10/
1/10/91

M.L.P.

(1)

CONF-9009321--1

SLAC-PUB--5388

DE91 005760

THE DISCOVERY OF THE TAU AND ITS MAJOR PROPERTIES: 1970–1985*

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

ABSTRACT

This paper recounts the history of the discovery of the tau lepton and its major properties: its mass, its lifetime and its main decay modes.

MASTER

Talk presented at the Workshop on Tau Lepton Physics
Orsay, France, September 24–27, 1990

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

INTRODUCTION

The history of the discovery of the tau and its major properties begins twenty years ago. In recreating that history I will describe the ideas which inspired and guided the discovery, the early data which led to the discovery, and the new accelerator and detector technology used in the discovery. I will tell you something of ups and downs of the research, of the uncertainties and the pleasures. And I will use this opportunity to reflect on the change in particle physics research style and atmosphere over twenty years.

BEFORE THE TAU: 1970–1974

The $e - \mu$ Problem and the Varieties of Leptons

The experiments at LEP and the SLC have given us a clear picture of the leptons: there are just three generations of lepton pairs with small mass neutrinos; and there are no new leptons with masses less than about 45.5 GeV/c^2. Twenty years ago our picture of the leptons was obscure and confused. First of all, there was the $e - \mu$ problem. In a 1971 paper

How does the muon differ from the electron,
M. L. Perl, *Physics Today*, July, 34 (1971)

I wrote about two then current ways of understanding the relationship between the e and the μ. One way was to suppose there was some additional property, other than mass, which differentiated the μ from the e. The other way was to suppose the e and μ were the first members of a sequence

$$e,\ \mu,\ \mu',\ \mu'' \ldots$$

$$\nu_e,\ \nu_\mu,\ \nu_{\mu'},\ \nu_{\mu''} \ldots$$

using the notation of that paper. The $e - \mu$ problem would then be part of a larger problem, understanding that sequence. But the larger problem might be solved if we found and studied several additional members of the sequence — the properties of the additional members giving us the clues we needed.

My colleagues and I at SLAC had measured muon-proton inelastic scattering cross sections for several years, comparing them with electron-proton inelastic scattering cross sections as measured by other experimenters. We hoped that an additional $e - \mu$ difference would show up in these higher q^2 processes. But no difference was found. Furthermore, the relative systematic error between $\mu - p$ and $e - p$ measurements was about 10 to 15% and we couldn't reduce that error.

Therefore I began to think about the alternative way to approach the $e-\mu$ problem, to look for the next lepton, ℓ, in what might be an e, μ, ℓ ... sequence. At that time B. Richter and colleagues at SLAC were beginning to build SPEAR and the search method which seemed best was electron-positron annihilation

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

At the same time, as I discuss below, experimenters at the ADONE e^+e^- storage ring at Frascati had similar thoughts. Today the use of the e^+e^- annihilation search method is obvious, but it was not obvious then; indeed there were a variety of search methods for a variety of hypothetical leptons: sequential leptons, excited leptons, ortholeptons, paraleptons, spin-0 leptons. The search methods in addition to e^+e^- annihilation included looking for new leptons produced by: neutrino-nucleon collisions, charged-lepton-nucleon collisions, photoproduction, electron beam dumps, and proton beam dumps.

Theory of Sequential Leptons

In the midst of this confusing variety of lepton types and search methods, my interest was centered on the e^+e^- search method and the sequential lepton concept. Here the work of my long-term friend and colleague, Y.-S. Tsai, was of great importance. His 1971 paper

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

provided the production and decay theory for our work from the very beginning. It is fascinating to look at Table II of that paper which gives the decay modes and their branching ratios for various lepton masses, branching ratios which we are still trying to measure precisely today for the τ. Tsai's work was incorporated in the heavy lepton search part of the Mark I detector proposal for SPEAR.

At the same time there was the work of H.B. Thacker and J.J. Sakurai

> *Lifetimes and Branching Ratios of Heavy Leptons,*
> H.B. Thacker and J.J. Sakurai, Phys. Letters **36B**, 103 (1971)

giving the same fundamental theory but not as comprehensive as the work of Tsai.

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 B. Richter and J. Rees. My SLAC Group E joined with their Group C and a Lawrence Berkeley Laboratory Group led by W. Chinowsky, G. Goldhaber, and G. Trilling. In 1971 we submitted the proposal SP-2 to SLAC shown in Figs. 1 and 2.

The reproduction is poor because copying machines were marginal in 1971 and I don't have the original proposal. Figure 1b shows the Contents, the heavy lepton search was left for last and allotted just three pages because it all seemed so impossible. But the search paragraph of page 16 of the proposal, Fig. 2., contained the essential idea — use the $e\mu$ joint decay modes. That is, look for

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

with

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

$\ell^- \rightarrow \mu^- +$ undetected neutrinos carrying off energy

or

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

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

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". 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.

Heavy Lepton Searches at ADONE

While SPEAR and the Mark I detector were being built heavy lepton searches 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 M. Bernardini and A. Zichichi reported in 1970 and 1973:

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

Figure 3 from

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

shows two search regions, the reach depending upon the lepton decay assumptions.

The other group led by S. Orioto and M. Conversi, reported in 1974 in the paper

A SEARCH FOR HEAVY LEPTONS WITH
e^+e^- COLLIDING BEAMS,
S. Orito *et al.*, Phys. Letters **48B**, 165 (1974)

Their search region also reached to somewhat above 1 GeV/c^2 in mass.

FIRST EVIDENCE FOR THE TAU: 1974–1976

The Mark I Detector

We began operating the Mark I detector in 1973. 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.

However, the original Mark I detector had no muon detection. As shown in Fig. 4, it was through the foresight and insistence of my colleague and friend, G. Feldman, that muon detection was added, resulting in the upgraded Mark I of Fig. 5.

The First $e\mu$ Events

The muon detection system was very crude, concrete slabs separated by spark chambers. And the electron detector was also crude by modern standards, lead-scintillator sandwich counters built by our Berkeley colleagues. But both detectors worked well enough and in 1974 we began to detect $e\mu$ events, a classic example is Fig. 6. The **x**'s show the hits in the magnetostrictive spark chambers; the numbers 13 and 113 are the relative size of the energies deposited by the μ and e respectively in the shower counters. There are no other shower counter signals, hence no photons within the shower counters acceptance. The solid squares give the position of thick longitudinal posts in the detector.

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. We then worked on the new objections before the next talk.

In June, 1975 I gave the first international talk on the $e\mu$ events:

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

The largest single energy data sample, Fig. 7, 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 J. Kirkby who was then at Stanford University and SLAC. He showed me that just using the numbers in the 0 charge, 0 photon columns of Fig. 7, 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.

