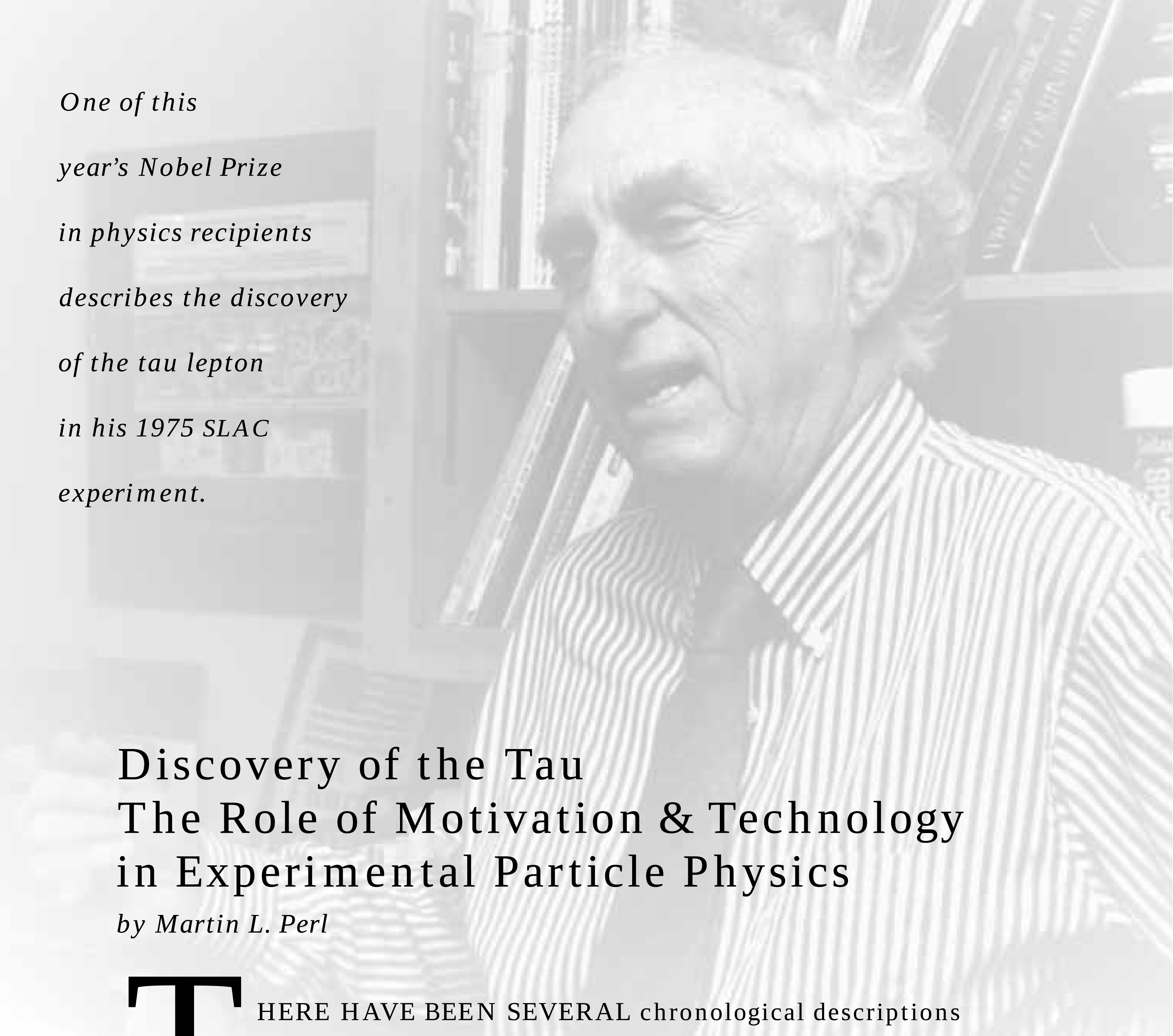


One of this year's Nobel Prize in physics recipients describes the discovery of the tau lepton in his 1975 SLAC experiment.

Discovery of the Tau
The Role of Motivation & Technology in Experimental Particle Physics

by Martin L. Perl

THERE HAVE BEEN SEVERAL chronological descriptions of the discovery of the tau lepton, Perl[1,2] Feldman.[3] In this article I take a different approach, I compare the discovery of the tau with the discovery of the other leptons: electron, muon, electron neutrino, and muon neutrino. My purpose is to illustrate the roles of motivation and of scientific technology in experimental elementary particle physics. I do not intend this article to be a thorough recounting or examination of the histories of lepton discoveries; I only discuss or reference those parts of the histories which are relevant to my purpose.

CATHODE RAYS AND THE ELECTRON'S DISCOVERY

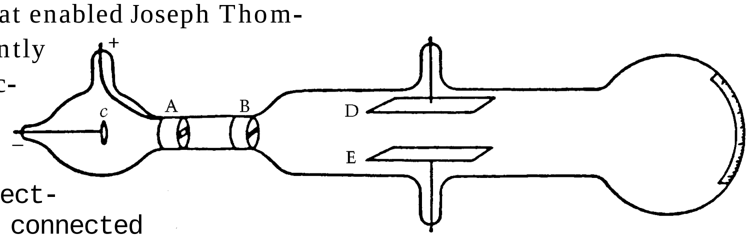
THE DISCOVERY OF THE ELECTRON was the result of almost a half century of experimental work and speculation on the nature of cathode rays.[4] It was already known in the eighteenth century that an electrical voltage applied between conductors in a partially evacuated glass tube could produce light. Inside the tube the gas glowed; the size and shape of the glowing region depended on the voltage, geometry, and pressure. By the 1870s it was recognized that in simple geometries the glowing region was caused by, or consisted of, rays which traveled in straight lines, with one end of the ray's path at the cathode and the other at the anode.

Many physicists of the late nineteenth century studied the cathode-ray phenomenon, including William Crookes, Eugen Goldstein, Heinrich Hertz, Walter Kaufman, Philipp Lenard, Joseph Thomson, and Emil Wiechert. Gradually more was learned experimentally about cathode rays—for example, sufficiently thick foils stopped them; they were bent in a magnetic field; and they either carried, or caused, the transfer of negative electric charge.

Still until the middle 1890s there was dispute about the nature of cathode rays. Some physicists thought the rays were made up of negatively charged matter—the particles we now call electrons. Others believed them to be a kind of electromagnetic wave. There were several objections to the particle explanation. First, if the rays consisted of charged particles similar to ions, the mean free path would be too short to explain the straight line behavior. Second, if the rays consisted of charged particles they should be bent in an electric field, but this had not been observed.

There were four types of instrument technology used in cathode-ray experiments: production of magnetic fields, production of electric fields, measurement of small amounts of charge using an electroscope, and the use of vacuum pumps to produce a partially evacuated discharge tube. It was the improvement of vacuum pump technology that enabled Joseph Thomson to demonstrate that in a tube with a sufficiently good vacuum, cathode rays were bent in an electric field.[5] Describing his experiment with the tube shown on the right he wrote:

> At high exhaustion the rays were deflected when the two aluminum plates were connected with the terminals of a battery of small storage cells. . . . The deflection was proportional to the difference of potential between the plates. . . . It was only when the vacuum was a good one that the deflection took place.



The cathode ray tube apparatus used by Thomson.

Earlier attempts to deflect cathode rays in an electric field had failed because there was electrical conduction in the partial vacuum. Gas ions collected on the deflecting plates, canceling the charges on the plates and hence the potential difference. Thus the discovery of the electron depended on the gradual improvement of late nineteenth century instrument technology, particularly vacuum pump technology. I have omitted discussion of the extensive research that led to the determination of the charge and mass of the electron and of the research that showed the electron has the same properties whether it is emitted from a cathode, produced by ionizing a gas, or produced in radioactive decay. The process of discovering the electron was interwoven with the process of determining the basic properties of the electron.

