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THE DISCOVERY OF THE TAU LEPTON AND THE CHANGES IN ELEMENTARY PARTICLE PHYSICS IN 40 YEARS

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Introduction

This is a history of my discovery of the tau lepton in the 1970s for which I was awarded the Nobel Prize in Physics. I have previously described some aspects of the discovery. In 1996 in my collection of papers entitled, "Reflections on Experimental Science,"[1] I gave a straightforward account of the experimental method and the physics involved in the discovery as an introduction to the collection. In a 2002 paper[2] written with Mary A. Meyer published in the journal *Theoria et Historia Scientiarum* I used the story of the discovery to outline my thoughts on the practice of experimental science. That 2002 paper was written primarily for young women and men who are beginning their lives in science and it was based on a lecture given at Los Alamos National Laboratory. Some of the historical material in this paper has appeared in those two earlier papers.

This history of the tau discovery has three goals. First, I want to give the history of the discovery. Second, I want to give a general picture of the high energy physics world of thirty to forty years ago. It was very different from today's world of high energy

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physics. Third, and particularly important to me, I want to try to describe the differences between today's world of high energy physics and that of forty years ago. Are there intrinsic differences—not just differences in the size of the community and in the size and complexity of the experiments? Has our greatly increased knowledge and understanding of elementary particles and forces changed the way we do research in particle physics? Today there seems to be more speculative work in elementary particle theory than there was forty years ago. Is this true? Is more speculative theory good or bad or irrelevant to the progress of particle physics? I will explore and discuss such questions as I recount the discovery history.

I will interrupt the narrative from time to time to present my observations on what I believe have been the changes in the world of high energy physics over the past forty years. I will put these observations in italics.

My Education and Early Work in Engineering

It has been a long and indirect voyage that led me to work in lepton physics and led to the discovery of the tau lepton. As a boy I was what used to be called 'mechanically inclined'. I loved building things out of scrap wood, I loved working with Erector Sets, and I did some home chemistry. I was very good in high school mathematics and physics. When I graduated from the Brooklyn, New York, academic high school, James Madison, in 1939, I won the physics medal. But neither I nor my parents knew that one could have a career in physics so the next choice was engineering. I enrolled in the Polytechnic Institute of Brooklyn, now Polytechnic University, and began studying chemical engineering. There were two reasons for choosing chemical engineering. Chemistry was a very exciting field in the late 1930s and early 1940s. There would always be a good job in chemical engineering.

My studies were interrupted by World War II. When the war ended, I returned to the Polytechnic Institute and received a summa cum laude bachelor's degree in chemical engineering in 1948. The skills and knowledge I acquired at the Polytechnic Institute have been crucial in all my experimental work, including the use of strength-of-materials principles in equipment design, machine shop practice, and engineering drawing.

Upon graduation, I joined the General Electric Company. After a year in an advanced engineering training program, I settled in Schenectady, New York, working as a chemical engineer in a group in the electron tube production factory. The group's purpose was to troubleshoot production problems, to improve production processes, and occasionally to do a little development work. We were not a fancy R&D office. I was happy as an engineer. I liked the combination of working with my hands, of designing equipment, of carrying out tests, and of being connected with science.

For my job I had to learn how electron vacuum tubes worked, so I took a few courses at Union College in Schenectady, specifically atomic physics and advanced calculus. I got to know a wonderful physics professor, Vladimir Rojansky. One day he said to me, "Martin, what you are interested in is called physics—not chemistry, not engineering!" At the age of 23, I finally decided to begin the study of physics. I enrolled at Columbia University in New York City.

Going Into Physics

Just as the Polytechnic Institute was crucial in my learning how to do engineering, just as Union College and Vladimir Rojansky[a] were crucial in my choosing physics, so Columbia University and my thesis advisor, I. I. Rabi, were crucial in my learning how to do experimental physics. I entered the physics doctoral program in Columbia University in the autumn of 1950. Looking back, it seems amazing that I was admitted with just a bachelor's degree in chemical engineering. True, I had a summa cum laude bachelor's degree, but I had taken only two courses in physics: one year of elementary physics and a half-year of atomic physics. It would be much harder to do this today.

Graduate study in physics was primitive in the 1950s, compared to today's standards. Most of us did not study quantum mechanics until the second year; the first year was completely devoted to classical physics. The most advanced quantum mechanics we ever studied was a little bit in Heitler,[3] and we were not expected to be able to do calculations in quantum electrodynamics. We did not know how to use Feynman diagrams.

> *This brings me to one of the differences between the graduate school physics of 50 years ago and today. Less was known and we had less to study. I don't think that learning so much less in graduate school was a complete disadvantage. It gave all the students more time to think about physics outside their specialty. In particular, experimenters had more time to learn all sorts of experimental techniques.*

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[a] Vladimir Rojansky may be known to some of the older readers through his textbooks on electromagnetism and on quantum mechanics.

I undertook for my doctoral research the problem of using the atomic-beam resonance method to measure the quadrupole moment of the sodium nucleus.[4] (The atomic-beam resonance method was invented by Rabi, for which he received a Nobel Prize in 1944.) This quadrupole measurement had to be made using an excited atomic state, and Rabi had found a way to do this. My experimental apparatus was boldly mechanical, with a brass vacuum chamber, a physical beam of sodium atoms, submarine storage batteries to power the magnets—and, in the beginning of the experiment, a wall galvanometer to measure the beam current. I developed much of my style in experimental science during this thesis experiment. When designing the experiment and when thinking about the physics, the mechanical view is always dominant in my mind. More importantly, my thinking about elementary particles is physical and mechanical. In the basic production process for tau leptons

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

I see the positron, e^+, and electron, e^-, as tiny particles that collide and annihilate one another. I see a tiny cloud of energy formed which we technically call a virtual photon, $\gamma_{\mathrm{virtual}}$. Then I see that energy cloud change into two tiny particles of new matter—a positive tau lepton, τ^+, and a negative tau lepton, τ^-.

My thesis was in atomic physics, but it was Rabi who always emphasized the importance of working on a fundamental problem, and it was Rabi who sent me into elementary particle physics. It would have been natural for me to continue in atomic physics, but he preached particle physics to me as the coming field and in 1955, the year I received my Ph. D., it indeed was the coming field. I went to the Physics Department of the University of Michigan as an Instructor to teach and to do research in particle physics. Yes, in the late 1950s, there were still instructors in physics departments.

High-Energy Physics at the Cosmotron and the Bevatron

At Michigan, I made the change from atomic physics to high-energy physics. I first worked in bubble chamber physics with Donald Glaser, the inventor of the bubble chamber. We carried out our bubble chamber experiments at the Cosmotron of the Brookhaven National Laboratory. But I wanted to be on my own. When the Russians flew SPUTNIK in 1957, I saw the opportunity and jointly with my colleague, Lawrence W. Jones, obtained research support from the Office of Naval Research. We began our own research program using first the now-forgotten luminescent chamber.[5] A luminescent chamber consists of one or more pieces of sodium iodide scintillator. We photographed and recorded the tracks of charged particles in the sodium iodide crystals using primitive electron tubes that intensified the light coming from the track. In 1960, at the Bevatron of the Lawrence Berkeley Laboratory, we carried out a somewhat primitive measurement of the elastic scattering of high-energy pions colliding with protons.[6]

But the newly invented optical spark chamber was a much better device for determining the paths of charged particles. Jones and I, using spark chambers, carried out at the Bevatron in the early 1960s, a definitive set of measurements on the elastic scattering of pions on protons.[7]

From the late 1960s to the early 1970s Michael Kreisler, Michael Longo, and I carried out some experiments on the high energy scattering of neutrons on protons[8] using optical spark chambers, one of them being a special thick-plate spark chamber where the scattered neutron was detected by its interaction in the thick plates. By this time I was at the Stanford Linear Accelerator Center.