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."

FIRST PUBLICATION

Finally in December 1975 the Mark I experimenters published

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

The paper's 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 worked with me in the early 1970's on the $e-\mu$ problem in the unpublished paper:

THE SEARCH FOR HEAVY LEPTONS AND MUON-ELECTRON DIFFERENCES,
M.L. Perl and P. Rapidis, SLAC-PUB-1496 (1974) .

τ is from the Greek $\tau\rho\iota\tau o\nu$ for third — the third charged lepton.

FROM CONFUSION TO CONFIRMATION: 1975–1977

Confusions and Controversies

Our first publication was followed by several years of confusion and unncertainty 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 <u>not</u> seen, the $\tau \to \pi\nu$ 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?

Muon-Hadron Events From τ Decay

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

$$e^+ + e^- \to \tau^+ + \tau^-$$
$$\tau^+ \to \bar{\nu}_\tau + \mu^+ + \nu_\mu$$
$$\tau^- \to \nu_\tau + \text{hadrons}$$

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. 5. For data acquired above 5.8 GeV he found the following.

> "Correcting for particle misidentifications, 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."

The result was published in

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

The second very welcome confirmation came from another SPEAR experiment

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

ANOMALOUS MUON PRODUCTION IN e^+e^- ANNIHILATION AS EVIDENCE FOR HEAVY LEPTONS,
J. Burmester *et al.*, Phys. Letters **68B**, 297 (1977) .

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 H. Meyer and E. Lohrman of the PLUTO Collaboration. Figure 8 is from the first PLUTO paper.

With the finding of μ-hadron events I was convinced we were 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 $\tau \to \pi\nu$ decay mode could not be found.

Electron-Hadron Events From τ Decays

The demonstration of the existence of e-hadron events required improved electron identification in the detectors. A substantial step forward was made by the new DELCO detector at SPEAR, Fig. 9, which I will discuss in connection with the determination of

the mass of the τ. The Mark I detector was also improved by Group E from SLAC and a Lawrence Berkeley Laboratory Group led by A. 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. 10.

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

FINAL CONFIRMATION: 1977–1978

1977 International Symposium at Hamburg

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

RECENT RESULTS FROM DASP,
S. Yamada, Proc. Int. Symp. Lepton and Photon Interactions at High Energies (Hamburg, 1977), Ed.F. Gutbrod

DIRECT ELECTRON PRODUCTION MEASUREMENTS BY DELCO AT SPEAR,
J. Kirkby, ibid.

The abstract in this paper 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."

Finally in my paper

REVIEW OF HEAVY LEPTON PRODUCTION IN e^+e^- ANNIHILATION,
M.L. Perl, ibid.

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."

The $\tau \to \pi\nu$ Decay Mode

Thus in the summer of 1977 the major problem in fully establishing the nature of the τ was the uncertainty in the branching ratio, $B(\tau \to \pi\nu)$. This was a serious problem because from $B(\pi \to \mu\nu)$ and $B(\tau \to e\nu\nu)$ it follows directly that $B(\tau \to \pi\nu)$ 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 $B(\tau \to \pi\nu)$ was substantial came from G. 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 taken from her internal note shows an excess of events, particularly at large x, if $B(\tau \to \pi\nu)$ is taken as zero.

By the middle of 1978 there was no longer a problem with $\tau \to \pi\nu$, the clouds of confusion parted and the sun shone on a $B(\tau \to \pi\nu)$ close to the expected 10%. Figure 12 from

REVIEW OF τ LEPTON PROPERTIES,
G. J. Feldman, Proc. 1978 Int. Meeting on Frontier of Physics (Singapore, 1978) p.421

shows the mid-1978 measurement.

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.

THE TAU MASS: 1976–1978

The 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. By the beginning of 1978 the DASP experiment at the DORIS e^+e^- storage ring showed $m_\tau = 1.807 \pm 0.020$ GeV/c^2 in

MEASUREMENTS OF TAU DECAY MODES AND A PRECISE DETERMINATION OF THE MASS
R. Brandelik *et al.*, Phys. Letters **73B**, 109 (1978) .

By the middle of 1978 the DELCO experiment at SPEAR had made the best measurement $m_\tau = 1.782^{+2}_{-7}$ GeV/c^2 as reported in

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

Figure 13 from this paper is probably the most used illustration in τ literature.

THE TAU AT HIGH ENERGIES – PETRA, PEP AND THE TAU LIFETIME: 1978–1984

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,
R. Brandelik *et al.*, Phys. Letters **92B**, 199 (1980)

MEASUREMENT OF $e^+e^- \to \tau^+\tau^-$ AT HIGH ENERGIES AND PROPERTIES OF THE τ LEPTON,
H.-J. Behrend *et al.*, Phys. Letters **114B**, 282 (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 at the SLC. I look forward to tau research from the BEPC storage ring and from the SLD experiment at the SLC.

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

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

used a primative secondary-vertex detector built by W. Innes and myself to improve the triggering efficiency of the Mark II detector. We measured $\tau_\tau = (4.6 \pm 1.9) \times 10^{-13}$ sec.

Two other early measurements were from the MAC experiment at PEP

Lifetime of the Tau Lepton,
W.T. Ford *et al.*, Phys. Rev. Letters **49**, 106 (1982)

with $\tau_\tau = (4.9 \pm 2.0) \times 10^{-13}$ sec; and from the CELLO experiment at PETRA

MEASUREMENT OF THE τ LIFETIME
H.-J. Behrend *et al.*, Nucl. Phys. **B211**, 369 (1983) .

Today's average value of τ_τ is $(3.03 \pm 0.08) \times 10^{-13}$ sec, so these first measurements were remarkably good for the detector technology of the early 1980's. Thus by the beginning of 1984 the second phase 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.

PRECISE THEORY OF 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 ratios. These papers are:

Hadronic τ Decay, Pion Radiative Decay, and Pion Polarizability,
Tran N. Truong, Phys. Rev. **D30**, 1509 (1984)

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

As you know, these papers showed that there was something wrong in the theory or in the measurements of the one-charged-prong decay modes of the τ. We still did not understand the τ at the 5% level!

Here I end this history because part of this 1990 Workshop will be dedicated to the one-charged-prong problem. Until this problem is understood the history of τ research in the late 1980's is not complete.

