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THE DISCOVERY OF THE TAU LEPTON

PART I: THE EARLY HISTORY THROUGH 1975

PART II: CONFIRMATION OF THE DISCOVERY AND MEASUREMENT OF MAJOR PROPERTIES, 1976–1982*

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PART I: THE EARLY HISTORY THROUGH 1975

A. INTRODUCTION

Several previous papers[1–5] have given the history of the discovery of the τ lepton at the Stanford Linear Accelerator Center (SLAC). These papers emphasized (a) the experiments which led to our 1975 publication of the first evidence for the existence of the τ, (b) the subsequent experiments which confirmed the existence of the τ, and (c) the experiments which elucidated the major properties of the τ. That history will be summarized in Part 2 of this talk.

In this Part 1, I describe the earlier thoughts and work of myself and my colleagues at SLAC in the 1960's and early 1970's which led to the discovery. I also describe the theoretical and experimental events in particle physics in the 1960's in which our work was immersed. I will also try to describe for the younger generations of particle physicists, the atmosphere in the 1960's. That was before the elucidation of the quark model of hadrons, before the development of the concept of particle generations. The experimental paths to progress were not as clear as they are today and we had to cast a wide experimental net.

B. SLAC, LEPTONS, AND HEAVY LEPTONS

At the start of the 1960's, I was at the University of Michigan; our experiments were carried out at the Brookhaven Cosmotron and the Berkeley Bevatron, experiments in strong interaction physics. But I was becoming interested in lepton physics for a number of reasons. I liked experiments in which the results could be summarized in a few numbers or a few graphs. Thus I worked primarily in elastic scattering and other two-body reactions. I also liked experiments where the theory was relatively simple, and it was clear that strong interaction theory was not becoming simpler. On the other hand, the physics of leptons seemed a simpler world.

In the lepton world I was intrigued by the careful measurements being made on the (g-2) of the muon by Charpak *et al.*[6] and on the (g-2) of the electron by Wilkinson and Crane[7] at my University. I was also interested in the precision studies of positronium and muonium then in progress as well as other precision atomic physics experiments. (Indeed as a graduate student at Columbia University in the years 1950 to 1955, I worked under I.I. Rabi on an atomic beam experiment. And it was there that I first learned about positronium from Vernon Hughes.) These low energy studies of the charged leptons were in very capable hands, and I thought that it would be most useful for me to consider high energy experiments on charged leptons, experiments which might clarify the nature of the lepton or explain the electron-muon problem.

The opportunity appeared to think seriously about such experiments in 1962 when W.K.H. Panofsky offered me a position at the yet-to-be built Stanford Linear Accelerator Center. Here was a laboratory which would have primary electron beams, a laboratory at which one could easily obtain a good muon beam, a laboratory in which one could easily obtain a good photon beam for production of particle pairs. And on the same campus at the High Energy Physics Laboratory, the Princeton-Stanford e^-e^- storage ring was operating.[8]

From the time that the SLAC linear accelerator began operation in 1966 until the discovery of the τ in 1975, my colleagues and I cast a wide experimental net in our studies of leptons. These studies fell into three classes which I shall describe in turn: photoproduction searches for new charged leptons, studies of muon-proton inelastic scattering to seek $e-\mu$ differences, and e^+e^- colliding beam searches for new charged leptons. Figure 1 shows schematically the history of our three classes of lepton studies set against the construction history of the SLAC linear accelerator and the SPEAR e^+e^- storage ring.

Before turning to these studies, I describe the general thinking in the 1960's in the lepton world about the possible existence and types of new leptons. Since the 1950's a great deal of thought had been given to the concept of lepton number and lepton number conservation. This is not the place to record that intricate history. It is sufficient to note

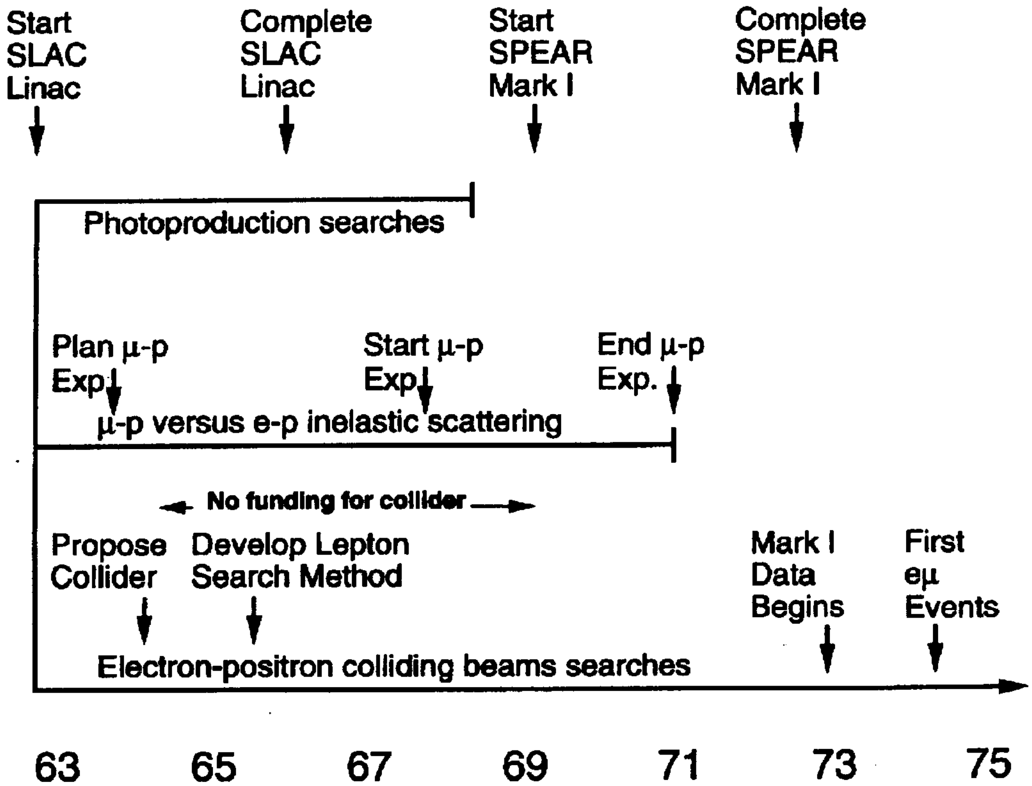


Fig. 1. The three classes of lepton studies carried out by my colleagues and myself at SLAC, set against the construction history of the SLAC linear accelerator and the SPEAR e^+e^- storage ring.

that by the beginning of the 1960's these concepts were well developed, although there was disagreement on how the leptons should be classified. And by the beginning of the 1960's there were papers on the possibility of the existence of charged leptons more massive than the e and μ, heavy leptons. I remember reading the 1963–1964 papers of Zel'dovich[9] and of Lipmanov.[10] But since the particle generation concept was not yet an axiom of our field, older models of particle relationships were used. For example, if one thought[11] that there might be an electromagnetic excited state e^* of the e then the proper search method was

$$e^- + \text{nucleon} \rightarrow e^{-*} + \ldots$$

$$e^{-*} \rightarrow e^- + \gamma$$

Or, if one thought (Lipmanov[10]) that there was a μ' which was a member of a μ, ν_μ, μ' triplet then the proper search method was

$$\nu_\mu + \text{nucleon} \rightarrow \mu^{-\prime} + \ldots$$

It is interesting to note in view of the decade later search for $\tau^- \rightarrow \nu_\tau \pi^-$ (Sec.L) that Lipmanov[10] calculated the branching fraction for this decay mode.