Thus, in fifteen years, a handful of colleagues and I worked on about a dozen experiments using all sorts of experimental techniques in elementary particle physics—scintillation counters, bubble chambers, luminescent chambers, spark chambers, coincidence and counting electronics, scanning and measuring tables for bubble chamber and spark chamber pictures. We also used the mainframe computers of the early 1960s with the programs and data usually on punch cards.

> *This illustrates several major differences between the high energy physics experiments of forty years ago and today. Forty years ago, one could build the apparatus in a year, except for bubble chambers, frequently using parts from previous experiments. And except for bubble chambers, the time spent acquiring data at an accelerator was often of the order of a month. We were not smarter than today's experimenters and we did not work harder. The experimental methods that we knew were much simpler and we could easily build anything we needed.*

> *It was therefore relatively easy to think about trying to measure something better or something new, then to build the apparatus, and then within several years to have the results. This gave the experimenter a wonderful freedom to try all sorts of new directions and new ideas, in contrast to today's high energy experiments that are typically very large, very complicated, and may take a decade to build. Of course, these modern experiments provide data for hundreds of different measurements and studies, and so are, in some ways, the equivalent of hundreds of experiments of forty years ago. But the experimental possibility of quick changes is mostly gone. There is nothing we can do about this; the easy elementary particle questions were answered thirty and forty years ago.*

The Attraction for Me of High Energy Experimental Lepton Physics

The discovery of the tau came out of my strong desire to do high energy experimental physics and to do research with leptons. My interest in lepton physics came from my growing dissatisfaction with the strong interaction physics of the 1960s and from a desire to measure or discover fundamental facts in particle physics.

For example, all the physics experiments that I have mentioned concerned measurements of how hadrons interact, principally elastic scattering. When we did our elastic scattering measurements the principle theory was Regge theory in which the mathematics of the complex plane had a fundamental role. I learned Regge theory but I gradually became dissatisfied with it. I could believe that complex variable theory could provide a framework for codifying the behavior of the elastic scattering of hadrons. Hadrons are particles such as protons, neutrons, pions and K mesons. All hadrons are composed of quarks, the behavior of the quarks and the structure of the hadrons involve the strong interaction. But I could not see how complex variable theory could provide a basic understanding of the interaction of objects as complicated as pions and protons.

The other areas of the theory of hadron interactions were to me also unsatisfactory —this was before the development of quantum chromodynamics. I understood that the barriers to a satisfactory theory were the complicated structure of hadrons and the large coupling constant of the strong interaction that prevented the use of perturbation theory. Therefore I began to think about doing experiments with the electron and the muon, elementary particles that do not participate in the strong interaction. These particles only participate in the electromagnetic, weak and gravitational interactions. All processes involving just the electromagnetic and weak interactions can be understood with perturbation theory calculations, and with enough patience. The effect of the gravitational force on the interactions of elementary particles is very small, too small to take into account.

There were two puzzles about the properties of the electron, e, and the muon, μ, in the 1960s and fundamentally these puzzles remain today, built into the so-called standard model of elementary particle physics. First, as shown in Table 1, the properties with respect to particle interactions are the same for the electron and the muon, but the muon is 208 times heavier. Why?

The second puzzle has to do with the instability of the muon. One might expect the muon to decay through the process

$$\mu^- \rightarrow e^- + \gamma \tag{1}$$

Here, γ means a photon, and the expectation would be that the γ carries off the excess energy produced by the difference between the muon mass and the electron mass. (An analogous decay equation can be written for the positive muon but to save space I will usually write the decay process for only the negative lepton.) However the muon decays to an electron by a more complicated process,

$$\mu^- \rightarrow e^- + \bar{n}_e + \nu_\mu \tag{2}$$

in which an electron antineutrino ($\bar{n}_e$) and a muon neutrino (ν_μ) are produced. The muon lifetime is 2.2×10^{-6} seconds due to this more complicated decay process. The simpler decay process using the photon, Eq. 1, has never been seen and the measured upper limit on its probability compared to the more complicated process, Eq. 2, is about 10^{-11}.[9] Our present understanding of the extreme suppression of the photon decay mode is that there is an intrinsic difference between the nature of the electron and the nature of the muon. Therefore the only substantial decay process is that depicted by Eq. 2 in which, when a muon decays, the intrinsic nature of the muon is carried on the muon neutrino and the production of an electron is compensated for by the simultaneous production of an antielectron neutrino.

SLAC and Leptons

In 1963, the opportunity arose to think seriously about high-energy experiments on charged leptons when Wolfgang K. H. Panofsky and Joseph Ballam offered me a position at the yet-to-be-built Stanford Linear Accelerator Center (SLAC). Here was a laboratory that would have primary electron beams: a laboratory at which one could easily obtain a good muon beam, and a laboratory at which one could easily obtain a good photon beam for producing lepton pairs. Furthermore, on the Stanford campus at the High Energy Physics Laboratory, the Princeton-Stanford $e^- e^-$ storage ring was operating.

When I arrived at SLAC in 1963, I began to plan various attacks on, and investigations of, the electron-muon problem. Although the linear accelerator would not begin operation until 1966, my colleagues and I began to design and build experimental equipment. My proposed attacks and investigations were of two classes. In one class, I proposed to look for unknown differences between the electron and the muon, the only known differences being the mass difference and the observation that the decay reaction $\mu \rightarrow e + \gamma$ does not occur. The other class of proposed attacks and investigations was based on my speculation that there might be more leptons similar to the electron and the muon, unknown heavier charged leptons. I dreamed that if we could find a new lepton, the properties of the new lepton might teach us the secret of the electron-muon puzzle. My first attack used an obvious idea.[10] An intense photon (γ) beam could be made at SLAC using the reactions

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

The photons so produced could then interact with another nucleus to produce a pair of charged particles: x^+ and x^-,

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

Any pair of charged particles could be produced if the γ had enough energy. My hope was that we would find a new x particle, perhaps a new charged lepton somehow related to the electron or muon, a vague hope by the standards of our knowledge of elementary particle physics today. We were certainly naive in the 1960s. We didn't find any new leptons or any new particles of any kind;[10] as we now know, there were no new particles to find given the experimental limitations of this search experiment. The search used the pair-production calculations of Y. S. Tsai and V. Whitis.[11]

Studies of Muon-Proton Inelastic Scattering

Although this first attempt to penetrate the mysteries of the electron and muon failed, we were already preparing to study muon-proton inelastic scattering,

$$\mu^- + p \rightarrow \mu^- + \text{hadrons}$$

to compare it with electron–proton inelastic scattering,

$$e^- + p \rightarrow e^- + \text{hadrons}.$$

Extensive studies of e–p inelastic scattering were planned at SLAC. Indeed, some of those studies, which revealed the presence of quarks in hadrons, led to the awarding of the 1990 Nobel Physics Prize to Jerome Friedman, Henry Kendall, and Richard Taylor. My hope was that we would find a difference between the μ and e other than the differences of mass and lepton type. For example, I speculated that the muon might have a special interaction with hadrons not possessed by the electron.[12,13]

My colleagues and I measured the differential cross sections for inelastic scattering of muons on protons, and then compared the μ–p cross sections with the corresponding e–p cross sections.[13] We were looking for a difference in magnitude or a difference in behavior of the cross sections. These differences could come from a new nonelectromagnetic interaction between the μ and hadrons or from the μ's not being a point particle. However we found no significant deviation.[14,15]

Other experimenters studied the differential cross section for μ–p elastic scattering and compared it with e–p elastic scattering but statistically significant differences between μ–p and e–p cross sections could not be found in either the elastic or inelastic cases.[16] Furthermore, there were systematic errors of the order of 5% or 10% in comparing μ–p and e–p cross sections because the techniques used were so different.