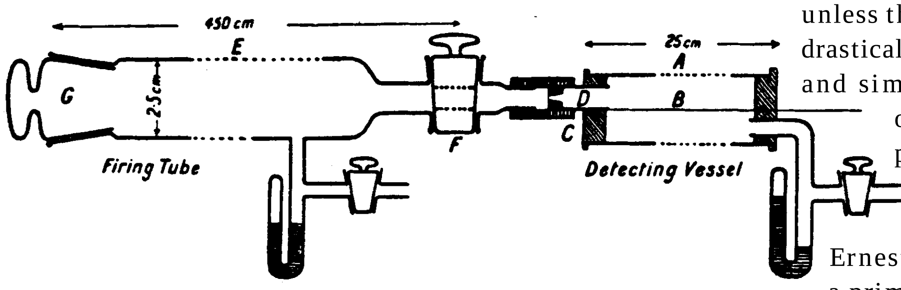
The motivation that led to the discovery of the electron was the need to explain the cathode-ray phenomenon. I call this a "phenomenon-driven" discovery.

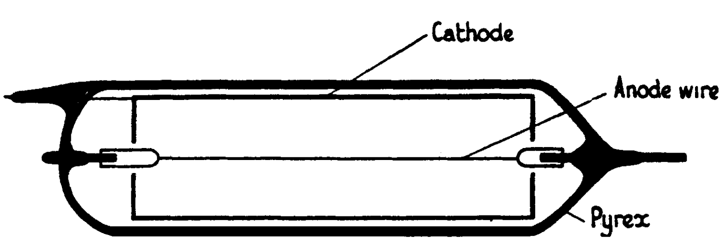
COSMIC RAYS AND THE MUON'S DISCOVERY

THE DISCOVERY OF THE MUON has many similarities to the discovery of the electron. Both discoveries were phenomenon driven and both discoveries depended upon improvements and inventions in scientific technology. As with the electron the muon discovery process was interwoven with the process of determining the properties of the muon; and as with the electron many physicists were involved in these processes. Some of these physicists have given fascinating accounts, Carl Anderson and Herbert Anderson,[6] Gilberto Bernardini,[7] Marcello Conversi,[8] Oreste Piccioni,[9] and Bruno Rossi.[10]

The first observed effect of cosmic rays was the discovery using electroscopes that air in the atmosphere was slightly ionized. As summarized by Rossi,[11] in the middle 1920s it was believed that cosmic rays began as high energy gamma rays. The ionization was attributed to the high energy secondary electrons produced when the gamma rays scattered on electrons in the atmosphere, the Compton process.

In a famous experiment in 1929 Walther Bothe and Werner Kolhörster[12] used two Geiger-Müller counters separated by four centimeters of gold to show that 75 percent of the ionizing rays passed through this gold. Gamma rays would not penetrate four centimeters of gold, nor would electrons, unless their interaction cross section declined drastically at high energies. This experiment—and similar contemporary and subsequent ones—established the existence of a penetrating component in cosmic rays.





Geiger-Müller counters. The top is a primitive type used by Ernest Rutherford and Hans Geiger, and the bottom is a traditional design.

The Geiger-Müller tube, shown on the left, has a long history. In 1908 Ernest Rutherford and Hans Geiger[13] used a primitive tube (above) to count the number of alpha particles coming from a radioactive source. The traditional type of Geiger-Müller tube (left) dates from 1928.[14] Thus progress in the investigation of the nature of cosmic rays depended on new technology.

During the first half of the 1930s there were many experimental and theoretical attacks on the problem of the nature of the penetrating component in cosmic rays. There was even the speculation that the electron interaction cross section decreased at high energy. Finally in 1937 three sets of experiments[15–17] reported that the penetrating component could be explained by the existence of a particle more massive than an electron but less massive than a proton. For simplicity I discuss the Seth Neddermeyer and Carl Anderson experiment.[15] They used a magnetic cloud chamber triggered by Geiger-Müller counters. The illustration on the right shows a typical one of that period.[18] Once again new technology was required. Quoting from the Neddermeyer and Anderson paper[15]:

> there exist particles of unit charge, but with a mass (which may not have a unique value) larger than that of a normal free electron and much smaller than that of a proton.
>
> The experimental fact that penetrating particles occur both with positive and negative charges suggests that they might be created in pairs by photons, and that they might be represented as higher mass states of ordinary electrons.

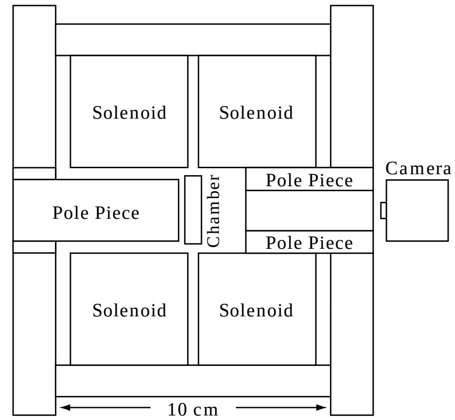
We now know that the positive and negative muons in cosmic rays came from the decays of positive and negative pions; still pair production was a good guess. And the last part of the quoted sentence is a prophetic nod to the electron-muon problem.

The box on the next page reproduces the cosmic radiation entry in the Analytic Subject Index for the 1937 *Physical Review* volume which contained references 15 and 17. It illustrates the large amount of research activity in cosmic-ray physics.

It was almost another ten years before the full nature of the muon was determined. Conversi,[8] Piccioni,[9] and Rossi[10] have described the research of themselves and their colleagues in the early 1940s; their experiments used the then newly developed coincidence and anti-coincidence circuits. One enormous source of confusion was the connection of the muon to the particle proposed by Hideki Yukawa[19] to explain the nuclear force, the pion. The masses seemed similar; could the muon and the pion be two different forms of one particle? In 1947 C. M. G. Lattes et al.[20] dispelled the confusion by finding in emulsions exposed on the top of a mountain the decay

$$\pi \rightarrow \mu + \text{missing energy}$$

with a measured π–μ mass difference of about 25 MeV. The 1947 Robert Marshak and Hans Bethe paper[21] summarized the solution of the confusion: the π partakes of the strong interaction but the μ does not; the π decays to the μ and the μ itself decays, both through beta decay, that is, through the weak interaction.



A 1.5 tesla magnetic cloud chamber built by Carl Anderson in 1933. The vertical cloud chamber itself is 16.5 centimeters in diameter and 4 centimeters deep.

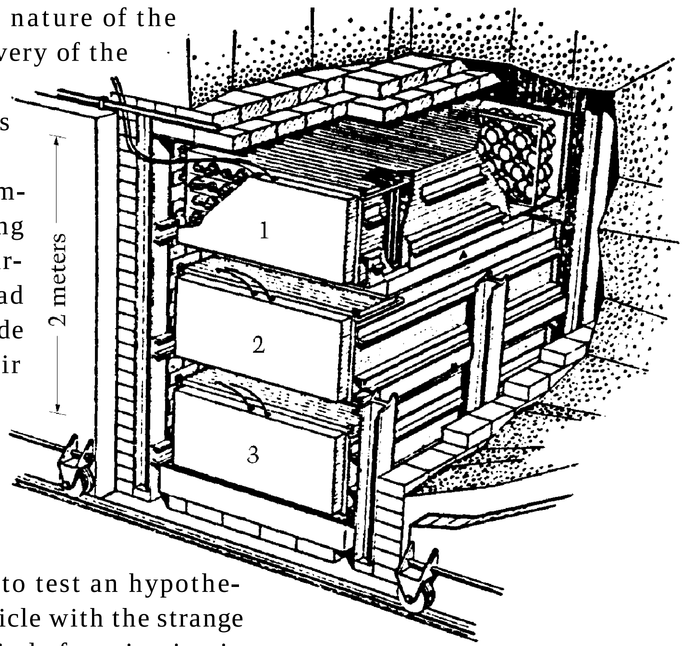
The Cosmic radiation *entry in the Analytic Subject Index of the 1937* Physical Review *volume that contained the important muon discovery papers by Seth Neddermeyer and Carl Anderson* [15] *and by Jabez Street and E. C. Stevenson.*

DISCOVERY OF THE ELECTRON ANTINEUTRINO

THERE ARE TWO MAJOR DIFFERENCES between the nature of the discoveries just described and the nature of the discovery of the electron antineutrino, an accomplishment for which Frederick Reines shares the 1995 Nobel Prize in Physics with me. The first major difference is in motivation.