(a)

SLAC Proposal SP-2

December 27, 1971

1. Title of Experiment: An Experimental Survey of Positron-Electron Annihilation into Multiparticle Final States in the Center of Mass Energy Range 2 GeV to 5 GeV

2. Spokesman: Rudolf R. Larsen

Experimenters:

Name	Group and Distribution
A. M. Boyarski	Group C - SLAC
J. Dakin	Group E - SLAC
G. Feldman	Group E - SLAC
G. E. Fischer	Group C - SLAC
D. Fryberger	Group EFD - SLAC
Rudolf R. Larsen	Group C - SLAC
H. L. Lynch	Group C - SLAC
F. Martin	Group E - SLAC
M. L. Perl	Group E - SLAC
J. R. Rees	Group C - SLAC
B. Richter	Group C - SLAC
R. F. Schwitters	Group C - SLAC
G. S. Abrams	LBL - UC Berkeley
W. Chinowsky	LBL - UC Berkeley
C. E. Friedberg	LBL - UC Berkeley
G. Goldhaber	LBL - UC Berkeley
R. J. Hollebeck	LBL - UC Berkeley
J. A. Kadyk	LBL - UC Berkeley
G. H. Trilling	LBL - UC Berkeley
J. S. Whitaker	LBL - UC Berkeley
J. E. Zipse	LBL - UC Berkeley

(b)

Contents

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

FIGURE 1(a). Title page of Proposal SP-2 to use the Mark I detector at SPEAR,
(b). Contents of Proposal SP-2.

E. SEARCH FOR HEAVY LEPTONS

The possible existance of muon-like particles (heavy-leptons) has been the subject of considerable experimental study and theoretical speculation in recent years. To date there have been no experiments which give an unambiguous answer on the existence of such particles with masses greater than about 500 MeV.[11-13] During this study of hadronic production processes we will collect a great deal of data bearing on the existence of such particles.

The production cross section of charged lepton pairs by a single time-like photon is

$$\sigma(\ell) \approx \frac{20}{E_o^{\,2}(\mathrm{GeV})} \quad \text{nanobarns}$$

independent of the lepton mass for a beam energy (E_o) a few hundred MeV above threshold. This is one of the largest cross sections in the e^+e^- annihilation channel and makes the detection of a heavy lepton (μ') fairly simple compared to experiments done at conventional accelerators. In this discussion we will make the conventional assumptions that the μ' has unit charge, spin 1/2, and a unique lepton number.

Using Tsai's[14] calculations on the branching ratio of a μ' into hadronic muonic and electronic decay modes (with the appropriate neutrinos, of course) we find the following for the joint decay modes of both members of heavy lepton pair.

μ' \ μ'	hadronic modes	μ mode	e mode
hadronic modes	0.38	0.12	0.12
μ mode	0.12	0.03	0.03
e mode	0.12	0.03	0.03

These joint decay probabilities are roughly independent of the μ' mass from about 600 MeV to our maximum detectable mass of somewhat above 2 GeV. The most unusual of the joint decay modes is that involving one μ and one e. To be specific, we shall assume that the final state μ and e must have energies greater than 600 MeV each (so that our particle identification system works reliably), the mass of the μ' is 1.5 GeV, and the SPEAR is operating at 2 GeV each beam. These three assumptions allow us to the calculate fraction of the

FIGURE 2. Page 16 of Proposal SP-2 outlining the strategy for searching for a heavy lepton.

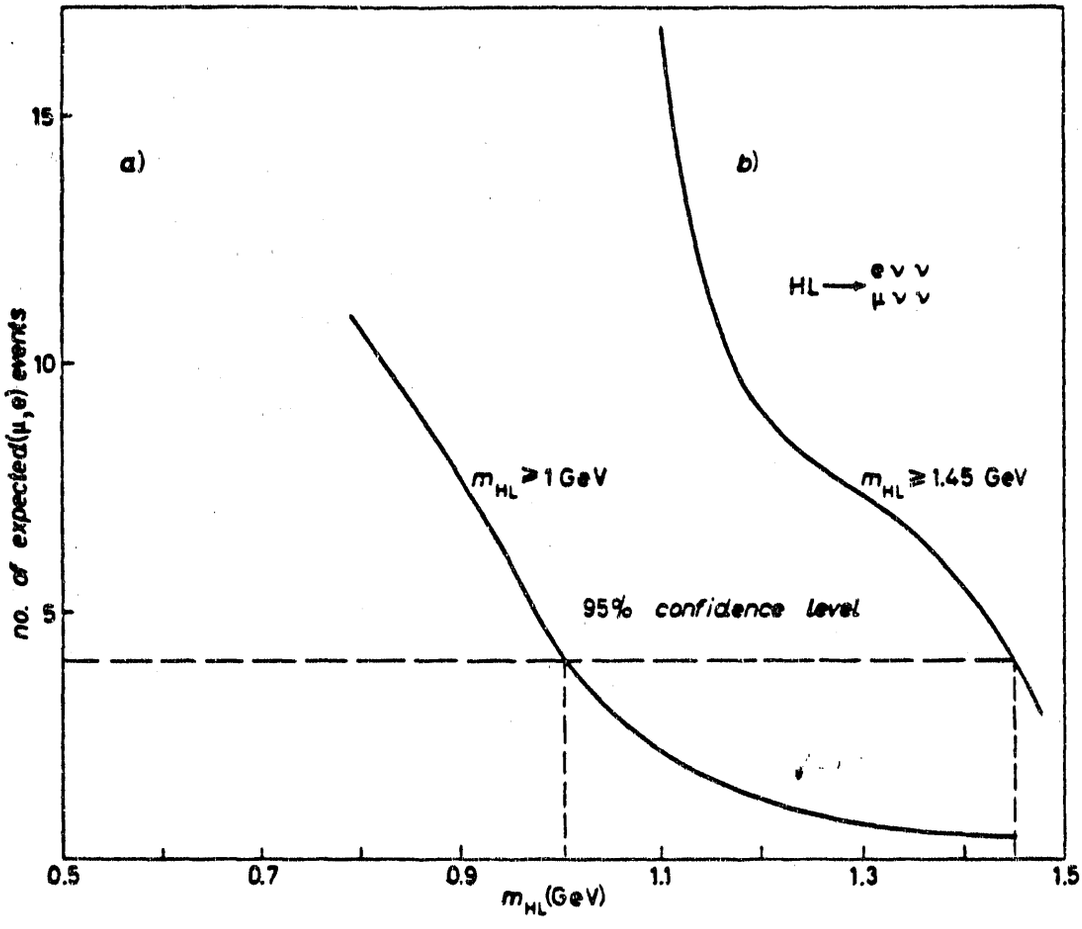

Fig. 2. – The expected number of ($\mu^{\pm}e^{\mp}$) pairs *vs.* m_{HL} for two types of universal weak couplings of the heavy leptons. The dashed lines indicate the 95% confidence levels for m_{HL}. *a*) HL universally coupled with ordinary leptons and hadrons, *b*) HL universally coupled with ordinary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

FIGURE 3. Figure with original caption from M. Bernardini *et al.*, Nuovo Cimento **17A**, 383 (1973) showing the heavy lepton search regions using the ADONE e^+e^- storage ring at Frascati.