> *Experimental science is a craft and an art, and part of the art is knowing when to end a fruitless experiment. There is a danger of becoming obsessed with an experiment even if it goes nowhere. At some point, you've got to say, "I really don't know how to improve this." I avoided obsession and gave up on the scattering experiment. That turned out to be a good decision because modern experiments have shown that these scattering experiments do not illuminate any differences between the electron and the muon beyond the mass difference.*

Heavy Leptons in the 1960s

While building the apparatus using our muon-proton inelastic scattering experiment, and during the first operation of that experiment, I was thinking of another way to look for new charged leptons, L, using the reaction

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

Before turning to this third attack on the electron-muon problem, I will describe the general thinking in the 1960s about the possible existence and types of new leptons. By the beginning of the 1960s, papers had been written on the possibility of the existence of charged leptons more massive than the e and μ, usually called heavy leptons. I remember reading the 1963–1964 papers of Ya B. Zel'dovich,[17] of E. M. Lipmanov,[18] and of L. B. Okun.[19] 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 that there might be an electromagnetic excited state e* of the e[20], then the proper search method was

$$e^- + \text{nucleon} \rightarrow e^{-*} + \ldots, \quad e^{-*} \rightarrow e^- + \gamma.$$

If one thought that the μ belonged to three-member family consisting of a μ, ν_μ, and a heavier version of the μ, μ', then the proper search method was

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

By the second half of the 1960s, the concept had been developed of a heavy lepton L and its neutrino ν_L forming an L, ν_L pair. Thus, in a paper written in 1968, K. W. Rothe and A. M. Wolsky[21] discussed the lower mass limit on such a lepton set by its absence in *K* meson decays. They also discussed the decay of such a lepton into the modes

$$L^- \rightarrow e^- + \bar{n}_e + \nu_L, \; L^- \rightarrow \mu^- + \bar{n}_\mu + \nu_L, \; L^- \rightarrow p^- + \nu_L .$$

> *This brings me to the question I raised in the Introduction: is there more and broader speculation these days in particle physics theory than forty years ago? Judging by the various ideas of forty years ago about possible types of leptons, we were rather timid about speculations. There was a fear of being thought unsound. There was reluctance to stray too far from what was known. Today the only limit to theoretical speculations about particle physics is that the mathematics be correct and that there be no obvious conflict with measured properties of particles and reactions. One example is string theory with all its different forms and extensions. Another example is the recent, tremendous amount of interweaving of particle physics with astrophysics and cosmology. I think this is a good change. It can stimulate the experimenter to go in new directions, but the experimenter must be cautious as to how she or he uses time. If possibly relevant data have already been produced, then it may be relatively fast to test the speculation against the data. But if a new experiment must be built to test the speculation, that is another story.*

Electron-Positron Colliders

The obvious and most general way to try to produce and detect new charged leptons was to use an electron-positron collider for the production process

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

The principle of operations of a circular electron-positron collider is shown in figure 1. A bunch of electrons (closed circles) and a bunch of positrons (open circles) circulate in opposite directions in a circular ring consisting of an evacuated pipe. The cross-sectional size of the pipe is much smaller than the diameter of the ring. For example, in the SPEAR collider (figure 2) the cross-sectional size of the pipe is of the order of 10 centimeters and the diameter of the ring is about 60 meters. As the bunches circulate they pass through each other in two places called interaction points. Almost all of the electrons and positrons pass by each other but occasionally an electron and a positron collide and interact, producing new particles.

The construction and operation of electron-positron colliders began in the 1960s.[22] By September 1967 at the Sixth International Conference on High Energy Accelerators, F. T. Howard[23] was able to list quite a few electron-positron colliders. The pioneer 500-MeV ADA collider was already operating at Frascati in the early 1960s. 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 by David Ritson, *et al.*[24] had already discussed the reaction

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

Of course, x might be a charged lepton. This proposal did not lead directly to the construction of an e^+e^- collider at SLAC because we could not get the funding. About five 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.

The Sequential Lepton Model

It was this 1964 proposal and the 1961 seminal paper of N. Cabibbo and R. Gatto[25] that focused my thinking on new charged lepton searches using an e^+e^- collider. As we carried out the experiments described previously, I kept looking for a model for new leptons—a model that would lead to definitive colliding beam searches, while remaining reasonably general. Helped by discussions with colleagues such as Paul Tsai and Gary

Feldman, I came to what I later called the sequential lepton model. I thought of a sequence of pairs

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

each pair having a unique lepton type. I usually thought about the leptons as being point Dirac particles. Of course, the assumptions of unique lepton type 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

$$e^{+} + e^{-} \rightarrow L^{+} + L^{-},$$

with

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

$L^{-} \rightarrow \mu^{-}$ + undetected neutrinos carrying off energy,

or

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

$L^{-} \rightarrow e^{-}$ + undetected neutrinos carrying off energy.

This search method had many attractive features:

- If the L was a point particle, we could 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 L decays 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.

- Perturbation calculations using weak interaction theory predicted that the L would have the weak decays

$$L^- \rightarrow \nu_L + e^- + \bar{n}_e$$

$$L^- \rightarrow \nu_L + \mu^- + \bar{n}_\mu ,$$

with corresponding decays for the L^+. The decay rate was easily calculated.

> *My ability to make detailed calculations on how the hypothetical L lepton would decay shows the major change that has occurred in the ability of a busy experimenter to make detailed calculations from first principles on her or his experiment. Suppose today I wanted to make analogous calculations on the decays of a particle predicted in a string theory. A kindly string theorist could set up the final equations for me but it would be impossible for me to do the calculations from first principles. Many areas of particle theory are now too advanced and too complicated for the amateur theorist. First-principle calculations can only be done by those who are devoted full time to theory. This is a sad change but there is nothing that can be done; many areas of theory require full time for understanding and use. Meanwhile the experimenter is busier than ever building or operating the experiment or analyzing the data.*

I incorporated this search method in our 1971 SLAC-LBL proposal to use the not-yet-completed SPEAR e^+e^- storage ring.[26] My thinking about sequential leptons and this search method was greatly helped by a 1971 seminal paper of Paul Tsai[27] providing detailed calculations on how a sequential lepton would decay. 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 Beginnings of the Sequential Lepton Search at SPEAR

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 1960s (figure 2). Gary Feldman and I, along with 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 a SLAC-LBL particle detector for use at SPEAR. In 1971 we submitted the SLAC-LBL proposal.[26]

The SLAC-LBL detector (figures 3 and 4) was one of the first of the large solid angle, general-purpose detectors. The purpose of a general-purpose detector is to detect the type and vector momentum of most of the particles coming from a reaction taking place at the center of the detector. The goal is to detect and identify electrons, muons, protons, pions, and K mesons.