As described in the original papers[22,23] and Reines' memoir[24] it was expected from the hypothesis of Wolfgang Pauli[25] that the missing energy in beta decay was carried off by a small mass particle. But the neutrino had never been detected. The motivation of Reines and Clyde Cowan was to see if the neutrino really existed; their experiment was designed:[23]

> to show that the neutrino has an independent existence, i.e. that it can be detected away from the site of its creation. . . .



The liquid scintillator apparatus used by Reines to detect the electron antineutrino in the late 1950s.

Therefore the motivation in the narrow sense was to test an hypothesis. In a broader sense the motivation was to see if a particle with the strange properties of the proposed neutrino could exist. This kind of motivation is very different from the phenomenon-driven motivations of the electron and muon discoveries.

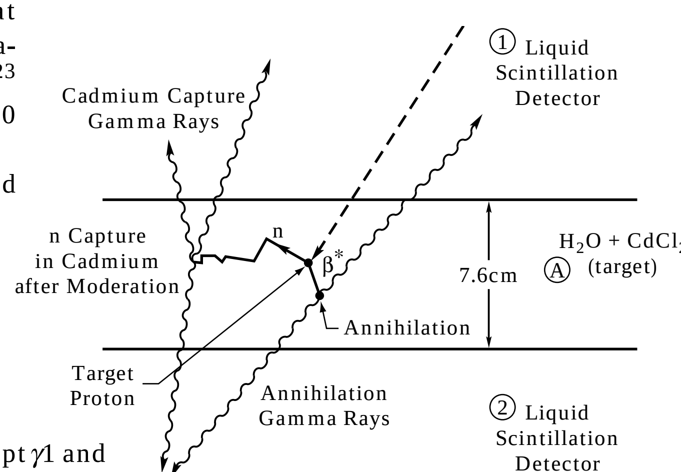
The second major difference was that all the work in the detection of the electron antineutrino, $\bar{\nu}_e$, was carried out by one small group of physicists, not by many small groups as was the situation with the muon discovery. This makes it all the more remarkable that Reines and Cowan were able to assemble an innovative and, for the time, very large detection apparatus[23] (above right); for example, the apparatus used over 300 five-inch photomultiplier tubes.

The detection method (right) used reactor-produced electron antineutrinos and the reaction sequence

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$e^+ + e^- \text{ (in scintillator)} \rightarrow \gamma 1 + \gamma 2$$

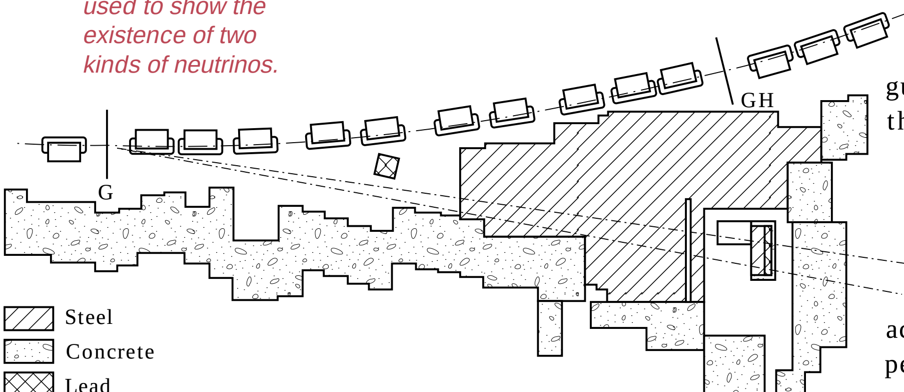
$$n + \text{Cd nucleus} \rightarrow \text{Cd nucleus} + \text{several } \gamma\text{'s}$$



The method used by Reines to detect the electron antineutrino.

The experimental signal was the detection of the prompt $\gamma 1$ and $\gamma 2$ and the delayed several γ's when the reactor was on. There would be no authentic signal with the reactor off—a very difficult experiment just inside the limit of the experimenter's technology and skill.

DISCOVERY OF TWO KINDS OF NEUTRINOS

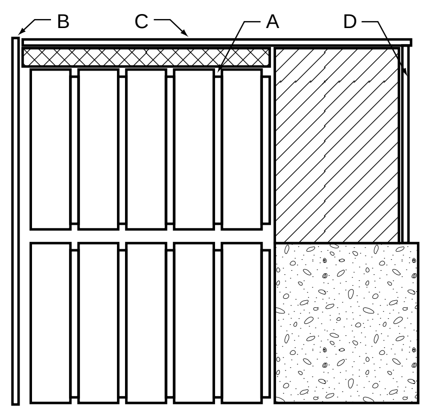


The pioneer muon neutrino beam of Gordon Danby and colleagues at the Brookhaven Alternating Gra– dient Synchrotron proton accelerator used to show the existence of two kinds of neutrinos.

IN 1960 MELVIN SCHWARTZ[26] AND BRUNO PONTECORVO[27] independently proposed the use of high energy neutrinos to study the interaction of neutrinos with matter. Their initial motivations were somewhat different. Schwartz in his letter[26] emphasizes that the use of high energy neutrinos, $E > 2$ GeV, increases the interaction cross section to about 10^{-38} cm^2. This is 10^6 times larger than the cross section with which Reines and Cowan struggled. Pontecorvo[27] emphasized the possibility of distinguishing the electron neutrino (ν_e) from the muon neutrino (ν_μ). That possibility was also discussed by T. D. Lee and C. N. Yang[28] in a letter following Schwartz's letter.

Here we see the beginning of the multiple motivations which characterize modern high energy physics experiments. The two-neutrino discovery paper of Gordon Danby et al.[29] summarizes the motivations: test the predicted behavior of the neutrino interaction cross section with energy; find out if neutrinos from $\pi^+ \to \mu^+ + \nu$ produce μ's when they interact; find out if such neutrinos produce e's when they interact; and look for the intermediate boson.

Once again the discoverers used innovative technology—a high energy neutrino beam (top) and large, thick plate optical spark chambers (bottom). They found that the electron neutrino is different from the muon neutrino, thus establishing the conservation of separate lepton numbers in the e–ν_e and μ–ν_μ systems. They also initiated the fertile field of high energy neutrino experiments. For these accomplishments, Leon Lederman, Melvin Schwartz, and Jack Steinberger received the 1988 Nobel Prize in Physics.



The large optical spark chamber and scintillation counter system used by Danby and colleagues to detect the muon neutrino.