By the second half of the 1960's the concept had been developed of a heavy lepton L and its neutrino ν_L forming an $L,\ \nu_L$ pair. Thus in a paper written in 1968, Rothe and Wolsky[12] discuss the lower mass limit on such a lepton set by its absence in K decays. They also discuss the decay of such a lepton into the modes

$$L \rightarrow e\bar{\nu}_e \nu_L, \mu\bar{\nu}_\mu \nu_L,\ \pi\nu_L$$

Incidentally, in our 1971 proposal[13] to SLAC to study e^+e^- annihilation physics using the SPEAR collider then under construction, we reference Rothe and Wolsky[12] as indicative of the thinking on heavy leptons in the second half of the 1960's. (In 1971 and 1972 I reviewed[14] the 1960's heavy lepton theory and searches.)

C. PHOTOPRODUCTION SEARCHES FOR NEW CHARGED LEPTONS

Soon after the Stanford linear accelerator began operation, Fig. 1, we made one cast of our net[15] to find a new charged lepton. We were looking for any new charged particle x from the reactions

$$e^- + \text{nucleus} \rightarrow \gamma + \ldots$$

$$\gamma + \text{nucleus} \rightarrow x^+ + x^- + \ldots$$

The search used the pair production calculations of Tsai and Whitis[16]; this experiment was the beginning of a long and fruitful collaboration between my colleague Y.-S.(Paul) Tsai and myself. We did not find anything new, lepton or not, and so we concentrated on other casts of our net.

D. STUDIES OF MUON-PROTON INELASTIC SCATTERING

As SLAC was being built, Fig. 1, we were preparing to study muon proton inelastic scattering

$$\mu^- + p \to \mu^- + \text{anything}$$

to compare it with

$$e^- + p \to e^- + \text{anything}$$

As you know, extensive studies of $e - p$ inelastic scattering were planned at SLAC. Indeed, some of those studies led to the Nobel Prize being awarded to J. Friedman, H. Kendall, and R. Taylor. My hope was that we would find a difference between the μ and e other than the differences of mass and lepton number. In particular, I hoped that we would find a difference at large momentum transfers. Some of our hopes, or at least my hopes, were naive by today's standards of knowledge of particle physics. For example, I speculated[17] that the muon might have a special interaction with hadrons not possessed by the electron.

Therefore, beginning in the late 1960's, we measured the differential cross sections for inelastic scattering of muons on protons, and then compared (Toner *et al.*[18], Braunstein *et al.*[19]) the $\mu - p$ cross sections with the corresponding $e - p$ cross sections.

Other experimenters studied the differential cross section for $\mu - p$ elastic scattering and compared it with $e - p$ elastic scattering (Ellsworth *et al.*[20], Camilleri *et al.*[21], Kostoulas *et al.*[22]). 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 turned to the third cast of our net, the use of e^+e^- colliding beams to search for heavy leptons.

E. ELECTRON-POSITRON COLLIDING BEAMS AND SEQUENTIAL LEPTONS

At this meeting my good friend Gustav Voss gave the history of electron-positron colliding beam machines. He has given a detailed history with references, and so here I simply need to set the atmosphere with respect to the discovery of the τ. By September 1967 at the Sixth International Conference on High Energy Accelerators, Howard[23] was able to list quite a few electron-positron colliders. There was the pioneer 500 MeV ADA collider already operated at Frascati in the early 1960's and, also at Frascati, ADONE was under construction. The 1 GeV ACO at Orsay and 1.4 GeV VEPP-2 at Novosibirsk were in operation. The 6 GeV CEA Collider at Cambridge was being tested. And, colliders had been proposed at DESY and SLAC.[24]

The 1964 SLAC proposal[24], Fig. 2, already discussed the reaction

$$e^+ + e^- \rightarrow x^+ + x^-$$

and gave the total production cross section as

$$\sigma = \frac{\pi}{3}\, r_e^2 \left(\frac{m_e}{E}\right)^2 \beta \left[1 + \frac{(1-\beta^2)}{2}\right]$$

where r_e is the classical electron radius. This proposal did not directly lead to the construction of an e^+e^- collider at SLAC because we could not get the funding. About 5 years later with the steadfast support of the SLAC director, Wolfgang Panofsky, and with a design and construction team led by Burton Richter, construction of the SPEAR e^+e^- collider was begun at SLAC, Fig. 1.

It was this 1964 proposal and the 1961 seminal paper of Cabibbo and Gatto[25] entitled "Electron-Positron Colliding Beam Experiments" which focussed my thinking on new charged lepton searches using an e^+e^- collider. As we carried out the experiments described in Sections C and D, I kept looking for a model for new leptons, a model which would lead to definitive colliding beam searches while remaining reasonably general. Helped by discussions

PROPOSAL FOR A HIGH-ENERGY

ELECTRON-POSITRON COLLIDING-BEAM STORAGE RING

AT THE

STANFORD LINEAR ACCELERATOR CENTER

March 1964

It is proposed that the Atomic Energy Commission support the construction at Stanford University of a Colliding-Beam Facility (storage ring) for high-energy electrons and positrons. This facility would be located at the Stanford Linear Accelerator Center, and it would make use of the SLAC accelerator as an injector.

This proposal was prepared by the following persons:

<u>Stanford Physics Department</u>

D. Ritson

<u>Stanford Linear Accelerator Center</u>

S. Berman

A. Boyarski

F. Bulos

E. L. Garwin

W. Kirk

B. Richter

M. Sands

Fig. 2. The title and first page of the 1964 SLAC proposal for an e^+e^- storage ring.

with my colleagues such as Paul Tsai[26] and Gary Feldman and by Refs. 10 and 12, I came to what I later called the sequential lepton model. (I used the terms sequential and sequence first in print in Refs. 13 and 14.)