> *Large solid angle, general-purpose detectors and other types of large detectors such as neutrino detectors have become the norm in experimental particle physics. These detectors are necessary to obtain the complicated and often subtle data in modern experiments. But large detectors have come at a human cost. It is no longer possible for a few people to build and operate such detectors. Hence there are often hundreds of experimenters in a typical group and the new very large and complicated detectors require groups with more than a thousand members. Of course such detectors produce tremendous amounts of data.*

The contents of the proposal[26] consisted of five sections (Introduction, Boson Form Factors, Baryon Form Factors, Inelastic Reactions, Search for Heavy Leptons), followed by figure captions, references, and the Supplement. 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 did contain the essential idea of searching for heavy leptons using eμ events.

I wanted to include a lot more about heavy leptons and the e–μ problem, but my colleagues thought that would unbalance the proposal. We compromised on a 10-page supplement titled, “Supplement to Proposal SP-2 on Searches for Heavy Leptons and Anomalous Lepton-Hadron Interactions,” which began as follows:

“While the detector is being used to study hadronic production processes it is possible to simultaneously collect data relevant to the following questions:

- Are there charged leptons with masses greater than that of the muon?
- Are there anomalous interactions between the charged leptons and the hadrons?”

Though my first interest was to look for heavy leptons, I still had my old interest of looking for an anomalous lepton interaction, the idea that led to the study of muon-proton inelastic scattering.

While SPEAR and the SLAC-LBL detector were being built, lepton searches were being carried out at the ADONE e^+e^- storage ring by two groups of experimenters in electron-positron annihilation physics: one group reported in 1970, Alles-Borelli, *et al.*,[29] and then in 1973, Bernardini, *et al.*.[30] In the later paper, they searched up to a mass of about 1 GeV for a conventional heavy lepton and up to about 1.4 GeV for a heavy lepton with decays restricted to leptonic modes. The other group of experimenters in electron-positron annihilation physics was led by Shuji Orito and Marcello Conversi. Their search region also extended to masses of about 1 GeV.[31] No heavy leptons were found in these searches because, as we now know, there are no heavy leptons in the mass range between the muon and the tau.

The SPEAR electron-positron 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 began operating the SLAC-LBL experiment in 1973 in the form shown in figure 3. The SLAC-LBL detector 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 thirty 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.

The SLAC-LBL detector contained two important elements now used in all modern particle detectors. First, we made extensive use of transistor electronics. The reliability, relatively small size, and relatively low cost of transistor electronics allowed a relatively fine division of the detector into many particle-detecting channels. The SLAC-LBL detector had hundreds of channels; modern large detectors may have hundreds of thousands of particle detecting channels.

The second important element was the extensive use of computers. The data were recorded on magnetic tape by a mainframe computer and monitoring of the detector performance was also done in real time using the computer. Of course, the processing of the raw data and the analysis of the processed data were also done by computer.

> *The tremendous advances in electronics and computer computation in the past thirty years have been crucial to the tremendous experimental progress in elementary particle physics. However this great good has led to deep change in the relationships between physicists and the*

development of new technology. There was a time when physicists were the inventors and innovators for most of the technology that they used. And if necessary they could build any piece of equipment they needed, even that involving the newest technology. But this is no longer true for electronics and computers. The use of electronics and computers in civilian, business and military areas now drives the major advances in the electronics and computer industry. Elementary particle experimenters can sometimes purchase variations of standard electronics and computer products, but mostly they purchase the standard products.

First Evidence for a New Lepton

In June 1975, I gave the first international talk on the e–μ events at the 1975 Summer School of the Canadian Institute for Particle Physics.[32] My purpose was to show that (1) we had good evidence for e–μ events and (2) to discuss possible sources of the e–μ events: heavy leptons, heavy mesons, or intermediate bosons. The largest, single energy data sample (table 2) was at 4.8 GeV, the highest energy at which we could then run SPEAR. The 24 e–μ events were the strongest evidence at that time for the tau. One of the cornerstones of this claim was an informal analysis carried out by Jasper Kirkby, who was then at Stanford University and at SLAC. He showed me that by just using the numbers in table 2, we could calculate the probabilities for hadron misidentification in this class of events. There were not enough e-h, μ-h, and h-h events to explain away the 24 e–μ events. The misidentification probabilities determined from three-or-more-prong hadronic events and other considerations are given in table 3. 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–μ events could not be explained away. And so the evidence for a new phenomenon was quite strong—not incontrovertible, but still strong.

My Canadian lecture ended with these conclusions:

- No conventional explanation for the signature e–μ events has been found.
- The hypothesis that the signature e–μ events come from the production of a pair of new particles—each of mass about 2 GeV—fits almost all the data.

I was still not able to specify the source of the e-μ events: was the source new leptons, new mesons, or new bosons? But I remember feeling strongly that the source was heavy leptons. It would take two more years to prove that.

Crucial Steps in the Identification of the Tau

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–μ event signal. Thus, I and my colleagues in the SLAC-LBL experiment became more and more convinced of the reality of the e–μ events and the absence of a conventional explanation. An important factor in this growing conviction was the addition of a special muon detection system to the detector (figure 5a), called the *muon tower*. This addition was conceived and built by Gary Feldman. Although we did not use events such as those in figure 5b in our first publication, seeing a few events like this was enormously comforting.

Finally, in December 1975, we published "Evidence for Anomalous Lepton Production in $e^+ - e^-$ Annihilation."[33] Figure 6 shows the observed cross section for e–μ events as a function of the total collider energy, 2E. The final paragraph reads

> "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 ."[33]

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 tau, τ, was suggested by Petros Rapidis, who was then a graduate student and worked with me in the early 1970s. The letter τ is from the Greek triton 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–μ events were significant, and we had to convince ourselves that the e–μ events came from the decay of a pair of heavy leptons.

> *The success of the search illustrates some basic principles for searches for new particles. These principles have remained the same over all these years. First, we had cast a wide net in studying the electron-muon problem: an attempt to photoproduce new leptons, experimental comparisons of muon-proton inelastic scattering with electron-proton inelastic scattering, and the use of the general reaction* $e^+ + e^- \rightarrow L^+ + L^-$ *to try to produce a heavy lepton. Second, a new technology, the electron-positron collider, was available to carry out the* $L^+ L^-$ *production. Third, we had a good way to detect the* $L^+ L^-$ *production, namely the search for e-μ events without photons. Fourth, I had smart, resourceful, and patient research companions. I think these are the elements that should be present in speculative experimental work: a broad general plan, specific research methods, new technology, and first-class research companions. Of course, the element of luck will in the end be dominant. We had two great pieces of luck. First, there was a heavy lepton within the energy range of the SPEAR collider. Second, the SLAC-LBL experimental apparatus was good enough to enable us to identify the e–μ events and prove their existence.*

Is It a Lepton?

