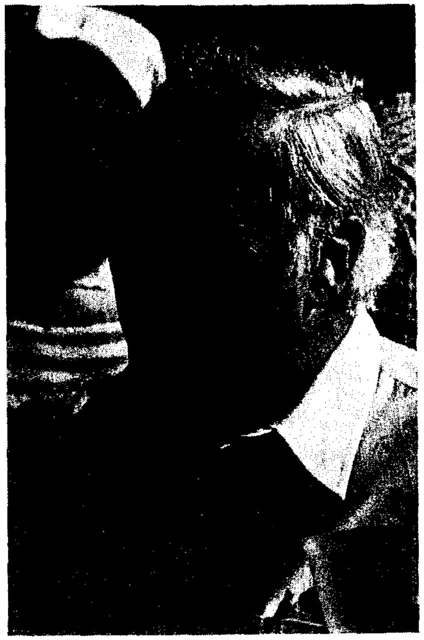

FORTY-FIVE YEARS OF e^+e^- ANNIHILATION PHYSICS: 1956 to 2001*

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ABSTRACT

Electron-positron physics is an appropriate subject to talk about at this symposium dedicated to W. K. H. Panofsky because the development of e^+e^- physics with storage rings has been intimately connected with laboratories that Pief has headed — the High Energy Physics laboratory at Stanford that he directed until 1962, and SLAC which he has directed since then. But talking only about the past gives no scope for the imagination and since I like to speculate, I will take on the task in this talk of describing not only what has been, but of what will be. I will divide this into five parts — (1) the beginnings of the field; (2) the decade of the 1970s when most of the spectacular discoveries were made; (3) the present period, which is a time of consolidation; (4) the near future, which is the era of the SLC and LEP; and finally (5) the period up to 2001 (an appropriate time to stop since I will be 70 then) that completes the 45 years of the title.

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IN THE BEGINNING

The beginnings of all colliding beam machines can be traced back to that marvelous organization, MURA, which did so much for accelerator physics but never got to build a full-scale machine of its own. It was in the mid-1950s when people first started talking seriously about colliding beams as a way to reach high center-of-mass energy and to beat the inexorable square root scaling law of center-of-mass energy with beam energy that comes with fixed-target machines. In principle, with colliding beams one could get the total amount of energy available into center-of-mass energy by colliding two equal-energy beams with each other. The people at MURA were thinking about proton-proton colliders, but in the mid-1950s accelerator physicists did not know nearly as much about accelerators as we now know. The job of injection and building up the circulating beam in a proton-proton colliding beam storage ring (stacking) looked to be formidable and one would also be faced with the problem of what would happen to beams that circulated for a very long time in an imperfect magnetic guide field.

In 1958 Gerard K. O'Neill of Princeton came to the High Energy Physics Laboratory (HEPL) at Stanford with a modification of the basic idea. Gerry wanted to use electrons rather than protons to test the colliding beam principle and also to do some first-rate particle physics experiments with the device that would be built to show that colliding beams would work. This should be familiar to those of you who know how we justified the new SLAC project — the SLC. It, like that first storage ring, is to be a demonstration of a new kind of colliding beam machine and to be a tool for first-rate high energy physics experiments as well.

Gerry wanted to use electrons rather than protons to test out the colliding beam principle because of two great advantages that come with electrons. The first of these was that an extremely intense source of electrons was available at the HEPL 1 GeV linac. The second, and more important, advantage, was that injection and stacking were vastly simpler if one used electrons rather than protons. Electrons emit synchrotron radiation as they are bent around a circle in a storage ring, and if the magnet field was configured properly, electrons that were injected into a ring off the central orbit would have their oscillations around that central orbit damped out by the emission of synchrotron radiation. Thus, one had only to inject particles near the edge of the useful aperture of the storage ring, wait while synchrotron radiation moved the orbits of these electrons toward the central orbit, and then inject a new bunch of particles at the edge of the aperture. In principle, injection and stacking were easy compared to what one would have to do to build up the circulating beam in a proton machine. In practice, it was a long way from easy, but then what new thing is not?