I thought of a sequence of pairs

$$
\begin{array}{cc}
e^- & \nu_e \\
\mu^- & \nu_\mu \\
\ell^- & \nu_\ell \\
\ell'^- & \nu_\ell \\
\vdots & \vdots
\end{array}
$$

each pair having a unique lepton number. I also usually thought about the leptons as being point Dirac particles. Of course, the assumptions of unique lepton number and point particle nature were not crucial, but I liked the simplicity. After all, I had turned to lepton physics in the early 1960's partly in a search for simple physics.

The idea was to look for

$$e^+ + e^- \to \ell^+ + \ell^-$$

with

$$
\begin{aligned}
\ell^+ &\to e^+ + \text{undetected neutrinos carrying off energy} \\
\ell^- &\to \mu^- + \text{undetected neutrinos carrying off energy}
\end{aligned}
\tag{1}
$$

or

$$
\begin{aligned}
\ell^+ &\to \mu^+ + \text{undetected neutrinos carrying off energy} \\
\ell^- &\to e^- + \text{undetected neutrinos carrying off energy}
\end{aligned}
$$

This search method had many attractive features:

- If the ℓ was a point particle, we 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 we proposed to use to detect the reactions in Eq. 1 would be 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

$$\ell^- \to \nu_\ell + e^- + \bar{\nu}_e$$

$$\ell^- \to \nu_\ell + \mu^- + \bar{\nu}_\mu$$

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

$$\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$$

I incorporated the e^+e^- search method summarized by Eq. 1 in our 1971 Mark I proposal[13] to use the not-yet-completed SPEAR e^+e^- storage ring.

My thinking about sequential leptons and the use of the method of Eq. 1 to search for them was greatly helped and influenced by two seminal papers of Paul Tsai. In 1965 he published with Anthony Hearn[26] the paper "Differential Cross Section for $e^+ + e^- \to W^+ + W^- \to e^- + \bar{\nu}_e + \mu^+ + \nu_\mu$". This work discussed finding vector boson pairs W^+W^- by their $e\mu$ decay mode. It was thus closely related to my thinking, described above, of finding $\ell^+\ell^-$ pairs by their $e\mu$ decay mode. Tsai's 1971 paper[27] entitled "Decay Correlations of Heavy Leptons in $e + e \to \ell^+ + \ell^-$" provided the detailed theory for the applications of the sequential lepton model to our actual searches. 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.

In 1971 Thacker and Sakurai[28] also published a paper on the theory of sequential lepton decays 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[29] was also very important in keeping my thinking general.

F. THE SLAC–LBL PROPOSAL

After numerous funding delays, a group led by Burton Richter and John Rees of SLAC Group C began to build the SPEAR e^+e^- collider at the end of the 1960's. 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 to build the Mark I detector. In 1971 we submitted the SLAC-LBL Proposal[13] for the experiment using the Mark I detector at SPEAR. (The detector was originally called the SLAC-LBL detector and only called the Mark I detector when we began to build the Mark II detector. For the sake of simplicity, I refer to it as the Mark I detector.) The contents of the proposal 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 to most others it seemed 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.

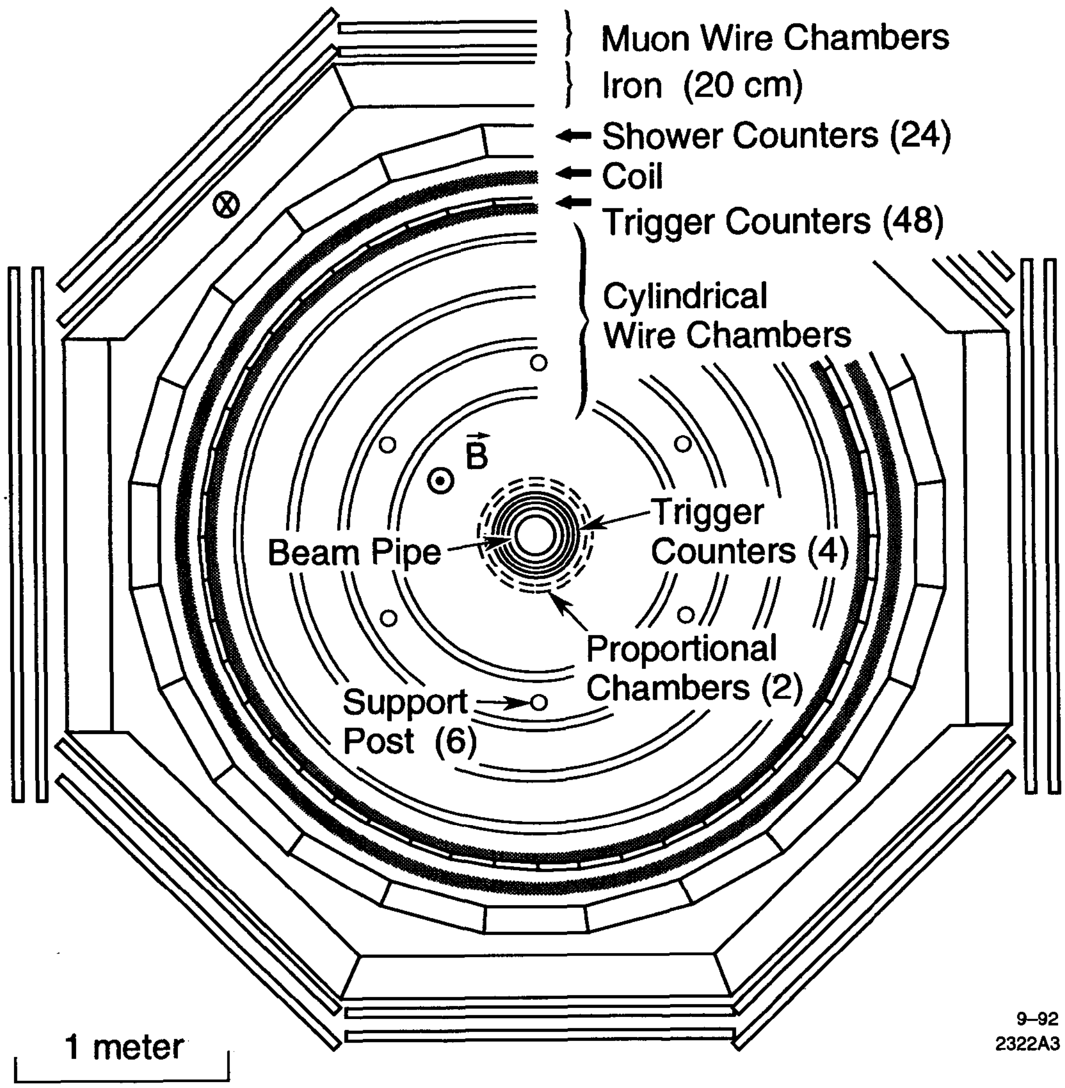


Fig. 3. The initial form of the Mark I detector.