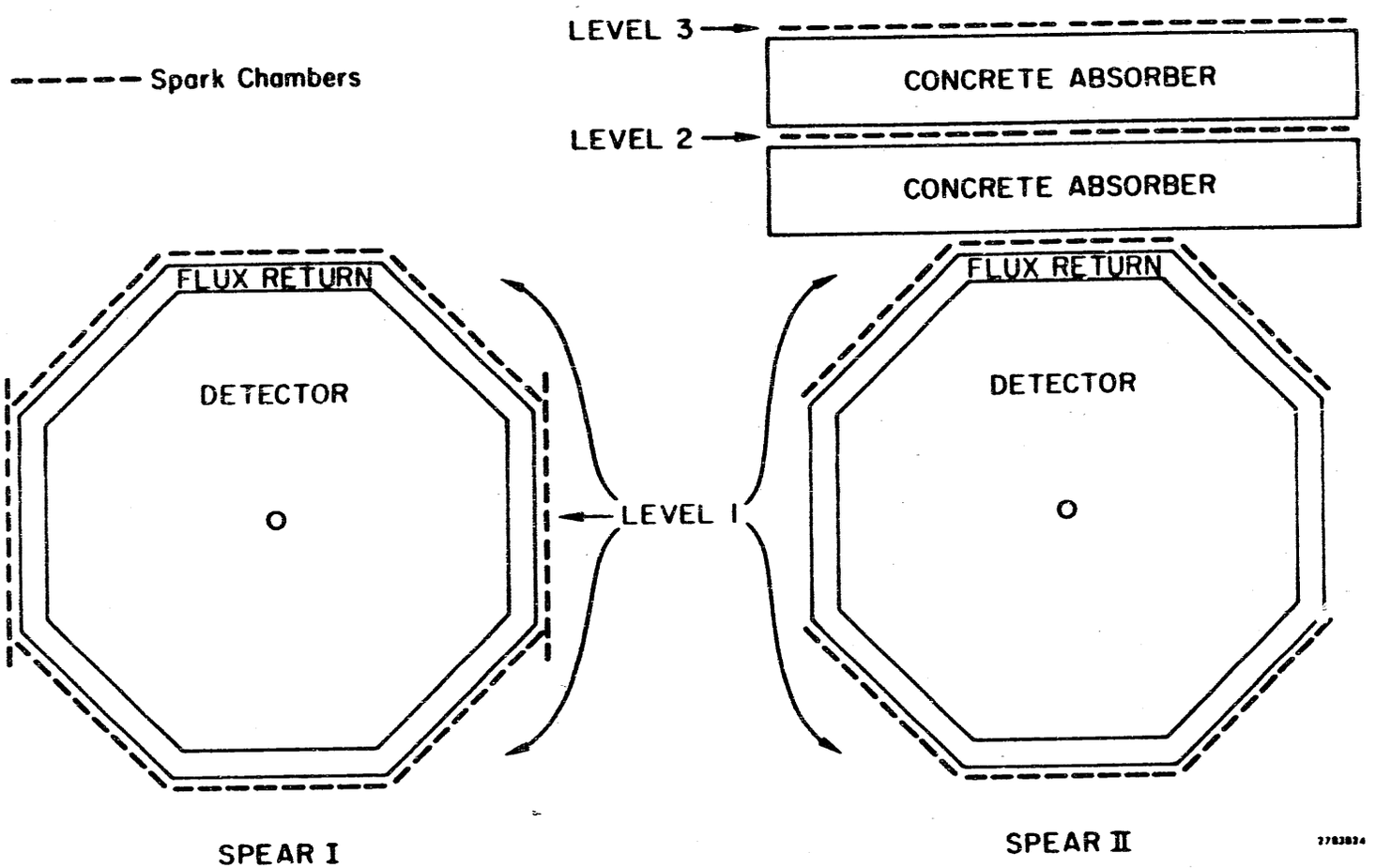

FIGURE 4. The addition of the muon detecting tower to the Mark I detector.