In 1958, W. C. Barber, B. Gittleman, Gerry, and I designed the machine and wrote the proposal. In that same year Pief raised $800,000 from the Office of Naval Research to fund the project. We, together with a small group of engineers and technicians–some of whom are in the audience today–began the construction of the Princeton/Stanford electron-electron collider in early 1959, thinking that it would take us about two years to get the facility built. A photo of the figure-8 shaped Princeton/Stanford storage ring is shown in Figure 1.

It took us much longer than two years to get the machine finished and working, for it was the pioneer in the colliding beam technique and much of what we now know about resonances, the beam-beam interaction, synchrotron light desorption of gas from metal walls, non-linear correctors, etc., was learned using that machine. The physics experiments that were promised in the proposal were eventually done, although it took us much longer than we thought it would. The first results on e^-e^- scattering were presented in 1963, and the final paper on e^-e^- scattering was published in 1965.[1] The last experiment carried out was a study of lepton number conservation[2] by searching for the reaction $e^- + e^- \to \mu^- + \mu^-$. The Princeton/Stanford machine is now shut down, but it still holds the world record for currents stored in a single bunch in a storage ring — 600 ma.

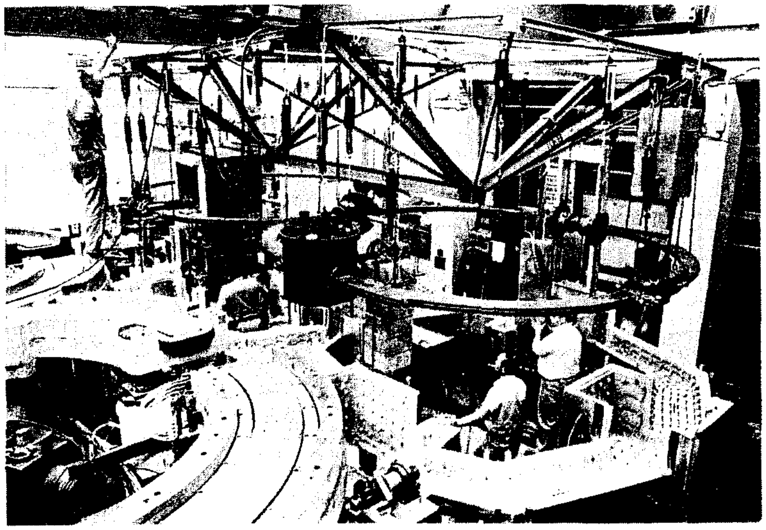

Figure 1: The Princeton/Stanford 500 MeV electron-electron colliding beam facility. Some of the magnets can be seen at the lower right. The device suspended from the crane is the figure-8 shaped ultra-high vacuum system.

From that machine came many successors, but the successors are all electron-positron colliding beam machines. It was realized throughout the physics community in the late 1950s that electron-positron collisions could teach us new things about particle physics. At that time I was close enough to my days as a graduate student to be able to do my own QED calculations, and I calculated what would happen when e^+e^- produced a pair of pointlike bosons. Bjorken told me I did the calculation properly but I was left with a question: what would happen if those bosons had structure? That was when I realized that electron-positron colliders could give basic information on the structure of the elementary particles that was not obtainable in any other way.

The first of the electron-positron descendants of the Princeton/Stanford rings was a tiny machine called ADA built in Italy at the Frascati National Laboratory. It was so small that in filling it, they first injected one beam, then reversed the polarity of the magnets in the injection line, turned the ADA machine upside down and injected the counter-rotating beam through the same injection channel. Nothing in the way of what we would call particle physics experiments was done with ADA, for its energy was too low to do much in the way of meson production and an unforeseen limitation on the beam lifetime was discovered in this machine.