H. DISCOVERY OF THE TAU IN THE MARK I EXPERIMENT: 1974–1976

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.

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.

Discovery of the $e - \mu$ events

Both detection systems worked just well enough, so 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?

The questions inside our Mark I Collaboration were answered by George Trilling, Gerson Goldhaber and Burton Richter putting together an independent team of collaboration members. The charge to that team was to reanalyze all the data to try to make the $e\mu$ signal go away. But the $e\mu$ signal would not go away. The independent analysis agreed with my work and that is what convinced the collaboration.

I worked through the skepticism of the outside world 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[34] at the *1975 Summer School of the Canadian Institute for Particle Physics*. The contents of the talk are shown here.

1. Introduction
   - *A*. Heavy Leptons
   - *B*. Heavy Mesons
   - *C*. Intermediate Boson
   - *D*. Other Elementary Bosons
   - *E*. Other Interpretations
2. Experimental Method
3. Search Method and Event Selection
   - *A*. The 4.8 GeV Sample
   - *B*. Event Selection
4. Backgrounds
   - *A*. External Determination
   - *B*. Internal Determination
5. Properties of $e\mu$ Events
6. Cross Sections of $e\mu$ Events
7. Hypothesis Tests and Remarks
   - *A*. Moments Spectra
   - *B*. θ_{coll} Distribution
   - *C*. Cross Sections and Decay Ratios
8. Compatibility of e^+e^- and μe Events
9. Conclusions

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 I, 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 I, 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.[34] 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, $\theta_{copl} > 20°$."

	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

Table II. From Perl.[34] 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

The misidentification probabilities determined from three-or-more prong hadronic events and other considerations are given in Table II. 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.

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 two more years to prove that.

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 convinced of the reality of the $e\mu$ events and the absence of a conventional explanation.

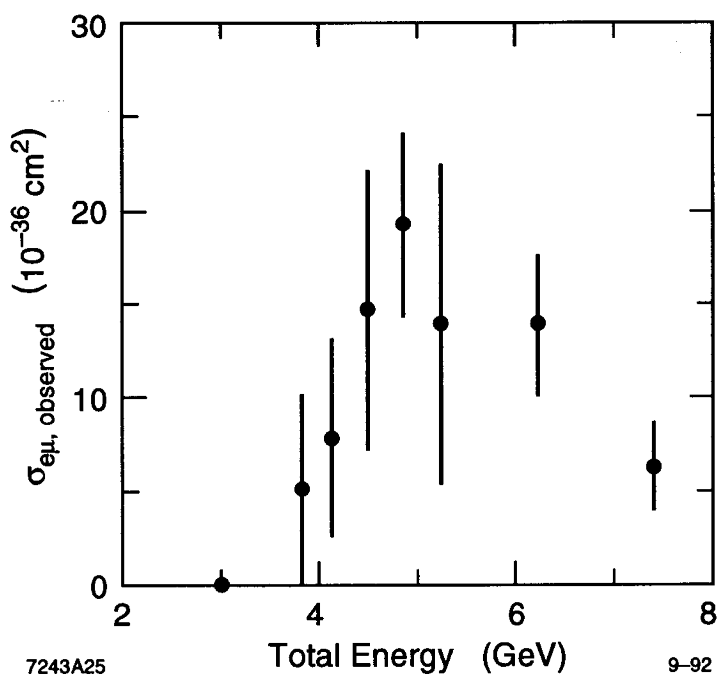


Fig. 4. From Perl *et al.*[35]: the observed cross section for the signature $e\mu$ events from the Mark I experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.

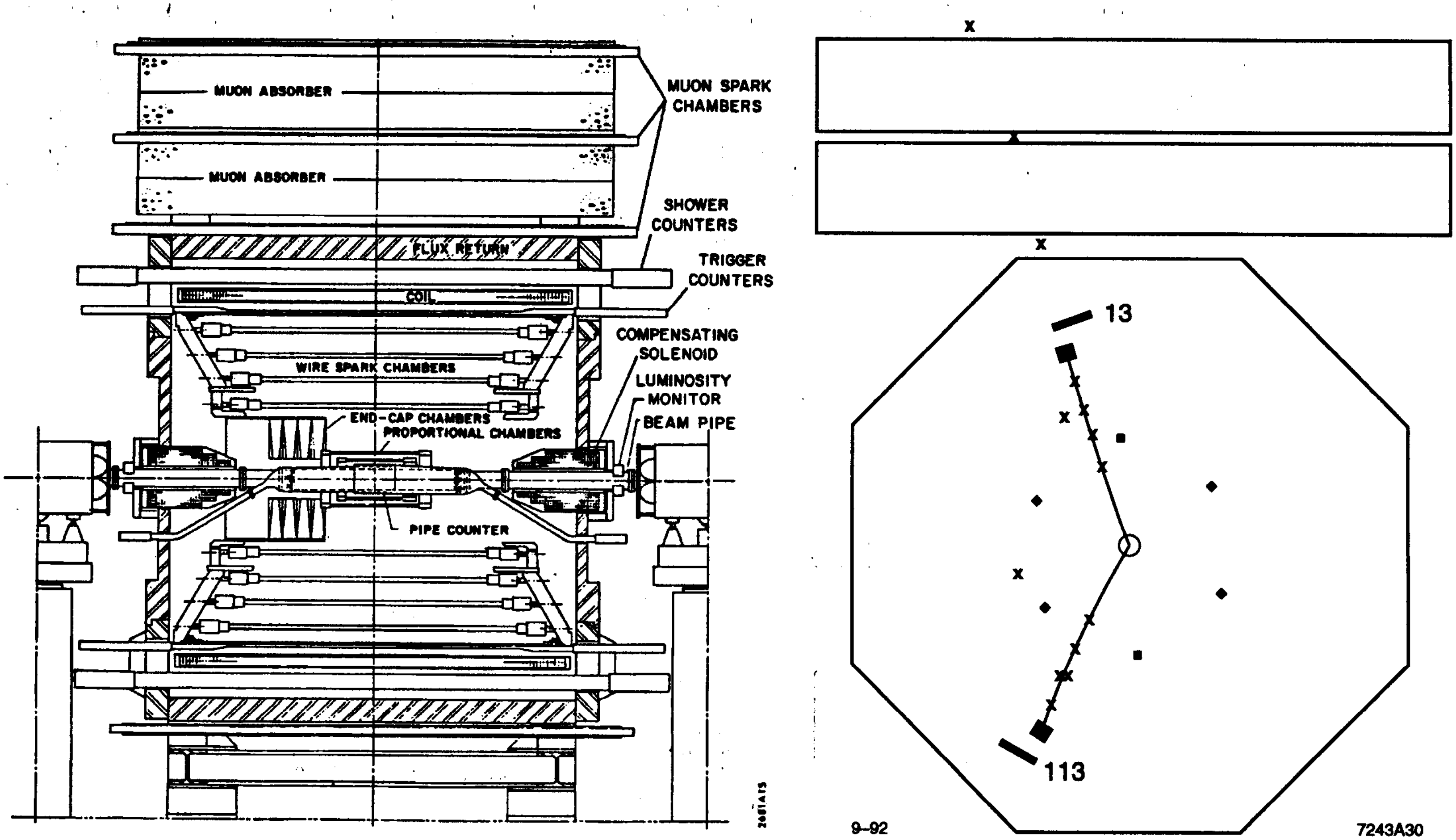
An important factor in this growing conviction was the addition of a special muon detection system to the detector, Fig. 5a, called the muon tower. This addition was conceived and built by Gary Feldman. Although we did not use events such as that in Fig. 5b in our first publication, seeing a few events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