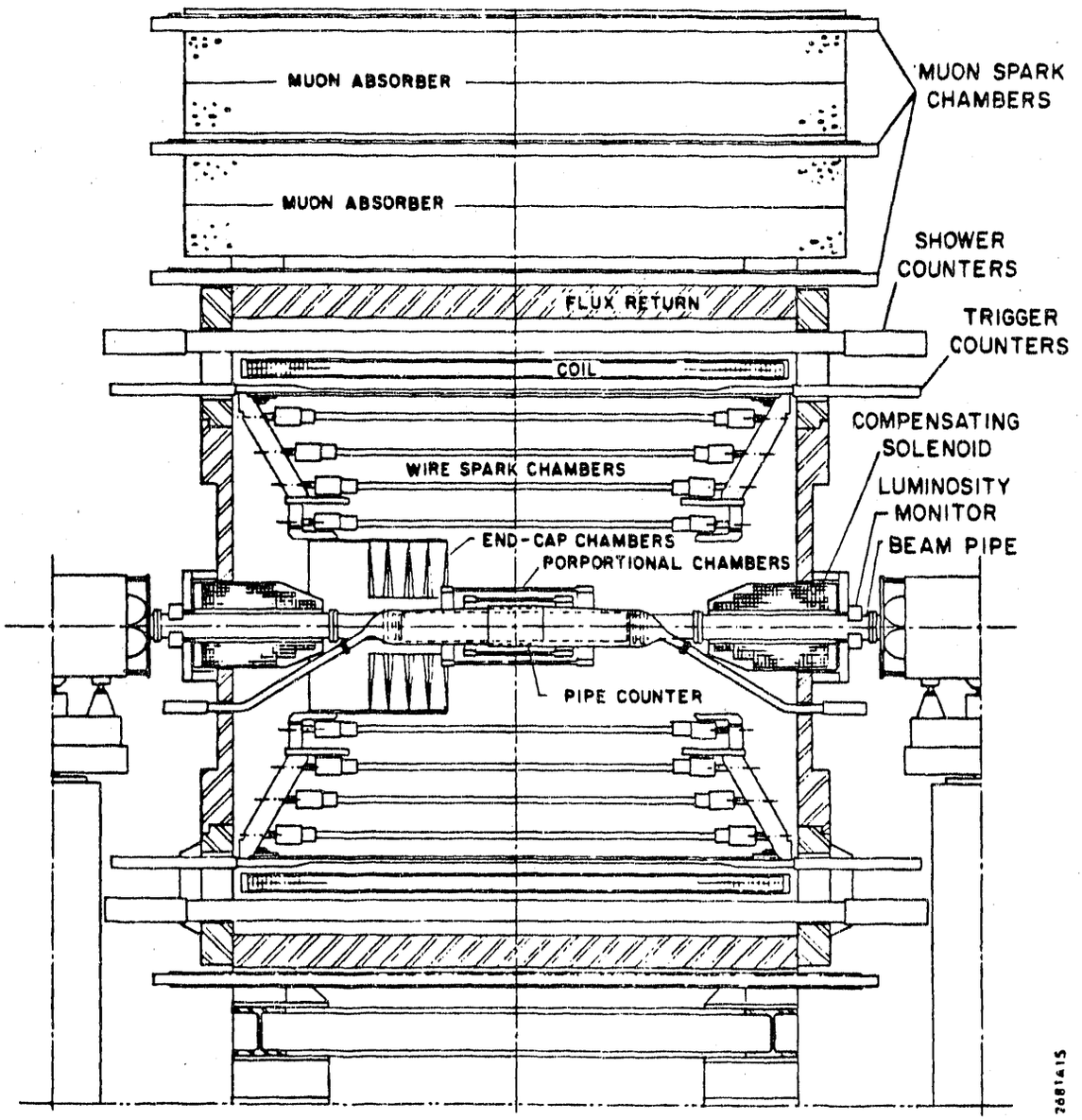

FIGURE 5. The Mark I detector in which the first $e\mu$ events were found.

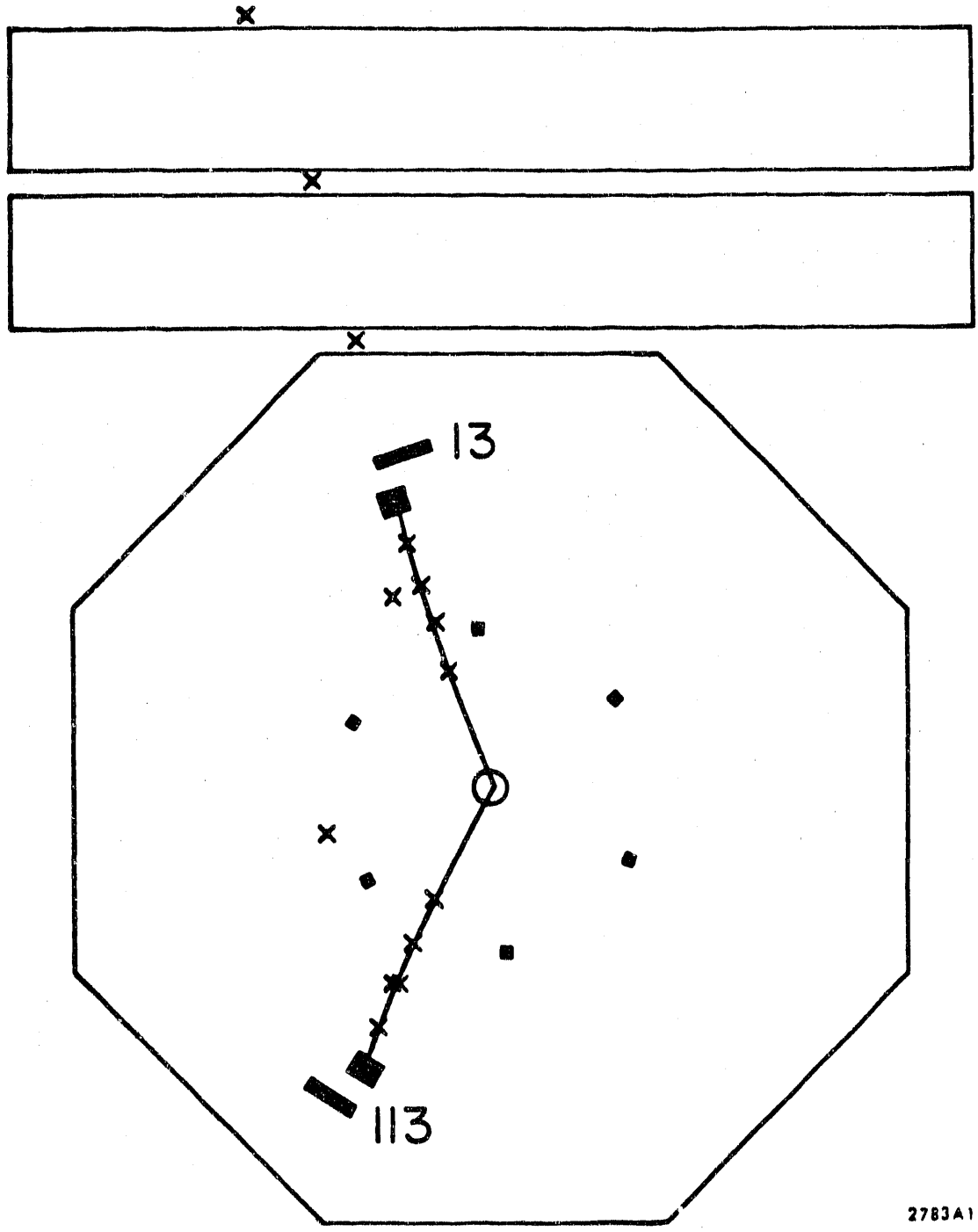

FIGURE 6. One of the first $e\mu$ events. The μ moves upward through the muon detector tower and the e moves downward. The numbers 13 and 113 give the relative amounts of electromagnetic shower energy deposited by the μ and e. The six square dots show the positions of longitudinal support posts of the magnetostrictive spark chamber used for tracking.

TABLE I

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 = $\pm$ 2		
Number Photons =	0	1	> 1	0	1	> 1
ee	40	111	55	0	1	0
eμ	24	8	8	0	0	3
μμ	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

FIGURE 7. Reproduction of a 1975 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. (M.L. Perl, Proc. Canadian Inst. Particle Physics Summer School (McGill Univ., Montreal, 1975) editors R.H. Heinzi and B. Margolis.