DISCOVERY OF THE TAU: MOTIVATION

THE DISCOVERY OF THE TAU came from a sequence of motivations. The first of my motivations was to explore the electron-muon problem of the 1960s. By the early 1960s it was known that the e and μ comprised a queerly related pair of particles (see box on next page). With respect to the strong and electromagnetic interactions the muon behaves simply as a heavier electron, 206.8 times heavier. But the expected electromagnetic decay

$$\mu^+ \to e^+ + \gamma$$
$$\mu^- \to e^- + \gamma$$

Properties of the Electron and Muon.*

Particle	Electron	Muon
Symbol	e	μ
Electric charge	+1 or –1	+1 or –1
Mass	1	206.8
Does particle have electromagnetic interactions?	yes	yes
Does particle have weak interactions?	yes	yes
Does particle have strong interactions?	no	no
Associated neutrino	ν_e	ν_μ
Associated antineutrino	$\bar{\nu}_e$	$\bar{\nu}_\mu$
Lifetime	stable	2.2×10^{-6} sec

**The electron charge is given in units of 1.6×10^{-19} coulombs. The mass is given in units of the mass of the electron 9.1×10^{-31} kilograms.*

does not occur, or occurs so rarely that it has never been detected. Instead the decay occurs through the weak interaction process

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

in which one neutrino and one antineutrino are produced in each decay. The μ and the e differ in some fundamental property such that in the decay of the μ^- its "muness" must be transferred to the muon neutrino, ν_μ; and in the creation of the e^- its "electronness" must be balanced by the creation of an electron antineutrino, $\bar{\nu}_e$, with an "anti-electronness" property.

The electron-muon problem consisted of several questions: Is there a connection between the e and the μ? What law sets the ratio of the μ mass to the e mass? What is the nature of the "muness" and "electronness" properties?

My initial motivation to explore the electron-muon problem is somewhat similar to the motivation of the research that led to the discovery of the two neutrinos (see opposite page). But unlike the two neutrinos research, the work of my colleagues and myself on the electron-muon problem was not fruitful. I have described elsewhere[1,2] our work at Stanford Linear Accelerator Center (SLAC) in the late 1960s and early 1970s on measuring muon-proton inelastic scattering and comparing it with electron-proton inelastic scattering. We were looking for a new difference between the e and the μ, but we didn't find any!

Since my attack on the electron-muon problem was thwarted by nature I turned to another idea that had been in my mind since the early 1960s. Perhaps there was another undiscovered and heavier charged lepton. This was the second motivation, look for a new charged heavy lepton. I held in my mind simultaneously the electron-muon problem motivation and the new lepton motivation. And as my attack on the electron-muon problem began to go badly I became more and more optimistic about finding a new charged lepton. As Voltaire wrote in *Candide*, "Optimism, said Candide, is a mania for maintaining that all is well when things are going badly."

My next question to myself was, what sort of new charged leptons should I look for? The box on the next page lists the speculations of the 1960s about the possible existence and types of new leptons. To choose among them I turned to a third motivation—simplicity. I had left research in strong interaction physics and started research in lepton physics to work in a simpler field[1,2] so why not continue in that direction? I fastened on the sequential lepton model. (To describe this model I take the remainder of this section from reference 1.)

Helped by my SLAC colleagues Paul Tsai and Gary Feldman I thought of a sequence of lepton pairs:

Speculations in the 1960s and early 1970s on Types of Heavy Leptons.*

Type	Remark or Example
singlet charged lepton	stable
fractional charge lepton	stable
singlet neutral lepton	stable
spin 0 or spin 1 lepton	precursor to supersymmetric theory
charged sequential leptons	e^-, ν_e; μ^-, ν_μ; L^-, ν_L; L', $\nu_{L'}$; . . . with $m(L) > m(\nu_L)$ $L^- \rightarrow \nu_L + . . .$
excited charged lepton	$e^{*+} \rightarrow e^+ + \gamma$ $\mu^{*+} \rightarrow \mu^+ + \gamma$
neutral lepton pairs	L^0, l^0 with $m(L^0) > m(l^0)$ $L^0 \rightarrow l^0 + ...$
reversed mass lepton pairs	L^0, L^- with $m(L^0) > (L^-)$ $L^0 \rightarrow L^- + . . .$
special e or μ related leptons	E^+, E^0 have lepton number of e^- $m(E^+) > m(e)$, $m(E^0) > m(e)$ ν_e + nucleon $\rightarrow E^+$ + nucleon $E^+ \rightarrow e^- + . . .$
pairs of doublet leptons	e^-, ν_e; e'^-, ν_e'

m is mass

$$\begin{array}{ll} e^- & \nu_e \\ \mu^- & \nu_\mu \\ L^- & \nu_L \\ L'^- & \nu_{L'} \\ \bullet & \bullet \\ \bullet & \bullet \\ \bullet & \bullet \end{array}$$

each pair having a unique lepton number. I 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 1960s in a search for simple physics.

The idea was to look for

$$e^+ + e^- \rightarrow L^+ + L^- \tag{1a}$$

with

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

or

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

This search method had many attractive features:

- If the L were a point particle, we could then search up to an L mass almost equal to the beam energy, if we had 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 the above equations 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 (see page 16).

There was little theory involved in predicting that the L would have the weak decays

$$L^- \to \nu_L + e^- + \bar{\nu}_e$$
$$L^- \to \nu_L + \mu^- + \bar{\nu}_\mu$$

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

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

I incorporated the search method summarized by Eqs. (1) in our 1971 SLAC–LBL proposal to use the not-yet-completed SPEAR e^+e^- storage ring.

My thinking about sequential leptons and the use of the method of Eqs. (1) to search for them was greatly helped and influenced by two seminal papers of Paul Tsai. In 1965 he published with Anthony Hearn the paper "Differential Cross Section for $e^+ + e^- \to W^+ + W^- \to e^- + \bar{\nu}_e + \mu^+ + \nu_\mu$."[30] 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 L^+L^- pairs by their $e\mu$ decay mode. Tsai's 1971 paper entitled "Decay Correlations of Heavy Leptons in $e^+ + e^- \to L^+ + L^-$"[31] provided the detailed theory for the application of the sequential lepton model to our actual searches. In 1971 Harry Thacker and J. J. Sakurai also published a paper on the theory of sequential lepton decays,[32] but it is not as comprehensive as the work of Tsai. Also important to me was the general paper "Spontaneously Broken Gauge Theories of Weak Interactions and Heavy Lepton" by James Bjorken and Chris Llewellyn Smith.[33]

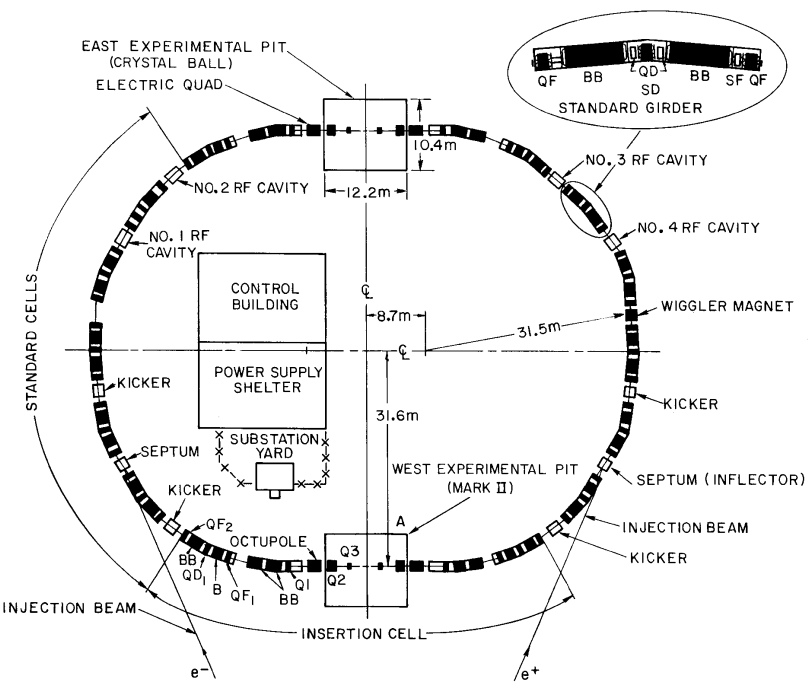
As the reader knows, the sequential lepton model turned out to be right for the first three leptons. The simplicity motivation worked here. But it is not always a wise motivation. For example, I don't recommend using this motivation in research on the strong interactions.