Finally in December 1975, the Mark I experimenters published Perl *et al.*[35] 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 to me by Petros Rapidis who was then a graduate student and worked with me in the early 1970's on the $e - \mu$ problem (Perl and Rapidis[36]). The letter τ is from Greek $\tau\rho\iota\tau o\nu$ for third – the third charged lepton.

Thus in 1975, twelve years after we began our lepton physics studies at SLAC, these studies finally bore fruit. But we still had to convince the world that the $e\mu$ events were significant and we had to convince ourselves that the $e\mu$ events came from the decay of a pair of heavy leptons.



(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.

PART II: CONFIRMATION OF THE DISCOVERY AND MEASUREMENT OF MAJOR PROPERTIES, 1976–1982

I. IS IT A LEPTON ?, 1976–1978

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 the 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 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.

Perhaps the greatest impediment to the acceptance of the τ as the third charged lepton was that there was *no* other evidence for a third particle generation. Two sets of particles u, d, e^-, ν_e and c, s, μ^-, ν_μ seemed acceptable, a kind of doubling of particles. But why three sets? A question which to this day has no answer.

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

Clearly other tau pair decay modes had to be found. Assuming the τ to be a charged lepton with conventional weak interactions, simple and very general theory predicted the branching fractions:

$$
\begin{aligned}
&B(\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e) \approx 20\% \\
&B(\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu) \approx 20\% \\
&B(\tau^- \rightarrow \nu_\tau + \text{hadrons}) \approx 60\%
\end{aligned} \tag{2}
$$

Therefore experimenters should be able to find the decay sequences.

$$
\begin{aligned}
&e^+ + e^- \rightarrow \tau^+ + \tau^- \\
&\tau^+ \rightarrow \bar{\nu}_\tau + \mu^+ + \nu_\mu \\
&\tau^- \rightarrow \nu_\tau + \text{hadrons}
\end{aligned} \tag{3}
$$

and

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

The first sequence, Eqs.3, would lead to *anomalous muon events.*

$$
e^+ + e^- \rightarrow \mu^\pm + \text{hadrons} + \text{missing energy} \tag{5}
$$

and the second, Eqs.4, would lead to *anomalous electron events*

$$
e^+ + e^- \rightarrow e^\pm + \text{hadrons} + \text{missing energy} \tag{6}
$$

One might also look for the sequence

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

$$\tau^+ \rightarrow \bar{\nu}_\tau + e^+ + \nu_e$$

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

leading to

$$\tau^+ + \tau^- \rightarrow e^+ + e^- + \text{missing energy} \quad , \tag{7}$$

and an analogous sequence for the μ decay modes. A student of mine, Frank Heile[37], did find some weak evidence for the process in Eq. 7, but the background from radiative Bhabha pairs was a severe problem. Incidentally, the great improvement in detectors in 15 years is illustrated by contrasting this measurement with the beautiful determination of $B(\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e)$ by Akerib *et al.*[38] using the CLEO II detector and the process in Eq. 7.

J. ANOMALOUS MUON EVENTS

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

$$e^+ + e^- \rightarrow \mu^\pm + \text{hadrons} + \text{missing energy}$$

The first and very welcome outside confirmation of anomalous muon events came in 1976 from another SPEAR experiment by Cavalli-Sforza *et al.*[39] This paper was entitled "Anomalous Production of High-Energy Muons in e^+e^- Collisions at 4.8 GeV".

I have in my files a June 3, 1976 Mark I note by Gary 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."

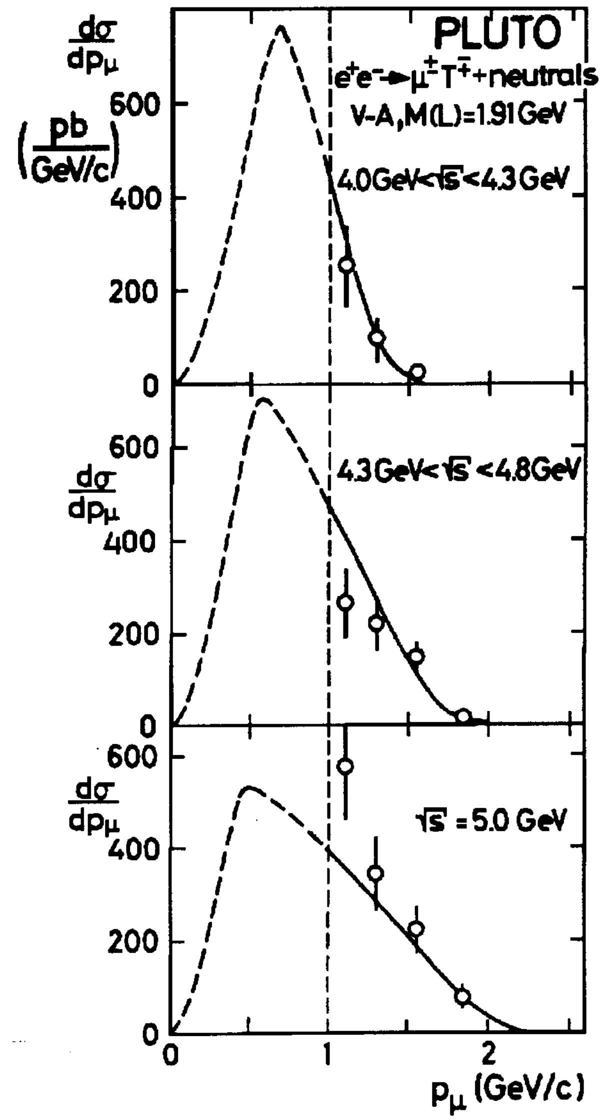


Fig. 6. The momentum spectra of μ's from anomalous muon events found by the PLUTO experimenters[41] using the DORIS e^+e^- storage ring.