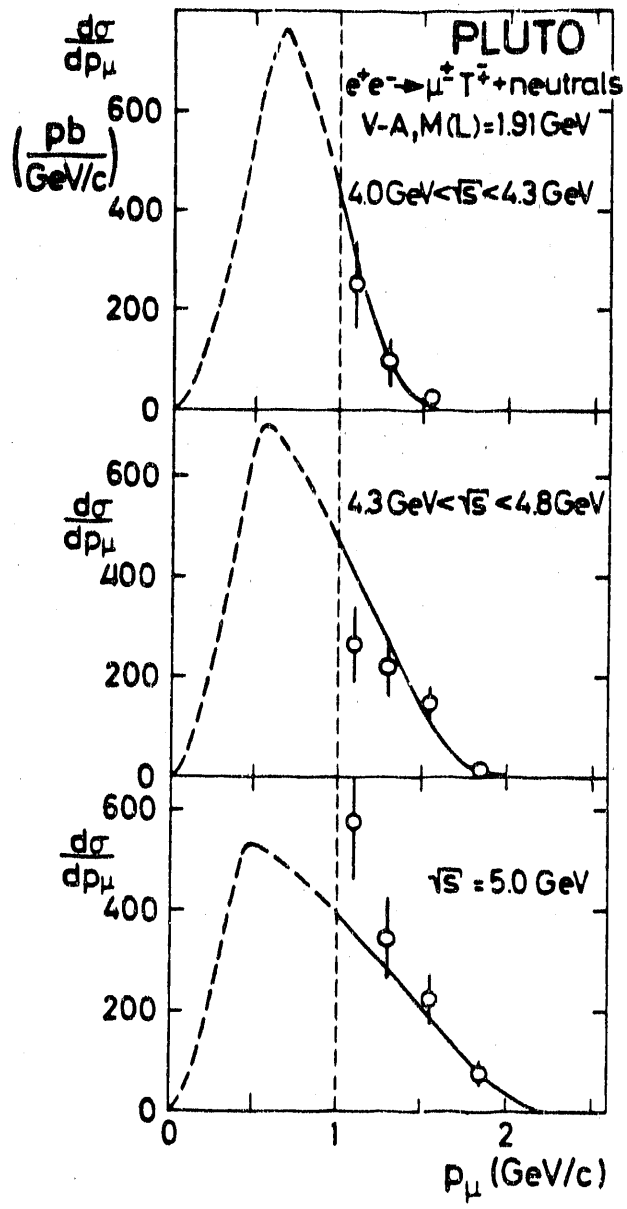

FIGURE 8. The momentum spectra of μ's from anomalous muon-hadron τ-pair events found by the PLUTO experimenters (J. Burmester *et al.*, Phys. Letters **68B**, 297 (1977).

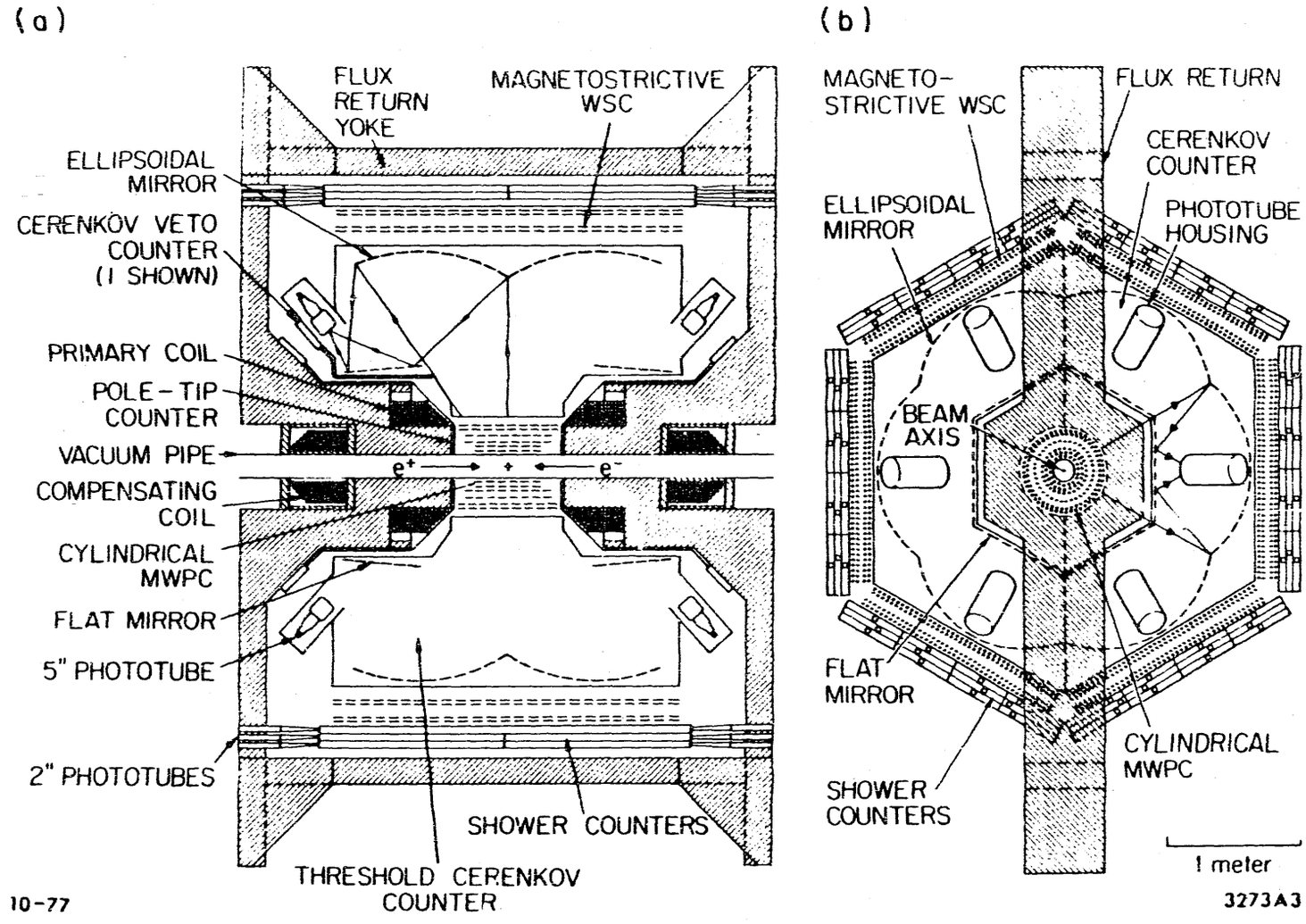

FIGURE 9. The DELCO detector used at SPEAR to find anomalous electron-hadron τ-pair events and measure the mass of the τ (W. Bacino *et al.*, Phys. Rev. Letters **41**, 13 (1978).