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 decades later when we know that $\tau^+\tau^-$pair production is 20% of the e^+e^- annihilation cross section below the Z°, when $\tau^+\tau^-$ pair events stand out so clearly at the Z°.

There were several reasons for the uncertainties of that period. It was hard to believe that both a new meson, the D charm meson, and a new lepton, the tau, would be found in the same narrow range of masses. The D mass is about 1.87 GeV/c^2 and the tau mass is about 1.77 GeV/c^2. Also, while the existence of the fourth quark, the charm quark, c, that comprises most of the mass of the D meson, was required by theory, there was no such requirement for a third charged lepton, so there were claims that the e-μ events were from the decays of pairs of D mesons. There were also claims that 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-1970s.

Perhaps the greatest impediment to the acceptance of the tau as the third charged lepton was that there was no other evidence for a third particle generation. Two generations of quarks and leptons—u, d, e^-, ν_e and c, s, μ^-, ν_μ—seemed acceptable, a kind of doubling of particles. But why three generations? To this day, this question has no answer. It was a difficult time. Rumors kept arriving of definitive evidence against the τ: e–μ events not seen, the expected decay modes not seen, theoretical problems with momentum spectra or angular distribution. With colleagues such as Gary Feldman, I went over our data again and again. Had we gone wrong somewhere in our analysis of the data? Clearly, other tau pair decay modes had to be found. Assuming the tau to be a charged lepton with conventional weak interactions, simple and very general theory predicted the branching fractions

$$B(\tau^- \to \nu_\tau + e^- + \bar{n}_e) = 20\%$$

$$B(\tau^- \to \nu_\tau + \mu^- + \bar{n}_\mu) = 20\%$$

$$B(\tau^- \to \nu_\tau + \text{hadrons}) = 60\%.$$

Experimenters therefore should be able to find the decay sequences

$$e^+ + e^- \to \tau^+ + \tau^-$$

$$\tau^+ \to \bar{n}_t + \mu^+ + \nu_\mu$$

$$\tau^- \to \nu_\tau + \text{hadrons}.$$

This sequence would lead to anomalous muon events

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

Analogously there should be anomalous electron events

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

Anomalous Muon Events, Anomalous Electron Events, and More Evidence for the Tau

The first advance beyond the e–μ events came with three different demonstrations of the existence of anomalous μ-hadron events:

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

The first and very welcome outside confirmation for anomalous muon events came in 1976 from another SPEAR experiment by M. Cavilli-Sforza, et al.[34] The paper was titled "Anomalous Production of High-Energy Muons in $e^+ + e^-$ Collisions at 4.8 GeV." The second confirmation came in a SLAC-LBL detector note by Gary Feldman discussing μ events using the muon identification tower of the detector (figure 5). For data acquired above 5.8 GeV, he found the following:

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

This conclusion was published in our 1977 paper "Inclusive Anomalous Muon Production in e^+e^- Annihilation".[35] 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".[36]

With the finding of μ–hadron events, I was convinced I was right about the existence of the τ as a sequential heavy lepton. Yet there was much to disentangle. It was still difficult to demonstrate the existence of anomalous e^- hadron events and the major hadronic decay modes

$$\tau^- \to \nu_\tau + p^-$$

$$\tau^- \to \nu_\tau + ?^-$$

had to be found. The demonstration of the existence of anomalous electron events,

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

required improved electron identification in the detectors. A substantial step forward was made by the new DELCO detector at SPEAR.[37] In his talk at the 1977 Hamburg Photon-Lepton Conference, Jasper Kirkby stated,[38] "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 SLAC-LBL detector was also improved by Group E from SLAC and a Lawrence Berkeley Laboratory group led by Angela Barbaro-Galtieri; some of the original SLAC-LBL experimenters had gone off to begin to build the Mark II detector. We installed a wall of lead-glass electromagnetic shower detectors in the SLAC-LBL detector. This led to an important 1977 paper by A. Barbaro-Galtieri, *et al.*[39] The abstract read in part: "We observe anomalous e–μ and e–hadron events in $e^+ + e^- \rightarrow \tau^+ + \tau^-$ with subsequent decays of $\tau^\pm$ into leptons and hadrons."

By the time of the 1977 Photon Lepton Conference at Hamburg, I was able to report[40] that:

- All data on anomalous e-μ, e-x, e-e, and μ-μ events produced in e^+e^- annihilation are consistent with the existence of a mass 1.9 ± 0.1 GeV/c^2 charged lepton, the τ.
- These data cannot be explained as coming from charmed particle decays.
- 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 Final Evidence – The Discovery of the Pi and Rho Decay Modes

The anomalous muon and anomalous electron events had shown that the total decay rate of the τ into hadrons, that is, the total semi-leptonic decay rate, was about the right size. But if the τ was indeed a sequential heavy lepton, two substantial semi-leptonic decay modes had to exist: $\tau^- \rightarrow \nu_\tau + \pi^-$ and $\tau^- \rightarrow \nu_\tau + \rho^-$. The branching fraction for $\tau^- \rightarrow \nu_\tau + \pi^-$ was calculated from the decay rate for $\pi^- \rightarrow \mu^- + \overline{n_m}$ and was predicted to be

$$B(\tau^- \rightarrow \nu_\tau \pi^-) \approx 10\%.$$

The branching fraction for $\tau^- \to \nu_\tau + \rho^-$ was calculated from the cross section for $e^+ + e^- \to \rho^0$ and was predicted to be

$$B(\tau^- \to \nu_\tau \rho^-) \approx 20\%.$$

One of the problems in the years 1977–1979 in finding these π^- and ρ^- decay modes was the poor efficiency for photon detection in the early detectors. The ρ^- decays into $\pi^- + \pi^0$ with $\pi^0 \to 2\gamma$. If the γ's are not detected efficiently then the p and ρ modes are confused with each other. Gradually, the experimenters understood the photon detection efficiency of their experiments. 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 $B(\tau^- \to \nu_\tau \pi^-)$ was substantial came from Gail Hanson[41] in an internal SLAC-LBL detector note dated March 7, 1978.

Within about a year, the $\tau^- \to \nu_\tau \pi^-$ decay mode had been detected and measured by experimenters using the PLUTO detector, the DELCO detector, the Lead–Glass Wall detector, and the new Mark II detector. These measurements were summarized in 1978 by Gary Feldman[42] in a review of $e^+ + e^-$ annihilation physics at the XIX International Conference on High Energy Physics. Although the average of the results of the branching fraction measurements were about 8%, smaller than the present value of 11%, the $\tau^- \to \nu_\tau \pi^-$ mode had been found.

The year 1979 saw the first publications of the branching fraction for $\tau^- \to \nu_\tau \rho^-$. The DASP Collaboration, using the DORIS $e^+ + e^-$ storage ring, reported[43] (24 ± 9)%, and the Mark II Collaboration reported[44] (20.5 ± 4.1)%. The measurements were crude, but they agreed with the 20% predicted value. The present value is 25%.

By the end of 1979, all confirmed measurements agreed with the hypothesis that the τ was a lepton produced by a known electromagnetic interaction and that, at least in its main modes, it decayed through the conventional weak interaction. So ends the sixteen-year history, 1963 to 1979, of the discovery of the tau lepton and the verification of that discovery.