Since those days we have had an exponential growth in the energy of e^+e^- machines because the physics research done with each generation of them has been important and there has been great pressure to get on with the next one. The electron-positron system gives a very clean and simple final state. It proceeds through a one photon annihilation process which I have always viewed in a three-step fashion. The electron-positron annihilate producing a virtual photon. This intermediate state has enormous energy density and very simple quantum numbers — a tiny fireball with nothing but energy and a spin of one to characterize it. This fireball then re-materializes into any collection of particles so long as the total mass of all the particles produced is less than the total fireball and the spin of the entire system is one. There is very little background and the angular distribution of the particles has no sharp forward and backward peaks as in the case with production from protons.

The first significant high energy physics results came from the next two e^+e^- machines to be completed. These were the VEPP II at Novosibirsk with 700 MeV beam energy and the ACO machine at the Orsay Laboratory with 450 MeV beam energy. The first to publish was the Novosibirsk group who measured the pion form factor at the ρ pole[3] and showed that the ρ had a much narrower width than had been determined from experiments on proton machines where a great deal of interfering background had been produced along with the ρ. A few months later, the Orsay group published the first precision measurement of the ρ to e^+e^- coupling constant.[4]

One can trace the importance of electron colliding beams by looking at the proceedings of the international conferences. The first discussion of the results from these machines is in Sam Ting's talk on vector mesons in the proceedings of the Vienna High Energy Physics Conference.[5] Considerably more was heard at the International Photon Conference at Daresbury[6] in the following year, and the tide has risen ever since.

Probably the most important result of the 1960s came from the ADONE e^+e^- machine which was built at Frascati as a follow-on to ADA. This machine was started in 1964 and began operation in 1968. It was built by Fernando Amman and collaborators and had a maximum beam energy of 1.5 GeV. The first results from ADONE were a surprise to most of the high energy physics community. The general expectation was that the cross section for electron-positron annihilation to produce hadrons would become very small above the peak of the ρ resonance. The first results from ADONE showed that, on the contrary, this cross section was "big," where big means that the ratio R of this cross section to the cross section for producing a pair of pointlike elementary particles was on the order of unity. Figure 2 shows a compilation of the results from a number of the early experiments done at Frascati. While there are clearly systematic normalization problems between experiments, the results are large