This conclusion was published, Feldman *et al.*[40], in a paper entitled "Inclusive Anomalous Muon Production in e^+e^- Annihilation".

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, Burmester *et al.*[41], published "Anomalous Muon Production in e^+e^- Annihilation as

Evidence for Heavy Leptons". Figure 6 is from this paper. 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 $\mu-$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 the major hadronic decay modes

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

had to be found.

K. ANOMALOUS ELECTRON EVENTS

The demonstration of the existence of anomalous electron events

$$e^+ + e^- \rightarrow e^\pm + \text{hadrons} + \text{missing energy}$$

required improved electron identification in the detectors. A substantial step forward was made by the new DELCO detector, Fig. 7, at SPEAR (Kirkby[42], Bacino *et al.*[43]). In Kirkby's talk[42] at the Photon-Lepton Conference, "Direct Electron Production Measurement by DELCO at SPEAR", he stated

> "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."

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. 8. This led to the important paper

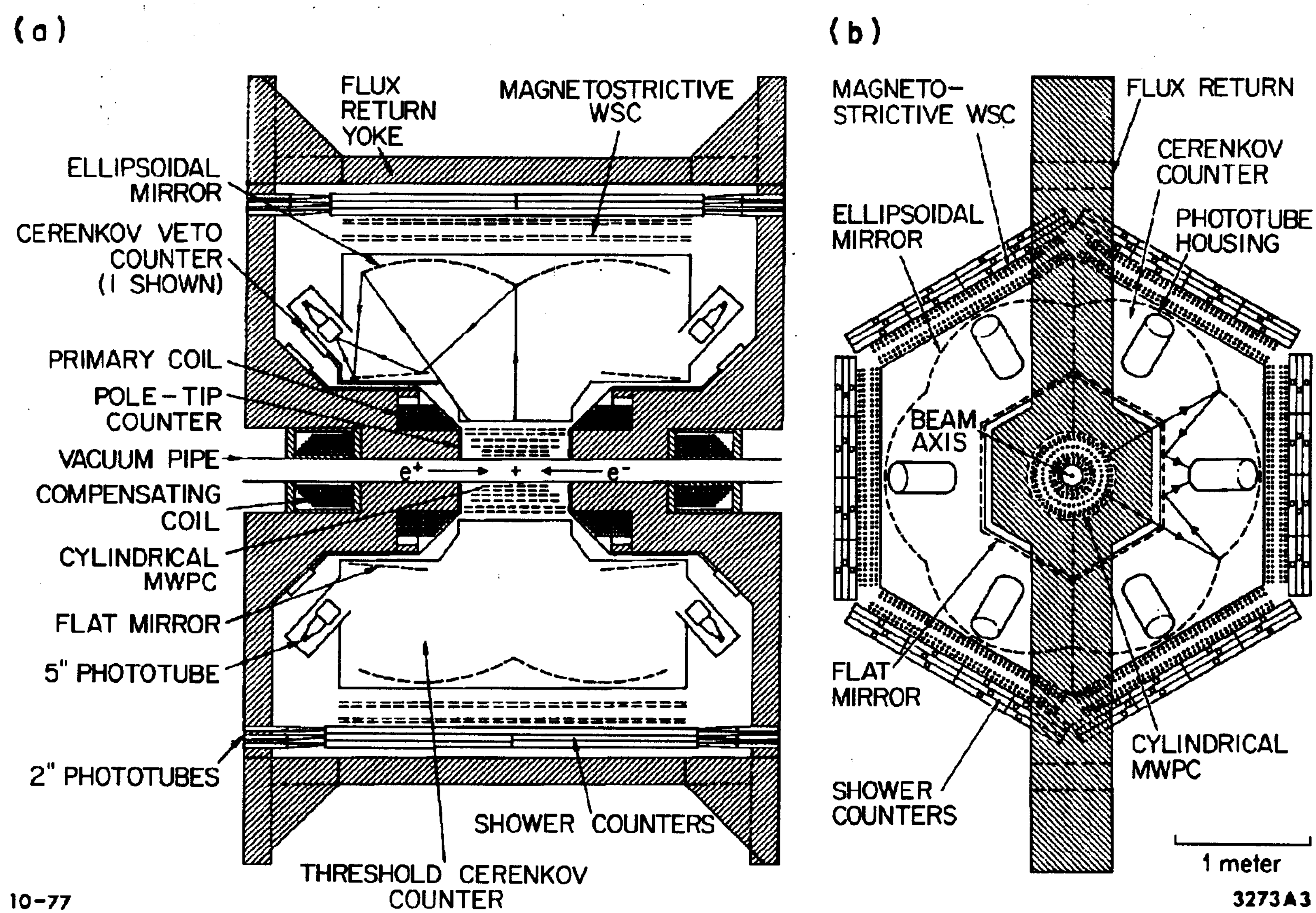


Fig. 7. The DELCO detector used at SPEAR to find anomalous electron events[42] and measure the mass of the τ.[43]