The gradual identification of all the major decay modes of the tau in the years 1975-1979 illustrates the necessity of improved experimental apparatus. The discovery of the pi and rho decay modes could not have been accomplished in the old SLAC-LBL detector. The need for this constant improvement in experimental equipment is well known in science. It generally leads to more complicated and more expensive equipment. Sometimes inventions led to simplification, but the overall trend is to increased complication, increased expense, and the need for more technical personnel to operate the equipment. This is one of the major changes that has occurred in experimental particle physics.

Today

Recall that the model for the search that led to the discovery of the tau was a sequence, possibly infinite, of increasingly massive charged leptons and a different neutrino associated with each of the charged leptons. To my astonishment, no more charged heavy leptons have been found in searches conducted up to about 100 GeV/c^2. Also, all fully accepted experimental results on neutrinos are satisfied by there being only three different neutrinos associated with the e, μ, and τ. Table 4 summarizes the properties of the three charged leptons and their neutrinos.

There is an irony in my discovery of the tau. My decision to work in lepton physics came from the desire to understand the two 1960 puzzles associated with the electron and the muon. The first puzzle was *why* the mass difference, or more generally, what sets the masses of the elementary particles. In spite of the development of Higgs theory we do not know how to specifically calculate the mass of the e or μ. In Higgs theory we still have to put in a different parameter for each mass. The same holds for the τ. Therefore, the discovery of the tau has added to a puzzle.

The second puzzle was: what is the intrinsic difference between the nature of the e and the nature of the μ. Now this question has extended to the τ also. The discoveries of the last decade that one type of neutrino can change into another type of neutrino may lead eventually to an understanding of what constitutes the intrinsic nature of elementary particles. But we are not there yet. Therefore the second puzzle also remains.

> *This is also the place to summarize my thoughts about the changes that have occurred in elementary particle physics in the past forty years. Most of the changes have been very good: we know a tremendous amount more about elementary particles; we have much more powerful and sensitive particle detectors; we have much higher energy accelerators and colliders; and our students are better trained. But some changes, I believe, are not so pleasant: we have lost the freedom to move quickly into new experiments; almost all experiments are large and complicated; usually experimenters have to work in very large collaborations; and it is no longer possible for a particle physicist to be a productive experimenter and at the same time be able to make calculations from first principles in much of modern particle theory. I do not see a way to reverse these unpleasant changes.*

Acknowledgement

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Tables

Table 1. The known leptons in the late 1960s. The mass is in units of MeV/c^2, a unit of mass used in particle physics. For comparison, recall that the mass of the electron is 9.11 $\times 10^{-31}$ kilogram. The electric charge is given in units of 1.60×10^{-19} coulombs.

Lepton	Electron	Muon
Symbol for charged lepton	e	μ
Electric charge	+1 or −1	+1 or −1
Mass of charged lepton	0.51	106
Does particle have electromagnetic interactions?	yes	yes
Does particle have weak interactions?	yes	yes
Does particle have strong interactions?	no	no
Lifetime of charged lepton	stable	2.2×10^{-6} sec
Associated neutrino	ν_e	ν_μ
Associated antineutrino	$\bar{n}_e$	$\bar{n}_\mu$
Mass of neutrino	close to 0	close to 0

Table 2. Distribution of 126 particle pair events obtained at 4.8 GeV[32] with total charge zero and no photons. In the table, e means electron, μ means muon and h means a hadron.

Type of particle pair	Number found
e-e	40
e-μ	24
μ-μ	16
e-h	18
μ-h	15
h-h	13
sum	126

Table 3. Misidentification probabilities for the 4.8-GeV Sample[32]. $P_{h \to e}$ means the probability that a hadron would be misidentified as an electron. $P_{h \to \mu}$ means the probability that a hadron would be misidentified as a muon. $P_{h \to h}$ means the probability that a hadron would be identified as a hadron

Momentum range of particle (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	.183 ± .007	.198 ± .007	.619 ± .012

Table 4. The known leptons in 2003. The mass is in units of MeV/c^2, a unit of mass used in particle physics. For comparison recall that the mass of the electron is 9.11×10^{-31} kilogram. The electric charge is given in units of 1.60×10^{-19} coulombs. All the leptons have weak interactions and the charged leptons have electromagnetic interactions. None of the leptons have strong interactions

Lepton	**Electron**	**Muon**	**Tau**
Symbol for charged lepton	e	μ	τ
Electric charge	+1 or –1	+1 or –1	+1 or –1
Mass of charged lepton	0.51	106	1777
Lifetime of charged lepton	stable	2.2×10^{-6} sec	2.9×10^{-13} sec
Associated neutrino	ν_e	ν_μ	ν_τ
Associated antineutrino	$\bar{n}_e$	$\bar{n}_\mu$	$\bar{n}_t$
Mass of neutrino	close to 0	close to 0	close to 0

Figure Captions

Fig. 1 The principle of operation of a circular electron-positron collider. A bunch of electrons, closed circles, and a bunch of positrons, open circles, circulate in opposite directions in a circular ring consisting of an evacuated pipe. The cross sectional size of the pipe is much smaller than the diameter of the ring. For example in the SPEAR collider, figure 2, the cross sectional size of the pipe is of the order of 10 centimeters and the diameter of the ring is about 60 meters, As the bunches circulate they pass through each other in two places called interaction points. Almost all of the electrons and positrons pass by each other but occasionally an electron and a positron collide and interact producing new particles.

Fig. 2 The SPEAR electron-positron collider at the Stanford Linear Accelerator Center in the early 1970s. The circular building with a diameter of about 80 meters contains the collider itself. The building astride the far end of the ring with the white roof contains the SLAC-LBL detector. Adjacent building contains the control rooms and power supplies for the collider and the detector. Colliders are usually built underground but SPEAR was built above ground because of budget restrictions. Courtesy Stanford Linear Accelerator Center.

Fig. 3 Cross sectional view of the initial form of the SLAC-LBL detector in 1974. The electron and positron interaction takes place at the center of the beam pipe. Particles produced in the interaction move out from the interaction point and through the detector. The wire chambers show the path of charge particles such as pions, electrons and muons. The paths of these charged particles are curved because of the magnetic field produced by the coil, the momentum of the particles is determined from the curvature. Photons from the interaction are detected in the shower counters where they produce electromagnetic showers. Electrons also produce electromagnetic showers in the shower counters and so are distinguished from pions and muons. Muons produced in the interaction with sufficient energy are detected in the muon wire chambers after they penetrate all the layers of the detector and the 20 cm of iron.

Fig. 4 Photograph of the open SLAC-LBL detector in 1974. Some of the layers of the detector shown schematically in Fig. 3 can be seen in this figure. Courtesy Stanford Linear Accelerator Center.

Fig. 5 (a) The SLAC-LBL detector in 1975 with additional concrete and muon wire chamber added on top of the detector. This addition called the muon tower enabled cleaner detection of muons. (b) One of the first e-μ events using the 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.