DISCOVERY OF THE TAU: GENERAL TECHNOLOGY

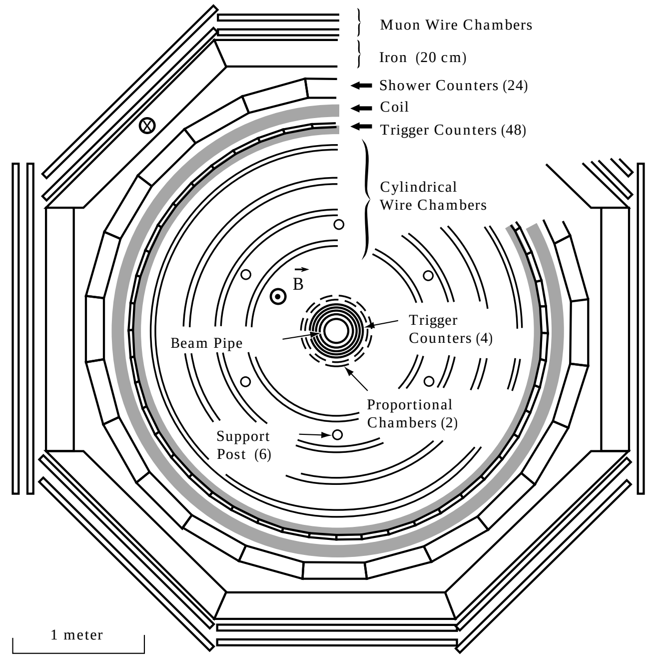
EACH OF THE PREVIOUS lepton discoveries depended on a different technology, and this was also true for the discovery of the tau. The crucial new technologies were

- Electron-positron circular colliders.
- Large solid angle detectors.
- Storage of data on computer tape.
- Computer-aided data analysis.

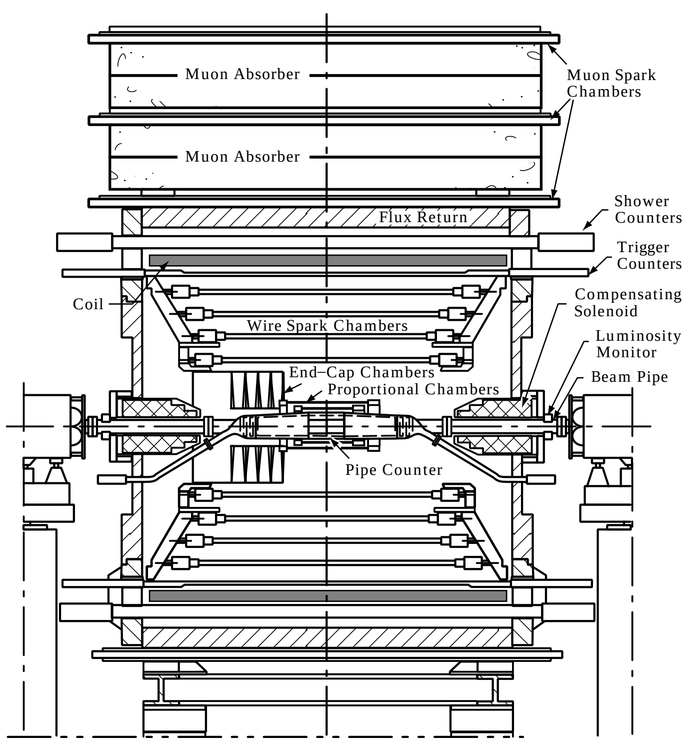
Gustav-Adolf Voss[34] has described the history of electron-positron circular colliders. In our case, SLAC Group C led by Burton Richter built the SPEAR collider (next page) over a period of several years, completing construction in 1973. Gary Feldman and I and our Group E joined with Group C and a Lawrence Berkeley Group led by William Chinowsky, Gerson Goldhaber, and George Trilling to build the SLAC-LBL detector, one of the first

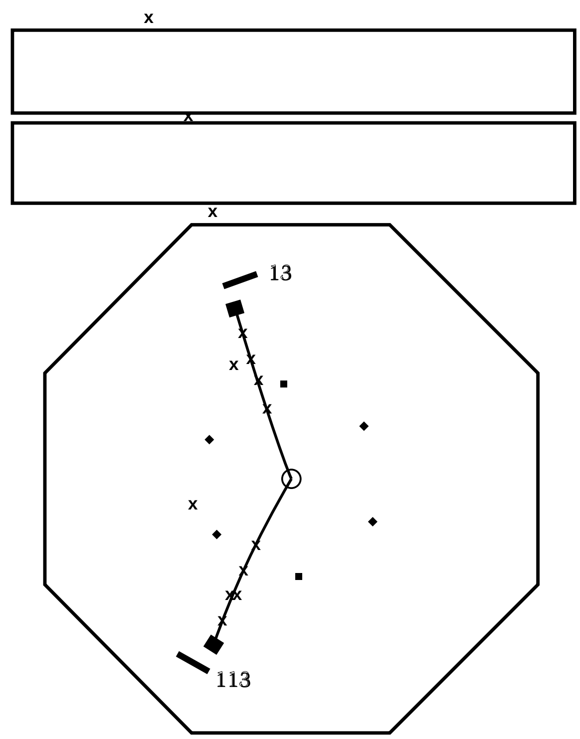


The SLAC electron-positron circular collider SPEAR where the tau lepton was discovered,

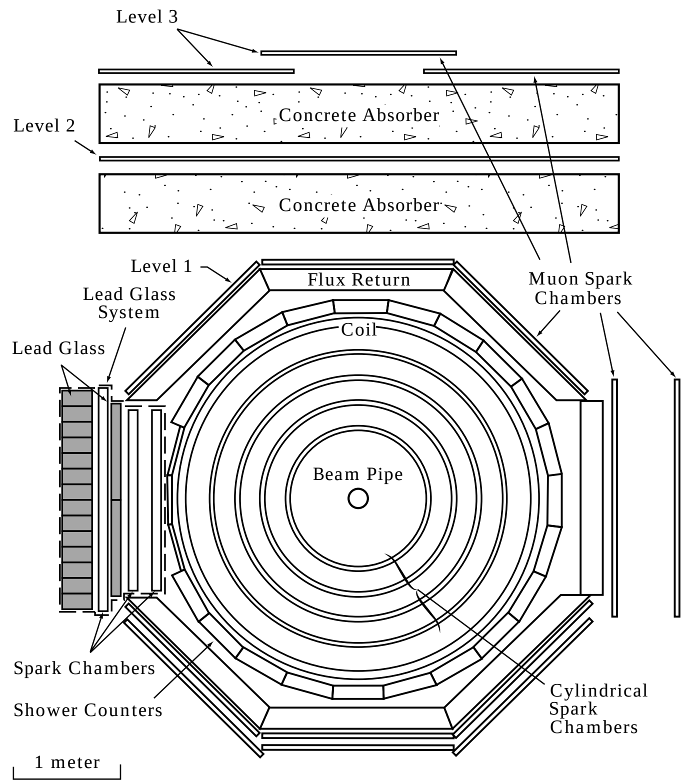


The SLAC-LBL detector, later called the Mark I, used in the discovery of the tau.