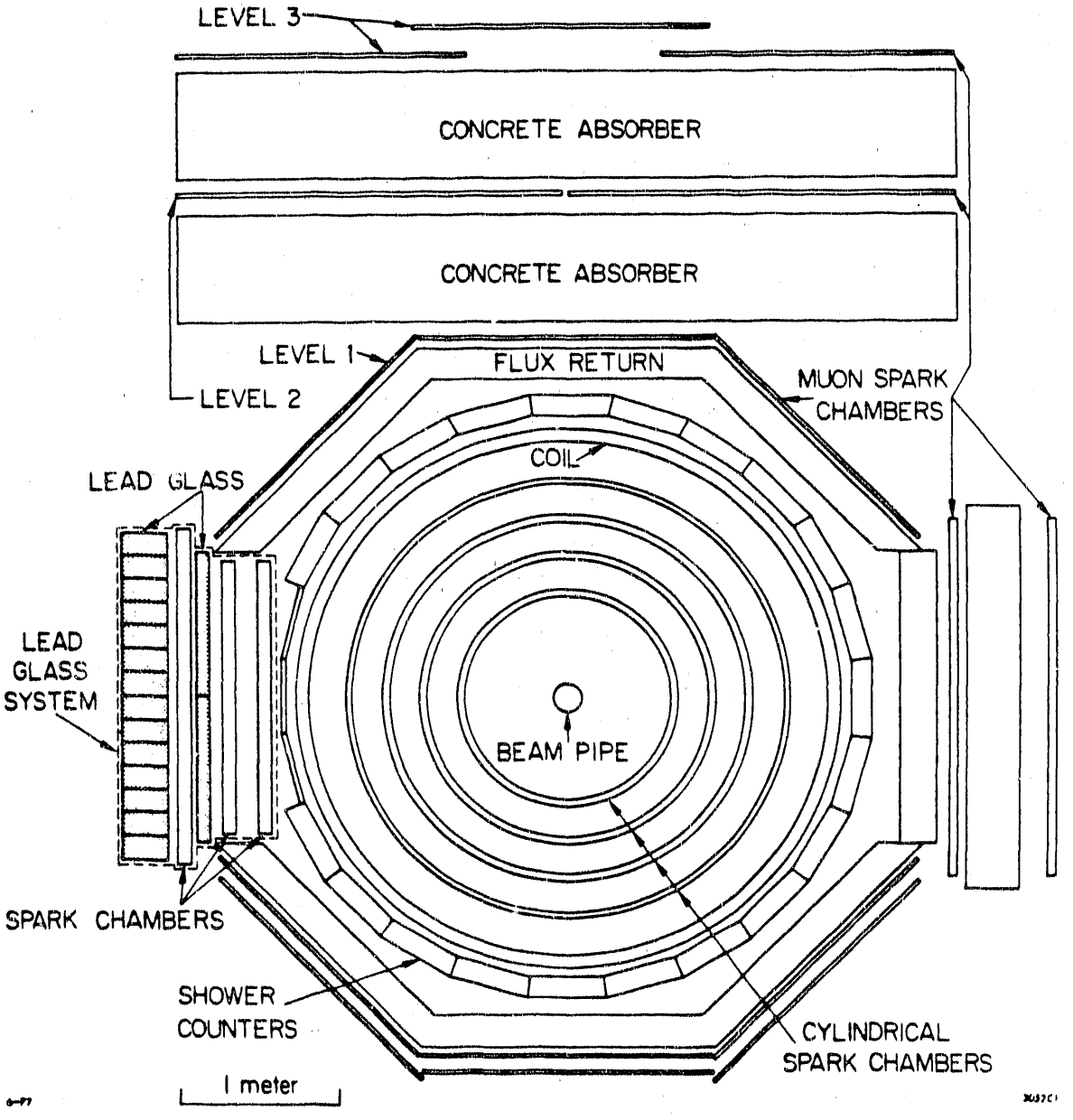

FIGURE 10. The "lead glass wall" modification of the Mark I detector used at SPEAR to find anomalous electron-hadron τ-pair events (A. Barbaro-Galtieri *et al.*, Phys. Rev. Letters **39**, 1058 (1977).