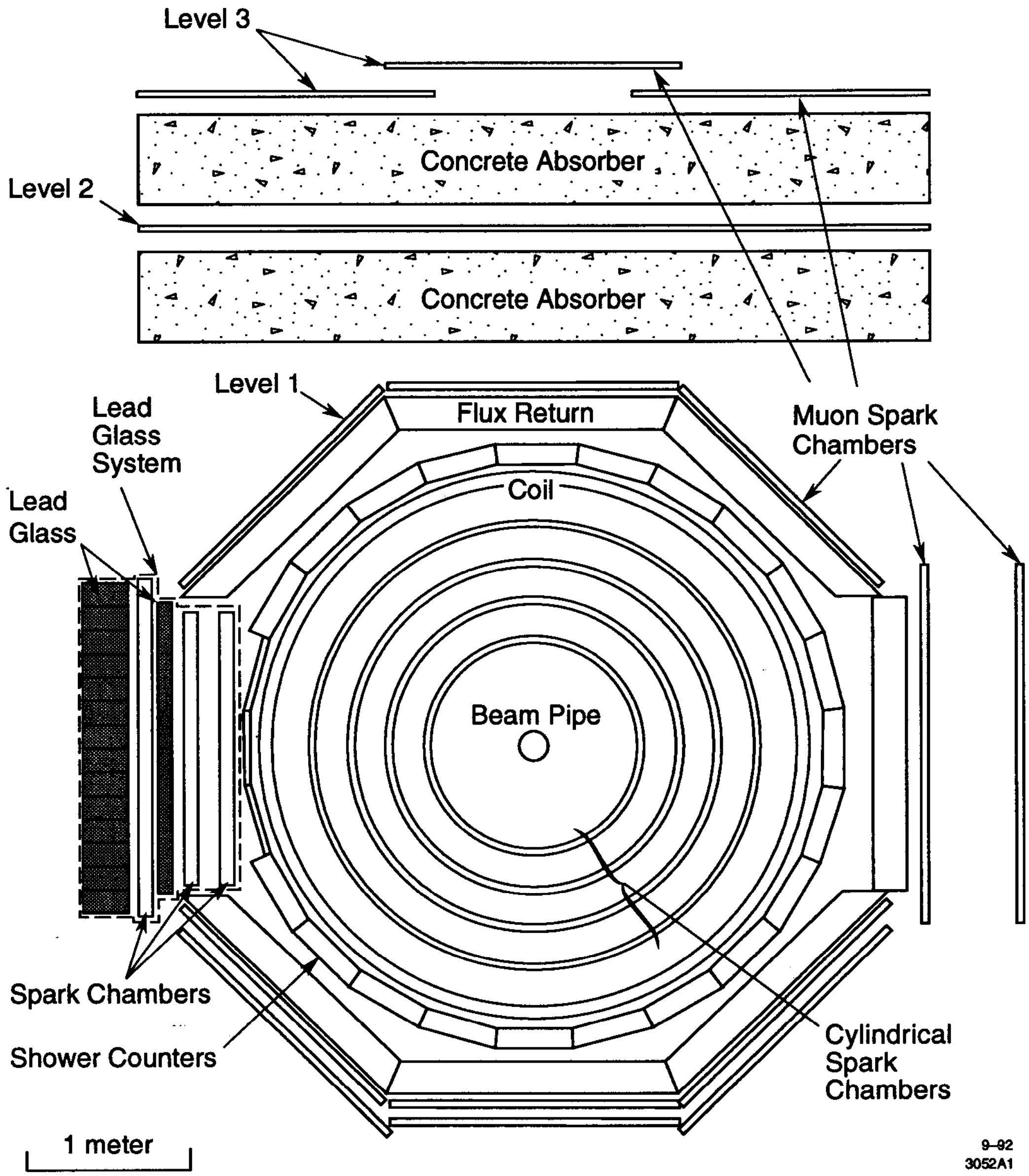


Fig. 8. The "lead glass wall" modification of the Mark I detector used at SPEAR to find anomalous electron events (Barbaro-Galtieri *et al.*).[44]

(Barbaro-Galtieri *et al.*[44]) 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 $B(\tau \rightarrow h + \text{neutrals}) = (45 \pm 19)\%$."

L. SEMILEPTONIC DECAY MODES AND THE SEARCH FOR $\tau^- \rightarrow \nu_\tau\pi^-$ AND $\tau^- \rightarrow \nu_\tau\rho^-$

By the time of the 1977 Photon Lepton Conference at Hamburg, I was able to report[45] in a "Review of Heavy Lepton Production in e^+e^- Annihilation" that

"*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."

The anomalous muon and anomalous electron events had shown that the total decay rate of the τ into hadrons, that is the total semileptonic decay rate, was about the right size. And, as pointed out as early as 1976 by De Rújula and Georgi[46], the measured total e^+e^- annihilation cross section required the τ to have the expected total semileptonic decay rate. But, if the τ was indeed a sequential heavy lepton, two substantial semileptonic decay modes had to exist: $\tau^- \rightarrow \nu_\tau\pi^-$ and $\tau^- \rightarrow \nu_\tau\rho^-$.

First, the branching fraction for

$$\tau^- \rightarrow \nu_\tau + \pi^- \qquad (9a)$$

could be calculated from the decay rate for

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad (9b)$$

and was found to be

$$B(\tau^- \rightarrow \nu_\tau\pi^-) \approx 10\% \qquad (9c)$$

Second, the branching fraction for

$$\begin{aligned}\tau^- \rightarrow \nu_\tau + \rho^- &\rightarrow \nu_\tau + \pi^- + \pi^0 \\ &\rightarrow \nu_\tau + \pi^- + \gamma + \gamma\end{aligned} \tag{10a}$$

could be calculated from the cross section for

$$e^+ + e^- \rightarrow \rho^0 \tag{10b}$$

and was found to be

$$B(\tau^- \rightarrow \nu_\tau \rho^-) \approx 20\% \tag{10c}$$

One of the problems in the years 1977–1979 in finding the modes in Eqs.9a and 10a was the poor efficiency for photon detection in the early detectors. If the γ's in Eq.10a are not detected then the π and ρ modes are confused with each other. Probably the first separation of these modes was achieved using the Mark I–Lead Glass Wall detector. As reported at the *Hamburg Conference* by Angelina Barbaro-Galtieri.[47]

$$B(\tau^- \rightarrow \nu_\tau \pi^-)/B(\tau^- \rightarrow \nu_\tau \rho^-) = 0.44 \pm 0.37$$

Gradually the experimenters understood the photon detection efficiency of their experiments and in addition new detectors, such as the Mark II, with improved photon detection efficiency were put into operation.

In our collaboration the first demonstration that $B(\tau \rightarrow \nu_\tau \pi^-)$ was substantial came from Gail Hanson[48] 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 9 taken from her internal note shows an excess of events, particularly at large x, if $B(\tau \rightarrow \nu_\tau \pi^-)$ is taken as zero.