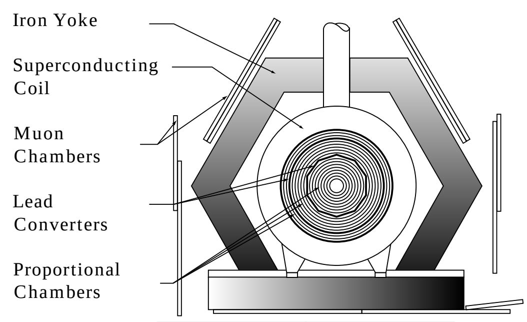
The Mark I detector (above) with the muon tower and one of the first eμ events (right) using the muon tower. The μ moves upward through the tower and the e moves downward. The numbers 13 and 113 give the relative amounts of electromagnetic shower energy deposited by the μ and the e.



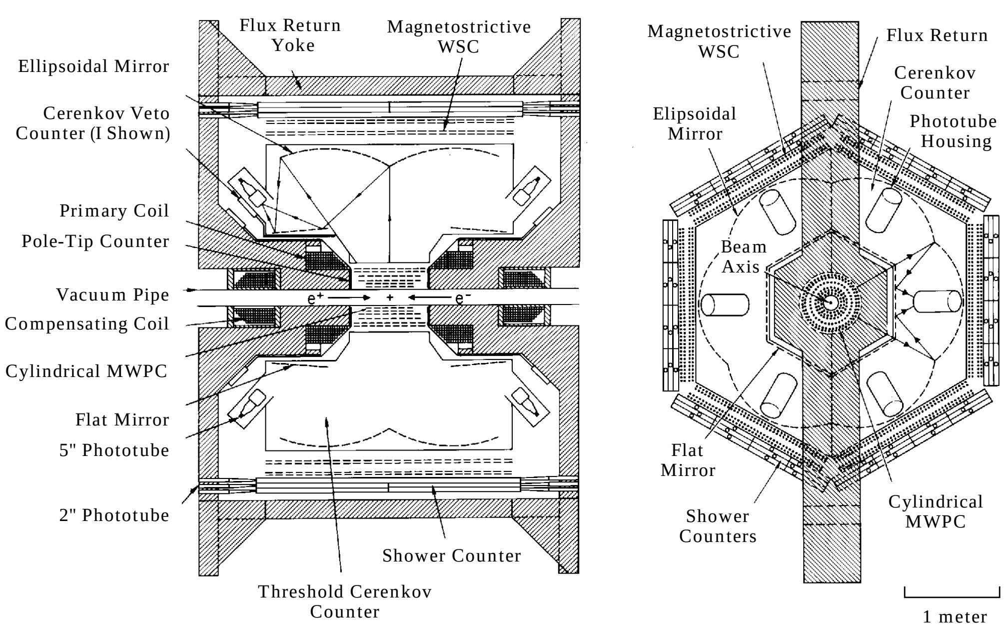
The "lead glass wall" modification of the Mark I detector.

large solid angle detectors (previous page, opposite). This detector was later expanded to improve the muon detector (previous page, bottom) and then modified to improve the electron and photon detection (right).[35]

In the first years of the tau discovery the PLUTO detector (middle right illustration) was important because of its new technology. It was used at the DORIS electron-positron collider at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany. Reference 36 describes PLUTO and reference 37 describes early work of the PLUTO experimenters on the tau. Also technologically important was the DELCO detector[38] at SPEAR. It was the first large solid angle detector to use Cherenkov radiation to identify electrons (bottom figures).



The PLUTO detector used at the DORIS electron-positron circular collider at DESY.



The DELCO detector used at SPEAR (far left and left).

DISCOVERY OF THE TAU: SPECIFIC TECHNOLOGY & FIRST EVIDENCE

THE BEST WAY TO DESCRIBE the specific technology we used to find the first evidence for the existence of the tau and at the same time describe that evidence is to reproduce with comments our 1975 *Physical Review Letter*[39] where we announced the discovery of unexplained $e\mu$ events. I will preserve the actual *Letter* format with the original table and figure numbers of the *Letter*. My comments on the material in the *Letter* are interspersed.

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

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(Received 18 August 1975)

We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp \geq 2 \text{ undetected particles} \qquad (1)$$

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-LBL) magnetic detector at the SLAC colliding-beams facility SPEAR.

We were cautious; we didn't claim to have found a new particle, and in particular we didn't claim to have found a new lepton. The data agreed well with the hypothesis of the production of a pair of new particles, still caution was best. Using the pair production hypothesis, the data agreed better with the three-body purely leptonic decay of a new heavy lepton than with the two-body purely leptonic decay of a new heavy meson, but this was far from conclusive. I already felt strongly that it was a new lepton. There is less caution these days in claims for the discovery of a new particle or a new particle physics phenomenon because so much speculative theory has been published and because there is so much pressure to be the first to break out of the standard model.

> Events corresponding to (1) are the signature for new types of particles or interactions. For example, pair production of heavy charged leptons[1-4] having the decay modes $l^- \to \nu_l + e^- + \bar{\nu}_e$, $l^+ \to \bar{\nu}_l + e^+ + \nu_e$, $l^- \to \nu_l + \mu^- + \bar{\nu}_\mu$, and $l^+ \to \bar{\nu}_l + \mu^+ + \nu_\mu$ would appear as such events. Another possibility is the pair production of charged bosons with decays $B^- \to e^- + \bar{\nu}_e$, $B^+ \to e^+ + \nu_e$, $B^- \to \mu^- + \bar{\nu}_\mu$, and $B^+ \to \mu^+ + \nu_\mu$. Charmed-quark theories[5,6] predict such bosons. Intermediate vector bosons which mediate the weak interactions would have similar decay modes, but the mass of such particles (if they exist at all) is probably too large[7] for the energies of this experiment.

We listed some possible explanations of the $e\mu$ events because we could not prove that the origin of these events was heavy lepton decays

> The momentum-analysis and particle-identifier systems of the SLAC-LBL magnetic detector[8] cover the polar angles $50^\circ \leq \theta \leq 130^\circ$ and the full 2π azimuthal angle. Electrons, muons, and hadrons are identified using a cylindrical array of 24 lead-scintillator shower counters, the 20-cm-thick iron flux return of the magnet, and an array of magnetostrictive wire spark chambers situated outside the iron. Electrons are identified solely by requiring that the shower-counter pulse height be greater than that of a 0.5-GeV *e*. Incidently, the *e*'s in the e-μ events thus selected give no signal in the muon chambers; and their shower-counter pulse-height distribution is that expected of electrons. Also the positions of the

e's in the shower counters as determined from the relative pulse heights in the photomultiplier tubes at each end of the counters agree within measurement errors with the positions of the *e* tracks. Hence the *e*'s in the *e*-μ events are not misidentified combinations of $\mu + \gamma$ or $\pi + \gamma$ in a single shower counter, except possibly for a few events already contained in the background estimates. Muons are identified by two requirements. The μ must be detected in one of the muon chambers after passing through the iron flux return and the other material totaling 1.67 absorption lengths for pions. And the shower-counter pulse height of the μ must be small. All other charged particles are called hadrons. The shower counters also detect photons (γ). For γ energies above 200 MeV, the γ detection efficiency is about 95%.

The SLAC-LBL detector was one of the first large solid angle detectors used in colliding-beam experiments. If the detector had had a small solid angle we would not have found the tau for two reasons. First, we would not have collected enough *eμ* events. Second, we could not have eliminated events with additional charged particles. The detection systems were primitive by today's standards. In particular the muon detection system had just 1.67 pion absorption lengths, leading to poor π-μ separation. By the time this *Letter* was written, Gary Feldman had built an addition to the muon detection system called the muon tower. We had already detected *eμ* events in which there was improved detection of the μ in the tower, but these events were not used in this paper.