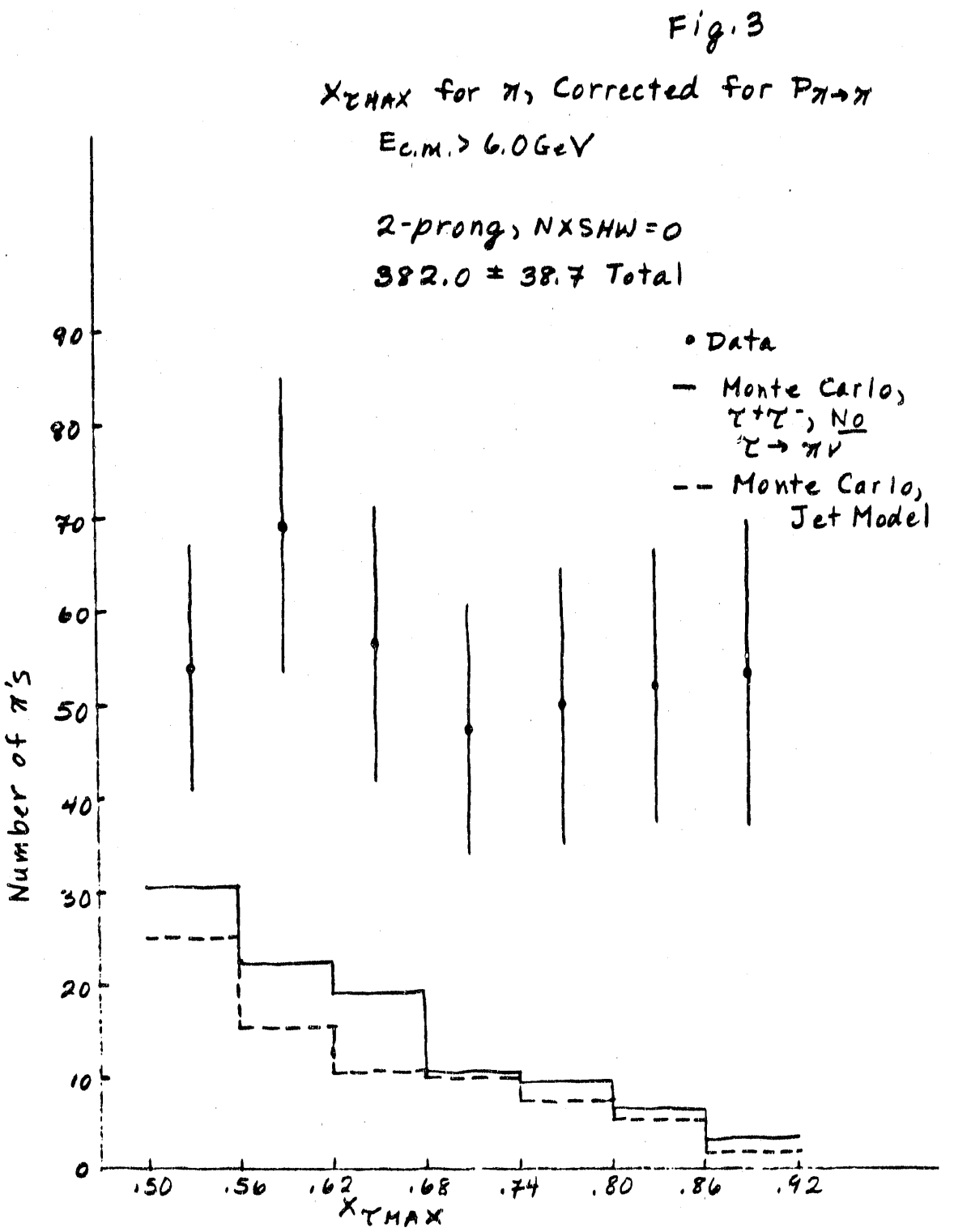

FIGURE 11. Evidence from an unpublished 1978 note of G. Hanson showing that Mark I data required the existence of a substantial $\tau^- \to \pi^- \nu_\tau$ decay mode.

Table V. Results on the $\tau \to \pi\nu$ decay mode. The first error is statistical, the second systematic.

Experiment	Mode	Events	Background	$B(\tau \to \pi\nu)$ (%)	Reference
SLAC-LBL	$x\pi$	∿200	∿70	9.3 ± 1.0 ± 3.8	26
PLUTO	$x\pi$	32	9	9.0 ± 2.9 ± 2.5	27
DELCO	$e\pi$	18	7	8.0 ± 3.2 ± 1.3	28
Mark II	$x\pi$	142	46	8.0 ± 1.1 ± 1.5	16
	$e\pi$	27	10	8.2 ± 2.0 ± 1.5	
Average				8.3 ± 1.4	

FIGURE 12. Reproduction of a table of measured $\tau^- \to \pi^-\nu_\tau$ branching ratios from a 1978 review by G. Feldman, Proc. 1978 Int. Meeting on Frontier of Physics (Singapore, 1978).

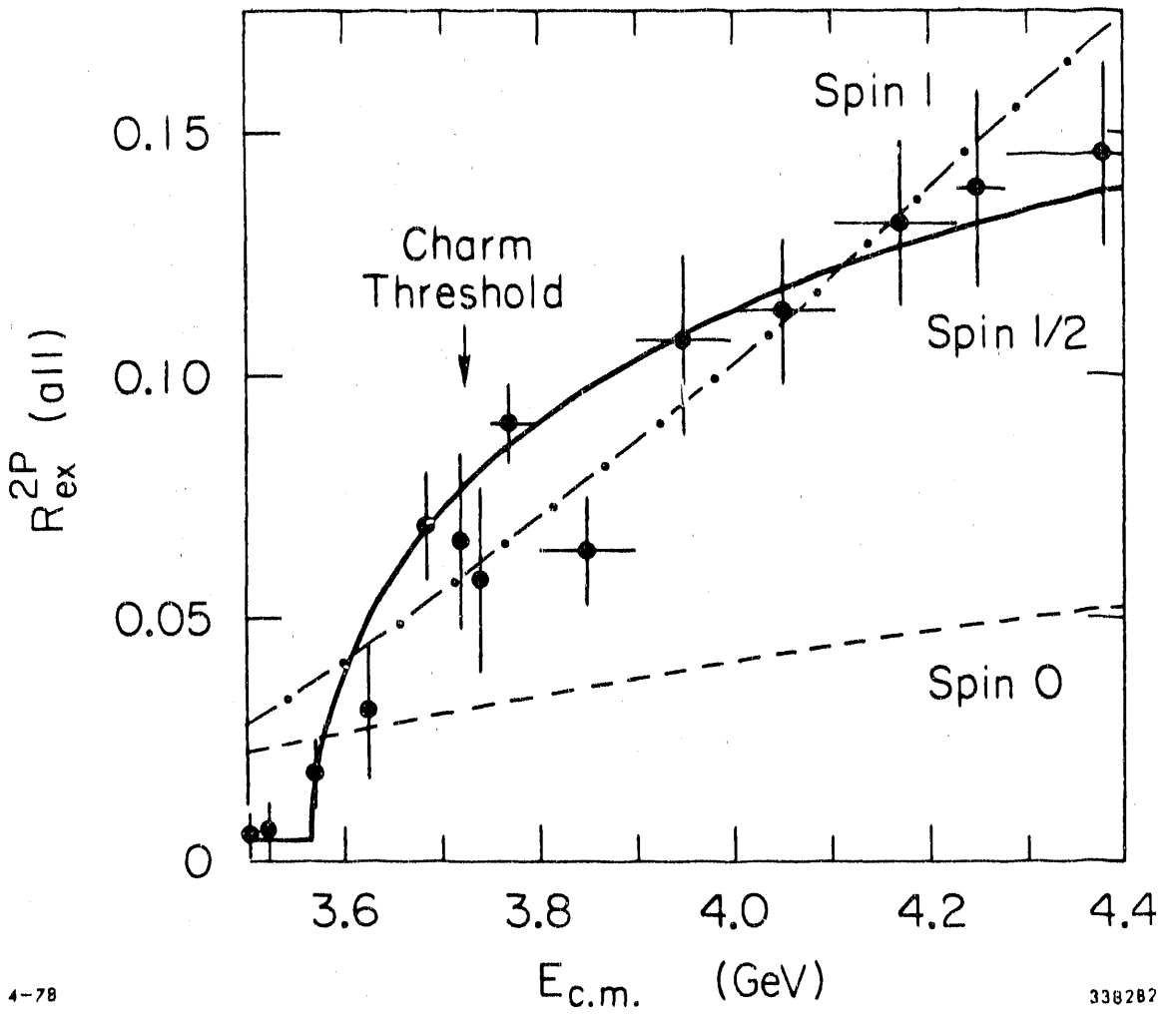

FIGURE 13. The 1978 measurement of the τ mass by the DELCO experiment at SPEAR (W. Bacino *et al.*, Phys. Rev. Letters **41**, 13 (1978).

END

DATE FILMED

02 / 05 / 91