Within about a year the $\tau \rightarrow \nu_\tau \pi^-$ decay mode had been detected and measured by experimenters using the PLUTO detector, the DELCO detector, the Mark I–Lead Glass Wall

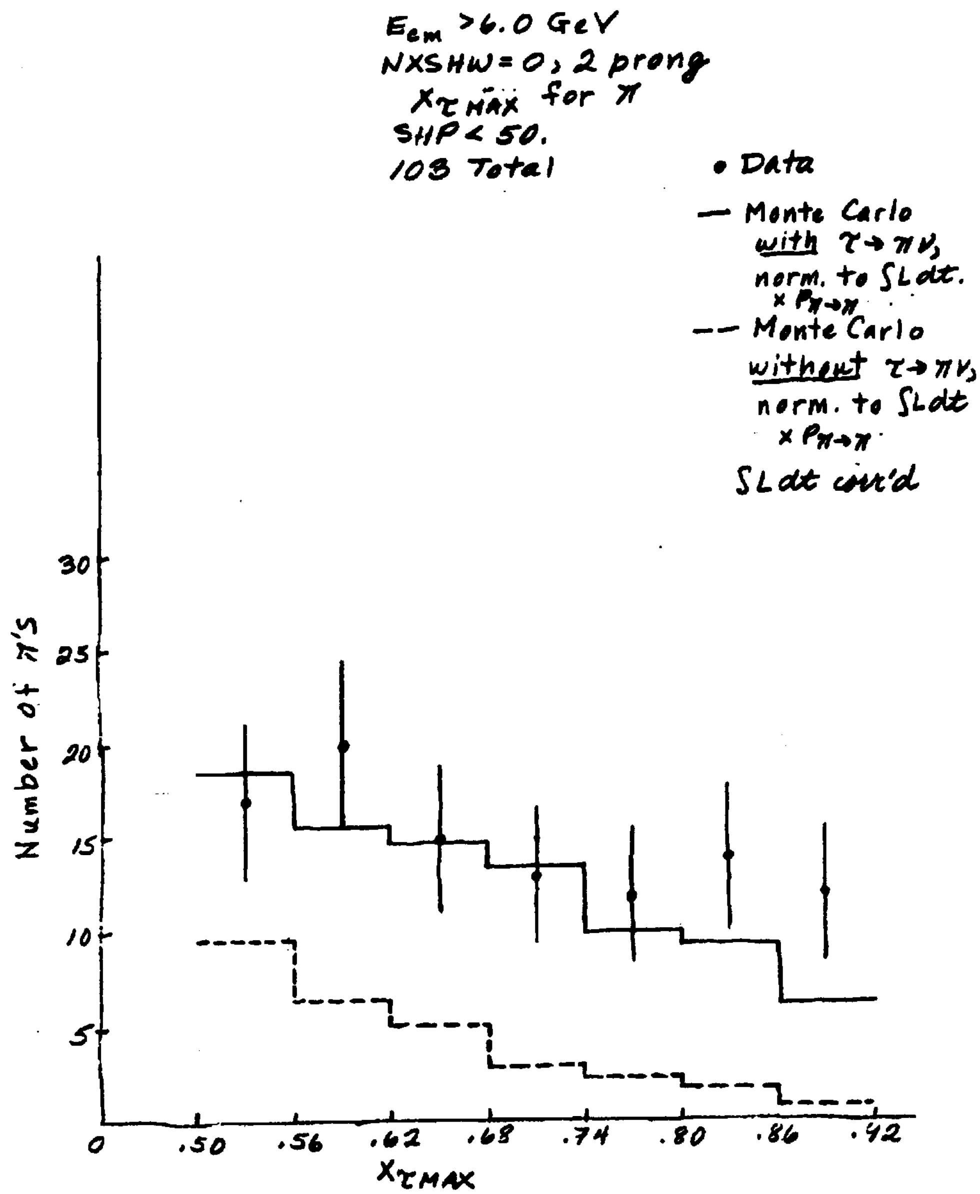


Fig. 9. Early evidence for $\tau^- \to \nu_\tau \pi^-$ using 2-prong, 0-photon events from a SLAC–LBL Collaboration Internal Note of G. Hanson.[48]

detector and the new Mark II detector. These measurements were summarized, Table II, by Gary Feldman[49] in his 1978 review of e^+e^- annihilation physics at the *XIX International Conference on High Energy Physics.* Although the average of the results in Table III is two standard deviations smaller than the present value[50] of $11.7 \pm 0.47\%$, the $\tau^- \rightarrow \nu_\tau \pi^-$ mode had been found.

Table III. From Feldman[49], 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	$8.0 \pm 3.2 \pm 1.3$
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

The year 1979 saw the first publications of $B(\tau^- \rightarrow \nu_\tau \rho^-)$. The DASP Collaboration using the DORIS e^+e^- storage ring reported[51] $(24 \pm 9)\%$ and the Mark II Collaboration reported[52] $(20.5 \pm 4.1)\%$. Crude measurements, but in agreement with the 20% estimate in Eq.10c. The present value is[50] $(25.5 \pm 0.4)\%$.

Thus by the end of 1979 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.

M. THE TAU MASS

In the final section of this paper I sketch some of the history of τ research in the years 1978 to 1982 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.

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.[35] By the beginning of 1978 the DASP experiment at the DORIS e^+e^- storage ring showed $m_\tau = 1807 \pm 20$ MeV/c^2.[53]

By the middle of 1978 the DELCO experiment at SPEAR (Bacino *et al.*[43]) had made the best measurement $m_\tau = 1784^{+2}_{-7}$ MeV/c^2 as reported in a paper entitled "Measurement of the Threshold Behavior of $\tau^+\tau^-$ Production in e^+e^- Annihilation". This paper contained the classic measurement of the τ pair production cross section at low energy. (It was only in 1992, fourteen years later, that there was an improvement in the measurement of m_τ, the BES Collaboration using the BEPC e^+e^- collider reported[54] $m_\tau = 1776.9 \pm 0.5$ MeV/c^2.)

N. THE TAU LIFETIME

The last major property of the τ to be determined was the τ lifetime. Measurements of the τ lifetime, τ_τ, could not be made at the energies at which SPEAR and DORIS operated; 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 used a primitive secondary-vertex detector built by Walter Innes and myself to improve the triggering efficiency of the Mark II detector.[55] 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 with $\tau_\tau = (4.9 \pm 2.0) \times 10^{-13}$ sec.[56]

The modern era in τ lifetime measurements began with the pioneering work of John Jaros on precision vertex detectors.[57] Table IV taken from his paper[57] shows the status of τ lifetime measurements at the end of 1982. Theory predicts

$$\tau_\tau = \tau_\mu \left(\frac{m_\mu}{m_\tau}\right)^5 B(\tau^- \to \nu_\tau e^- \bar{\nu}_e) \quad , \tag{11a}$$

Table IV. From Jaros[57], the status of τ lifetime measurements in 1982.

Experiment	Number of Decays	Average Decay Length Error (mm)	$\tau_\tau(10^{-13}\text{ s})$
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	$3.31 \pm .57 \pm .60$

which using modern values give

$$\tau_\tau\,(\text{predicted}) = 2.9 \times 10^{-13}\text{ sec} \tag{11b}$$

Thus the 1982 measurement of τ_τ agreed with theory and the overall identification of the τ as a heavy lepton was complete.

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