To illustrate the method of searching for events corresponding to Reaction (1), we consider our data taken at a total energy ($\sqrt{s}$) of 4.8 GeV. This sample contains 9550 three-or-more-prong events and 25 300 two-prong events which include $e^+ + e^- \rightarrow e^+ + e^-$ events, $e^+ + e^- \rightarrow \mu^+ + \mu^-$ events, two-prong hadronic events, and the *e*-μ events described here. To study two-prong events we define a coplanarity angle

$$\cos\theta_{copl} = -(\vec{n}_1 \times \vec{n}_{e+}) \cdot (\vec{n}_2 \times \vec{n}_{e+}) / |\vec{n}_1 \times \vec{n}_{e+}|\,|\vec{n}_2 \times \vec{n}_{e+}|, \quad (2)$$

$e^+ + e^- \rightarrow e^+ + e^-$ and $e^+ + e^- \rightarrow \mu^+ + \mu^-$ is greatly reduced if we require $\theta_{copl} > 20^\circ$. Making this cut leaves 2493 two-prong events in the 4.8-GeV sample.

To obtain the most reliable *e* and μ identification[9] we require that each particle have a momentum greater than 0.65 GeV/*c*. This reduces the 2493 events to the 513 in Table I. The 24 e-μ events with no associated photons, called the signature events, are candidates for Reaction (1). The e-μ events can come conventionally from the two-virtual-photon process[10] $e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \mu^-$ Calculations indicate that this source is negligible, and the absence of e-μ events with charge 2 proves this point since the number of charge-2 e-μ events should equal the number of charge-0 e-μ events from this source.

We developed criteria for selecting $e\mu$ events from heavy leptons which are still used. Events with just two charged particles and no photons were selected. The *e* and μ were not allowed to be back to back to eliminate contamination from $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ events. Minimum momentum criteria were applied to each particle because *e* and μ selection was less certain at small momenta, as is still the situation today.

We determine the background from hadron misidentification or decay by using the 9550 three-or-more-prong events and assuming that every particle called an *e* or a μ by the detector either was a misidentified hadron or came from the decay of a hadron. We use $P_{h\rightarrow l}$ to designate the sum of the probabilities for misidentification or decay causing a hadron *h* to be called a lepton *l*. Since the *P*'s are momentum dependent[9] we use all the *e*-*h*, μ-*h*, and *h*-*h* events in column 1 of Table I to determine a "hadron" momentum spectrum, and weight the *P*'s accordingly. We obtain the momentum-averaged probabilities $P_{h\rightarrow e} = 0.183 \pm 0.007$ and $P_{h\rightarrow\mu} = 0.198 \pm 0.007$. Collinear *e*-*e* and μ–μ events are used to determine $P_{e\rightarrow h} = 0.056 \pm 0.02$, $P_{e\rightarrow\mu} = 0.011 \pm 0.01$, $P_{\mu\rightarrow h} = 0.08 \pm 0.02$, and $P_{\mu\rightarrow e} < 0.01$.

TABLE I. Distribution of 513 two-prong events, obtained at $E_{c.m.}$ = 4.8 GeV, which meet the criteria $|\vec{p}_1| > 0.65$ GeV/c, $|\vec{p}_2| > 0.65$ GeV/c, and $\theta_{copl} > 20^\circ$. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ± 2		
e-e	40	111	55	0	1	0
e-μ	24	8	8	0	0	3
μ-μ	16	15	6	0	0	0
e-h	20	21	32	2	3	3
μ-h	17	14	31	4	0	5
h-h	14	10	30	10	4	6

$P_{h\to e}$ and $P_{h\to\mu}$ were very large by modern standards, yet as shown next there were so few *hh* events with 0 photons and 0 charge that only 3.7±0.6 events were calculated to come from *hh* misidentification.

Using these probabilities and assuming that all *e-h* and *μ-h* events in Table I result from particle misidentifications or particle decays, we calculate for column 1 the contamination of the *e-μ* sample to be 1.0 ± 1.0 event from misidentified *e-e*,[11] < 0.3 event from misidentified *μ–μ*,[11] and 3.7 ± 0.6 events from *h-h* in which the hadrons were misidentified or decayed. The total *e-μ* background is then 4.7 ± 1.2 events.[12,13] The statistical probability of such a number yielding the 24 signature *e-μ* events is very small. The same analysis applied to columns 2 and 3 of Table I yields 5.6 ± 1.5 *e-μ* background events for column 2 and 8.6 ± 2.0 *e-μ* background events for column 3, both consistent with the observed number of *e-μ* events.

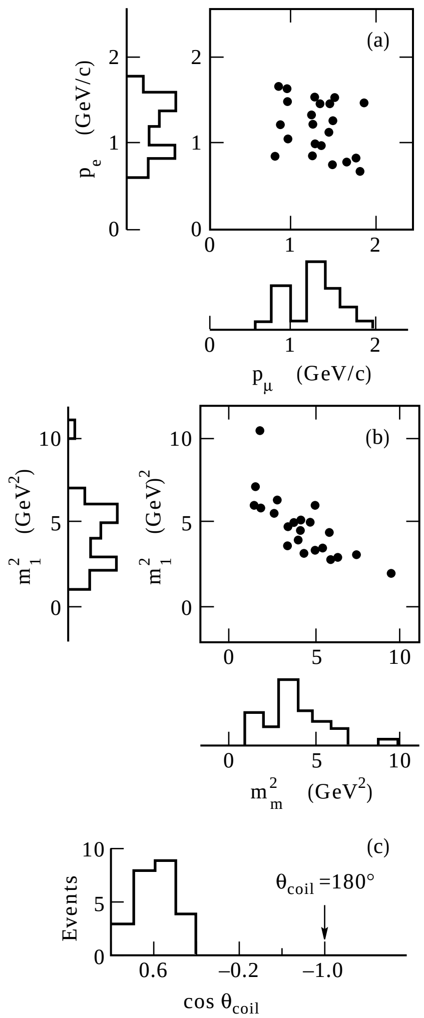

FIG. 1. Distribution for the 4.8-GeV e-μ signature events of (a) momenta of the e (p_e) and μ (p_μ); (b) square of the invariant mass (M_i^2) and square of the missing mass (M_m^2); and (c) cosθ_{coll}.

Thus the crucial 24 $e\mu$ events were contaminated by about 5 misidentified events and so the $e\mu$ signal was very strong. This wonderful result was a combination of two very fortunate things. First the e and μ detection systems were sufficiently selective; for example, if the P's were 50 percent larger, the contamination would have been uncomfortably large. The second piece of good fortune was that the weak interaction gives 20 percent branching fractions for the e and μ decay modes of heavy leptons with masses of several GeV. If these branching fractions were 10 percent the 24 events would have been 6 events. Sometimes, but not often, the gods are kind to the speculative experimenter.

> Figure 1(a) shows the momentum of the μ versus the momentum of the e for signature events.[14] Both p_μ and p_e extend up to 1.8 GeV/c, their average values being 1.2 and 1.3 GeV/c, respectively. Figure 1(b) shows the square of the invariant e-μ mass (M_i^2) versus the square of the missing mass (M_m^2) recoiling against the e-μ system. To explain Fig. 1(b) at least two particles must escape detection. Figure 1(c) shows the distribution in collinearity angle between the e and μ ($\cos\theta_{coll} = -\vec{p}_e \cdot \vec{p}_\mu / |\vec{p}_e||\vec{p}_\mu|$). The dip near $\cos\theta_{coll} = 1$ is a consequence of the coplanarity cut; however, the absence of events with large θ_{coll} has dynamical significance.

We didn't say it, but I knew these distributions were consistent with heavy lepton production.

