy Leptons, Phys. Rev.* **D7** 887

Brandelik R *et al.* 1978, *Measurements of Tau Decay Modes and a Precise Determination of the Mass, Phys. Lett.* **73B** 109

Brandelik R *et al.* 1980, *Production and Properties of the τ Lepton in e^+e^- Annihilation at C.M. Energies from 12 to 31.6 GeV, Phys. Lett.* **92B** 199

Braunstein *et al.* 1972, *Comparison of Muon-Proton and Electron-Proton Inelastic Scattering, Phys. Rev.* **D6** 106

Burmester J *et al.* 1977, *Anomalous Muon Production in e^+e^- Annihilation as Evidence for Heavy Leptons, Phys. Lett.* **68B** 297

Calder N 1977a, *The Key to the Universe* (British Broadcasting Company, London, 1977)

Calder N 1977b, *The Key to the Universe* (Penguin Books, Harmondsworth, 1978)

Camilleri L *et al.* 1969, *High Energy Muon-Proton Scattering: Muon-Electron Universality, Phys. Rev. Lett.* **23** 153

Cavalli-Sforza M *et al.* 1976, *Anomalous Production of High-Energy Muons in e^+e^- Collisions at 4.8 GeV, Phys. Rev. Lett.* 36 558

Dakin J T *et al.* 1972, *Measurement of the Inclusive Electroproduction of Hadrons, Phys. Rev. Lett.* **29** 746

Ellsworth R W *et al.* 1968, *Muon-Proton Elastic Scattering at High Momentum Transfers, Phys. Rev.* **165** 1449

Feldman G J *et al.* 1977, *Inclusive Anomalous Muon Production in e^+e^- Annihilation*, *Phys. Rev. Lett.* 38 117

Feldman J G 1978, *e^+e^- Annihilation*, Proc. XIX Int. Conf. on High Energy Physics (Tokyo 1978), eds S Homma, M Kawaguchi, H Miyazawa

Feldman G J *et al.* 1982, *Measurement of the τ Lifetime*, *Phys. Rev. Lett.* 48 66

Feldman G J 1992, *The Discovery of the τ 1975–1977: A Tale of Three Papers*, *Proc. 20th SLAC Summer Inst. Particle Physics*, ed J Hawthorne (to be published), also Preprint 92-0321

Ford W T *et al.* 1982, *Lifetime of the Tau Lifetime*, *Phys. Rev. Lett.* 49 106

Gilman F J and Rie S H 1985, *Calculation of Exclusive Decay Modes of the Tau*, *Phys. Rev.* D31 1066

Jaros J A 1982, *Measurement of the τ Lifetime*, *Proc. Paris High Energy Phys.*, *J. Physique* 43 Supp. C-3 p 106

Kirkby J 1977, *Direct Electron Production Measurements by DELCO at SPEAR*, *Proc. Int. Symp. Lepton and Photon Interactions at High Energies* (Hamburg, 1977), ed F Gutbrod p. 3

Kostoulas I *et al.* 1974, *Muon-Proton Deep Elastic Scattering*, Phys. Rev. Lett. 32 489

Larsen R R *et al.* 1971, *An Experimental Survey of Positron-Electron Annihilation into Multiparticle Final States in the Center-of-Mass Energy Range 2 GeV to 5 GeV*, SLAC Proposal SP-2 (unpublished)

Martin J F *et al.* 1976, *Particle Ratios in Inclusive Electroproduction from Hydrogen and Deuterium*, *Phys. Lett.* 65B 483

Orito S *et al.* 1974, *A Search for Heavy Leptons with e^+e^- Colliding Beams*, Phys. Lett. 48B 165

Perl M L 1971, *How Does the Muon Differ from the Electron? Physics Today*, July 34

Perl M L 1972, *Searches for Heavy Leptons and Anomalous Leptonic Behavior-the Past and the Future*, SLAC-PUB-1062 (unpublished)

Perl M L and Rapidis P 1974, *The Search for Heavy Leptons and Muon-Electron Differences*, SLAC-PUB-1496 (unpublished)

Perl M L 1975, *Lectures on Electron-Positron Annihilation – Part II: Anomalous Lepton Production*, *Proc. Canadian Inst. Particle Physics Summer School* (McGill Univ., Montreal, 1975), eds R Heinzi and B Margolis

Perl M L *et al.* 1975, *Evidence for Anomalous Lepton Production in e^+e^- Annihilation*, *Phys. Rev. Lett.* 35 1489

Perl M L 1977, *Review of Heavy Lepton Production in e^+e^- Annihilation, Proc. Int. Symp. Lepton and Photon Interactions at High Energies* (Hamburg, 1977), ed F Gutbrod p.145

Perl M L 1990, *The Discovery of the τ and its Major Properties: 1970–1985, Workshop on Tau Lepton Physics*, (Gif-sur-Yvette: Editions Frontières , 1991) eds M Davier and B Jean-Marie

Perl M L 1992a, *The Tau Lepton, Rep. Prog. Phys.* 55 653

Perl M L 1992b, *Tau Physics, Proc. 20^{th} SLAC Summer Inst. Particle Physics*, ed J Hawthorne (to be published), also SLAC-PUB-5900

Thacker H B and Sakurai J J, *Lifetimes and Branching Ratios of Heavy Leptons, Phys. Lett* **36B** 103

Toner W T *et al.* 1972, *Comparison of Muon-Proton and Electron-Proton Deep Inelastic Scattering, Phys. Lett.* 36B 251

Treitel J 1987, *Centaurus* 30 140

Truong T N 1948, *Hadronic τ Decay, Pion Radiative Decay, and Pion Polarizability, Phys. Rev.* D30 1509

Tsai Y-S 1971, *Decay Correlations of Heavy Leptons in $e^+ + e^- \to \ell^+ + \ell^-$, Phys. Rev.* D4 2821

Yamada S 1977, *Recent Results from DASP, Proc. Int. Symp. Lepton and Photon Interactions at High Energies* (Hamburg, 1977), ed F. Gutbrod p.69

Zichichi A 1992, *Heavy Lepton Searches Before the Tau, Proc. 20^{th} SLAC Summer Inst. Particle Physics*, ed J Hawthorne (to be published)