Fig. 6 The observed cross section for the signature e-μ events from the SLAC-LBL experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.[33]

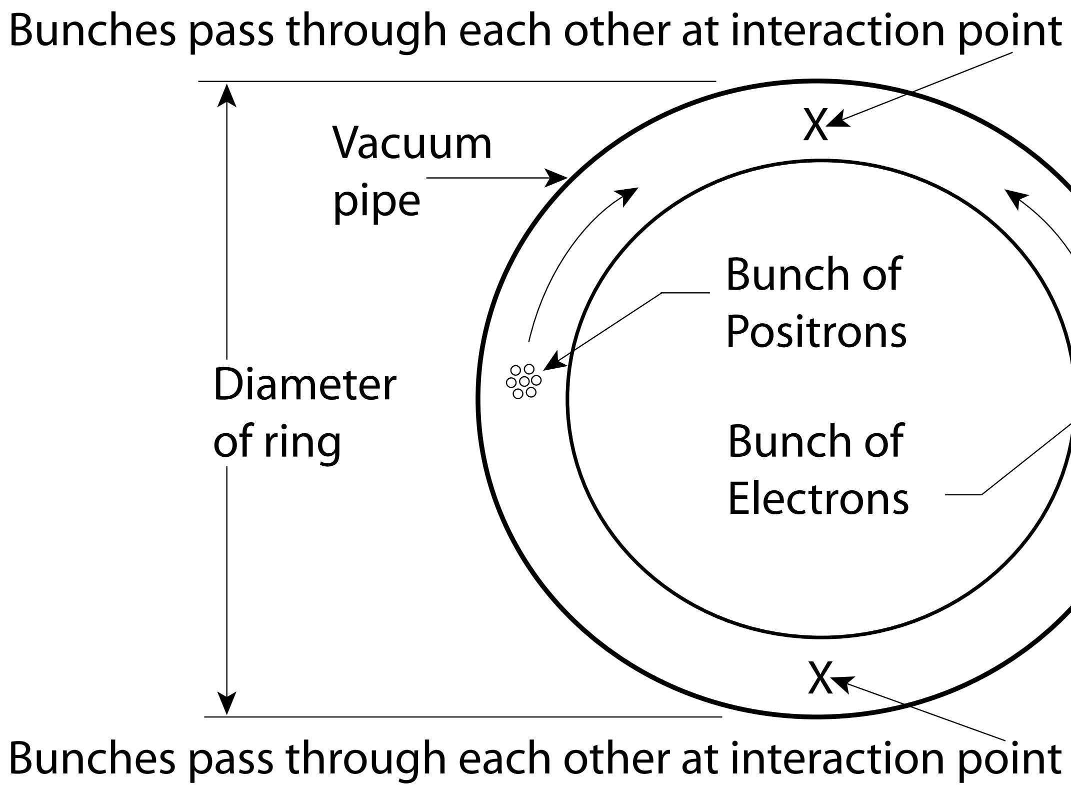

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Fig. 2 The SPEAR electron-positron collider at the Stanford Linear Accelerator Center in the early 1970s. The circular building with a diameter of about 80 meters contains the collider itself. The building astride the far end of the ring with the white roof contains the SLAC-LBL detector. Adjacent building contains the control rooms and power supplies for the collider and the detector. Colliders are usually built underground but SPEAR was built above ground because of budget restrictions.

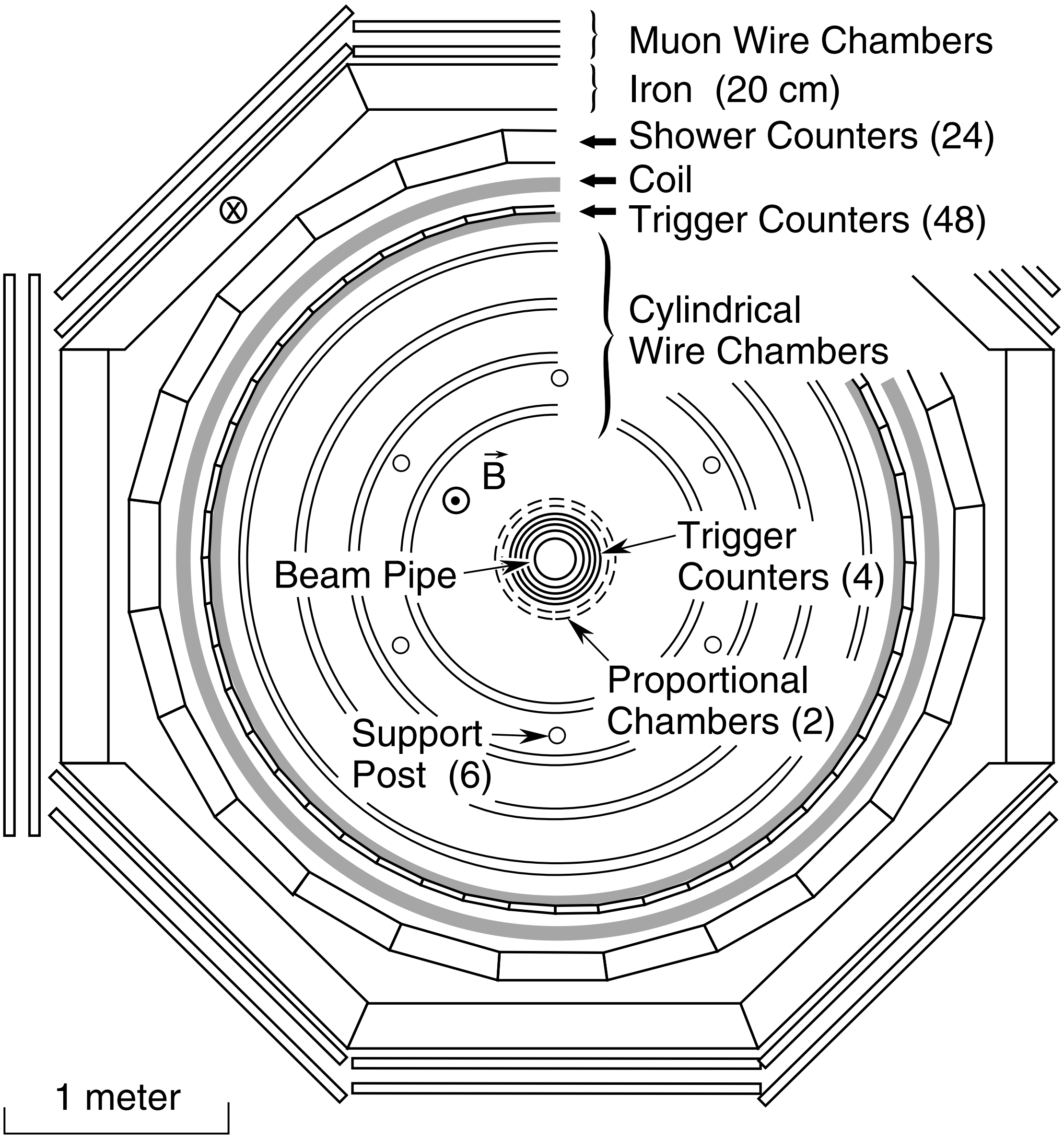


Fig. 3. Cross sectional view of the initial form of the SLAC-LBL detector in 1974. The electron and positron interaction takes place at the center of the beam pipe. Particles produced in the interaction move out from the interaction point and through the detector. The wire chambers show the path of charge particles such as pions, electrons, and muons. The paths of these charged particles are curved because of the magnetic field produced by the coil, the momentum of the particles is determined from the curvature. Photons from the interaction are detected in the shower counters where they produce electromagnetic showers. Electrons also produce electromagnetic showers in the shower counters and so are distinguished from pions and muons. Muons produced in the interaction with sufficient energy are detected in the muon wire chambers after they penetrate all the layers of the detector and the 20 cm of iron.