> Figure 2 shows the *observed* cross section in the range of detector acceptance for signature e-μ events versus center-of-mass energy with the background subtracted at each energy as described above.[9] There are a total of 86 e-μ events summed over all energies, with a calculated background of 22 events.[12] The corrections to obtain the true cross section for the angle and momentum cuts used here depend on the hypothesis as to the origin of these e-μ events, and the corrected cross section can be many times larger than the observed cross section. While Fig. 2 shows an apparent threshold at around 4 GeV, the statistics are small and the correction factors are largest for low $\sqrt{s}$. Thus, the apparent threshold may not be real.

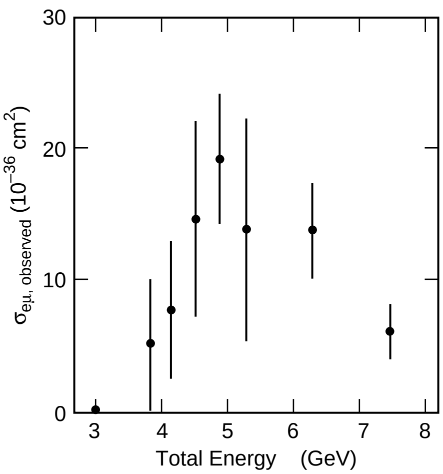

FIG. 2. The *observed* cross section for the signature e-μ events.

A perfect detector with 4π solid angle coverage would have given a peak cross section of 2×10^{-34} cm^2. The reduction to an observed cross section 1/10 that size came mostly from the limited solid angle acceptance and from the 0.65 GeV/c lower limits on the momenta of the e and μ. I am surprised that we were so cautious about claiming a threshold.

We conclude that the signature e-μ 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.

A cautious but challenging conclusion. Thus we presented the first evidence for the existence of the tau lepton and the third family of particles.

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[11]These contamination calculations do not depend upon the source of the e or μ; anomalous sources lead to overestimates of the contamination.
[12]Using *only* events in Column 1 of Table I we find at 4.8 GeV $P_{h\to e} = 0.27\pm0.10$, $P_{h\to\mu} = 0.23\pm0.09$, and a total e-μ background of 7.9 ± 3.2 events. The same method yields a total e-μ background of 30 ± 6 events summed over all energies. This method of background calculation (Ref. 9) allows the hadron background in the two-prong, zero-photon events to be different from that in other types of events.
[13]Our studies of the two-prong and multiprong events show that there is *no* correlation between the misidentification or decay probabilities; hence the background is calculated using independent probabilities.
[14]Of the 24 events, thirteen are $e^+ + \mu^-$ and eleven are $e^- + \mu^+$.

DISCOVERY OF THE TAU: CONFIRMATION & ELUCIDATION

BY 1982 OUR DISCOVERY of the tau lepton was confirmed and the basic properties of the tau were elucidated. This has been described in references 1–3. I will not repeat that history here, except to make a few remarks.

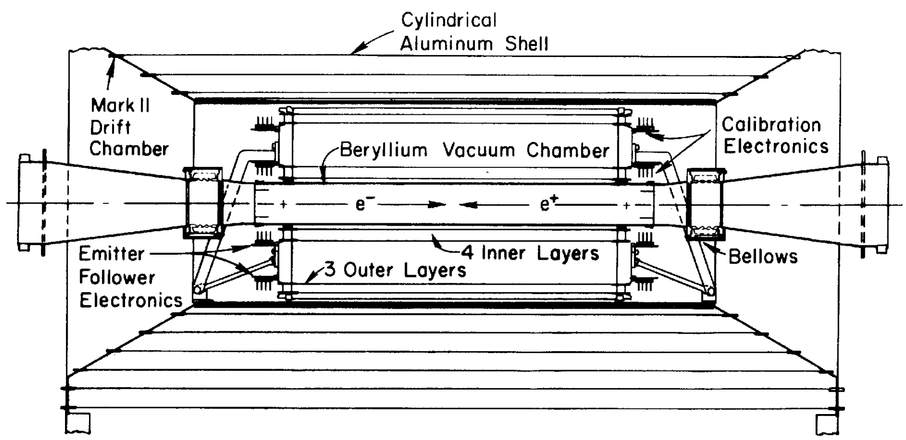
First, there are parallels between the 1937–1945 period of research on the muon and the 1975–1982 period of research on the tau. Both periods involved research by many groups confirming the original discovery and determining the basic properties of the lepton. In the muon case there was confusion between the muon and the pion since these particles have similar masses. Similarly in the tau case there was confusion between the tau and the charm meson since these particles have similar masses.[1,2]

Second, during the 1975 to 1985 period the improvements of technology described at the end of the section on general technology were necessary for the separation and measurement of the major decay modes of the tau:

$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e$
$\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu$
$\tau^- \to \nu_\tau + \pi^-$
$\tau^- \to \nu_\tau + \rho^-$
$\tau^- \to \nu_\tau +$ several mesons;

and for measurement of the τ mass.

Substantial improvements in technology were necessary for the measurement of the τ lifetime. Thus the measurement of the τ lifetime required the higher energy electron-positron colliders, PEP and PETRA, and secondary vertex detectors[40] (see illustration above).



Cross section of the first precision vertex detector used at SLAC in the Mark II detector at PEP to measure the lifetime of the tau.[40]

DISCOVERY OF THE LEPTONS: LOOKING BACK & LOOKING FORWARD

LOOKING BACK ON THE DISCOVERIES of the electron, muon, tau, electron neutrino, and muon neutrino, we see that each discovery required and used a different technology. This is not surprising; the advance of experimental science depends upon new technology. But there may be a warning in this history with respect to the future, with respect to the discovery of new leptons. We all think that if new leptons exist, they can best be found using the e^+e^- annihilation processes:

$$e^+ + e^- \to \text{neutral boson} \to L^+ + L^-$$
$$e^+ + e^- \to \text{neutral boson} \to \nu + \bar{\nu},$$

where the neutral boson is a photon, a Z^0, or yet to be discovered. But perhaps another technology will be required? An obvious possibility is the use of very high energy *pp* colliders. Or a future technology will be required which is beyond our dreams.

While the requirement of new technologies for new discoveries is well known, the connection between different motivations and different discoveries is rarely discussed. The electron and the muon discoveries were motivated by the desire to understand already known phenomena. The motivation in the discovery of the electron neutrino was the desire to see if a proposed particle with peculiar properties actually existed. The discovery of the two kinds of neutrinos had multiple motivations directed to the learning about the properties of neutrinos and of the weak interaction. The discovery of the tau was initially motivated by the desire to find another example of a charged lepton, that new lepton to be used to solve the electron-muon problem. It is ironic that the discovery of the tau did not help us with the electron-muon problem, the discovery simply extended the mystery to the electron-muon-tau problem (see table on the left).

Properties of the electron, muon, and tau. The electron charge is given in units of 1.6×10^{-19} coulombs. The mass is given in units of the mass of the electron 9.1×10^{-31} kilograms.

Particle	Electron	Muon	Tau
Symbol	e	μ	τ
Electric charge	+1 or –1	+1 or –1	+1 or –1
Mass	1	206.8	3480
Does particle have electromagnetic interactions?	yes	yes	yes
Does particle have weak interactions?	yes	yes	yes
Does particle have strong interactions?	no	no	no
Associated neutrino	ν_e	ν_μ	ν_τ
Associated antineutrino	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_t$
Lifetime	stable	2.2×10^{-6} sec	3.0×10^{-13} sec

The importance of motivation is that it sets the questions asked by the experimenter. In today's world of particle physics the great motivation is to break out of the standard model of elementary particle physics. Therefore we search for new particles and for unsuspected phenomena, we search for deviations from the predictions of the standard model. If this break-out motivation is wrong, then the questions we are asking may be false guides to the technology we should develop and the experiments we should do. This is a new thought for me—it came from writing this paper. I have begun to wonder if there could be another motivation for experimenting in elementary particle physics.

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