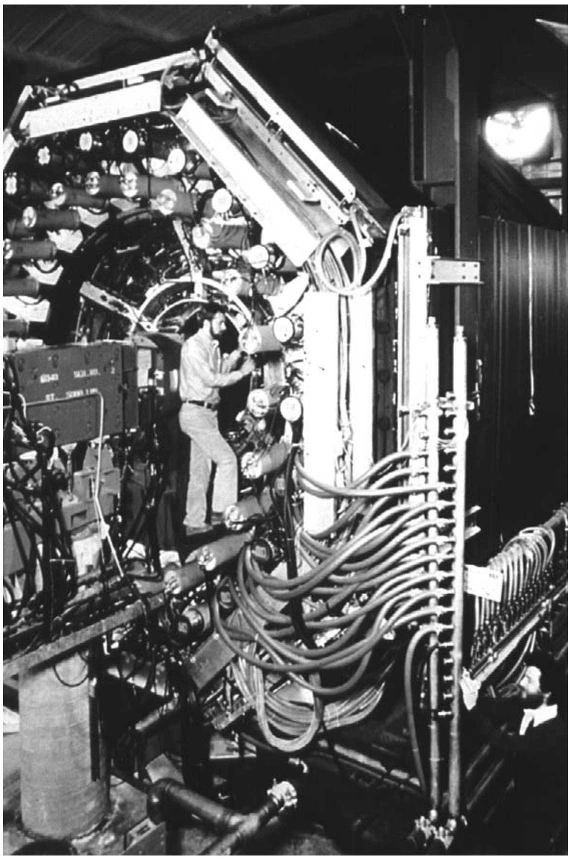
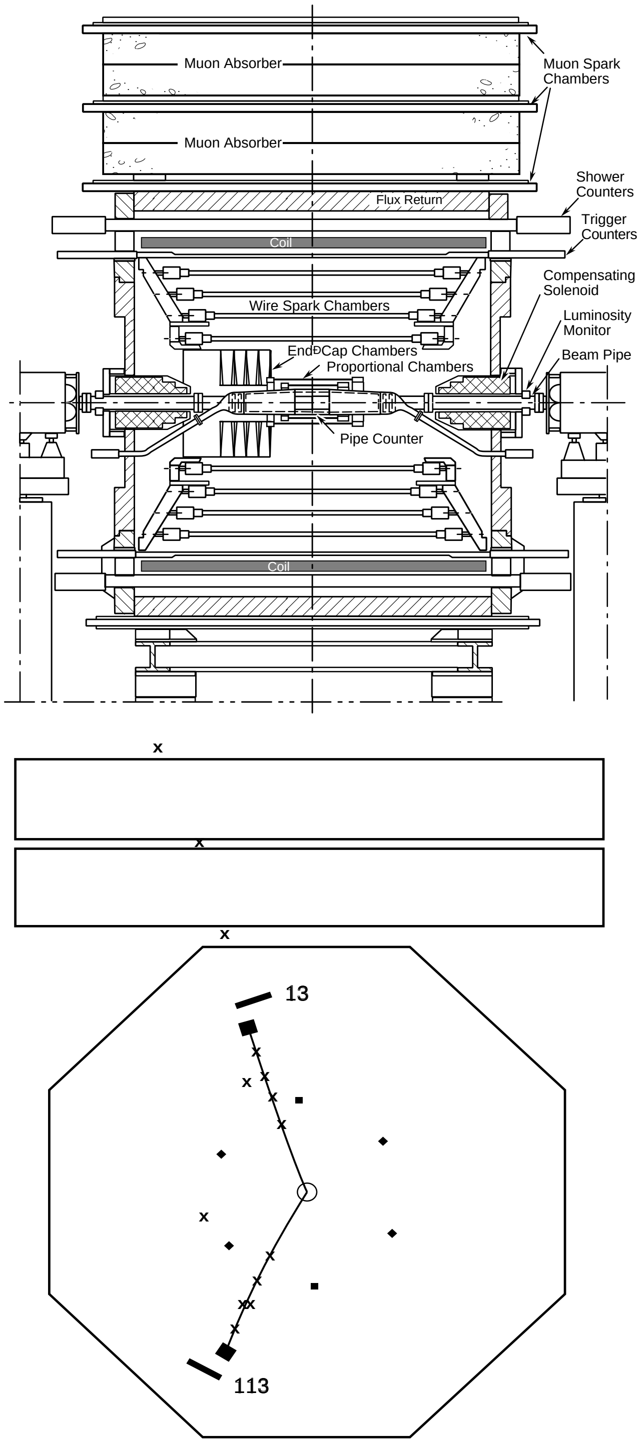


Fig. 4 Photograph of the open SLAC-LBL detector in 1974. Some of the layers of the detector shown schematically in Fig. 3 can be seen in this figure.

(a)



(b)

Fig. 5(a). The SLAC-LBL detector in 1975 with additional concrete and muon wire chamber added on top of the detector. This addition called the muon tower enabled cleaner detection of muons. (b) One of the first e-μ events using the 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.

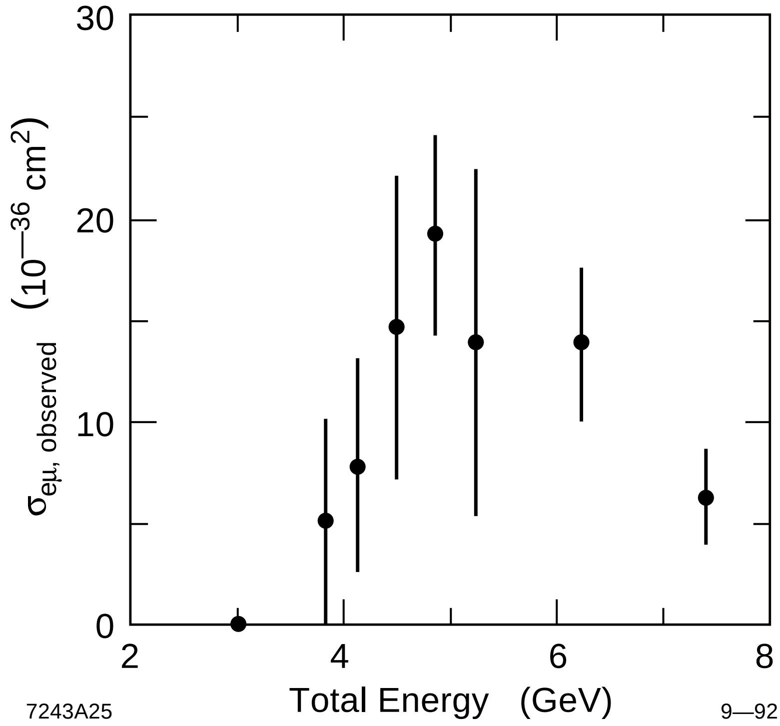


Fig. 6 The observed cross section for the signature e-μ events from the SLAC-LBL experiment at SPEAR. This observed cross section is not corrected for acceptance. There are 86 events with a calculated background of 22 events.[33]