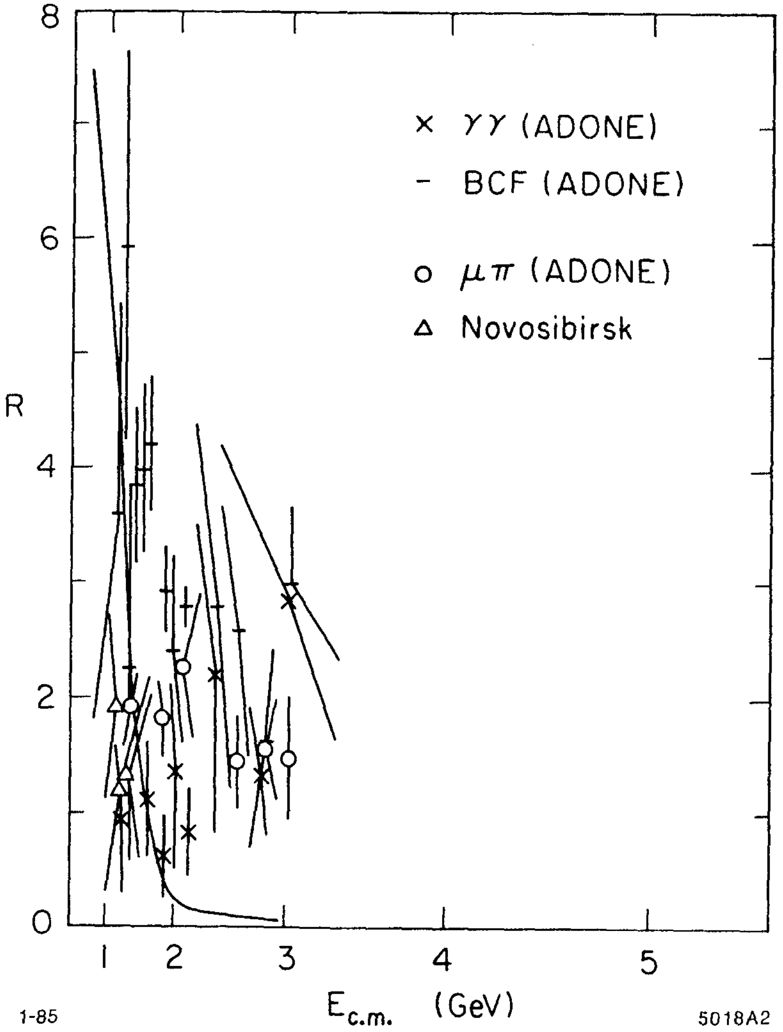

Figure 2: Early data from the Frascati storage ring ADONE showing R as a function of center-of-mass energy. The solid line is what was expected from the tail of the ρ resonance.

compared to what was expected which is shown in the solid curve.

Although it is slightly ahead of the story, I must mention here also the results from the Cambridge Electron Accelerator (CEA) on the measurement of e^+e^- to hadrons that were actually produced very early in the 1970s. CEA had converted their synchrotron into a colliding-beam storage ring and had succeeded in getting a couple of data points at considerably higher energy than was accessible to ADONE. This work showed that the ratio R was still large at CEA energies, and that the ADONE results were not merely some low energy phenomenon.

The ADONE experiment was particularly important to me personally. I had been working since 1961 on the design of a machine that was to become SPEAR and SLAC had submitted the proposal for this machine in 1964. The proposal to build SPEAR as a construction project was never approved by the U.S. authorities, and by 1969 I was very discouraged. The encouragement of Pief, and particularly of Matt Sands, was especially important in keeping me going. I first saw the ADONE results in 1969 at a meeting in Rome, and I realized that we not only needed the much higher energy of the SPEAR storage ring to understand what was going on, but that it would be essential to have nearly a 4π solid angle magnetic detector to be able to understand the final states that were produced at this "large" rate.

THE DECADE OF DISCOVERY

I now turn to the 1970s: the decade of discovery. Most of you know a great deal about the results of the e^+e^- annihilation experiments of those days, for it is all relatively recent. I will touch on a few of the high points in this section. SPEAR itself was finished in 1972 and is shown in Figure 3 as it looked just after completion. Figure 4 shows the Mark I detector with which a great deal of the discoveries of the 1970s were made. The Mark I was a solenoid magnet with a cylindrical spark chamber tracking system, shower counters and muon identifiers inside it. It was the first of its kind.

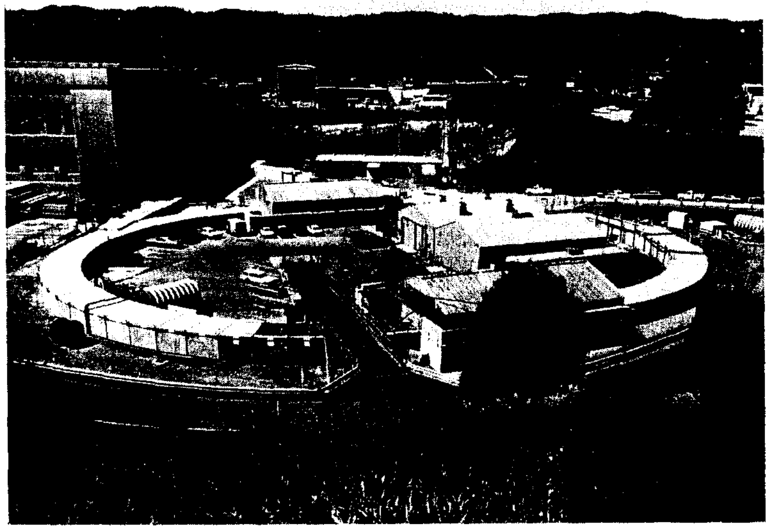
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Figure 3: The SPEAR storage soon after its completion.

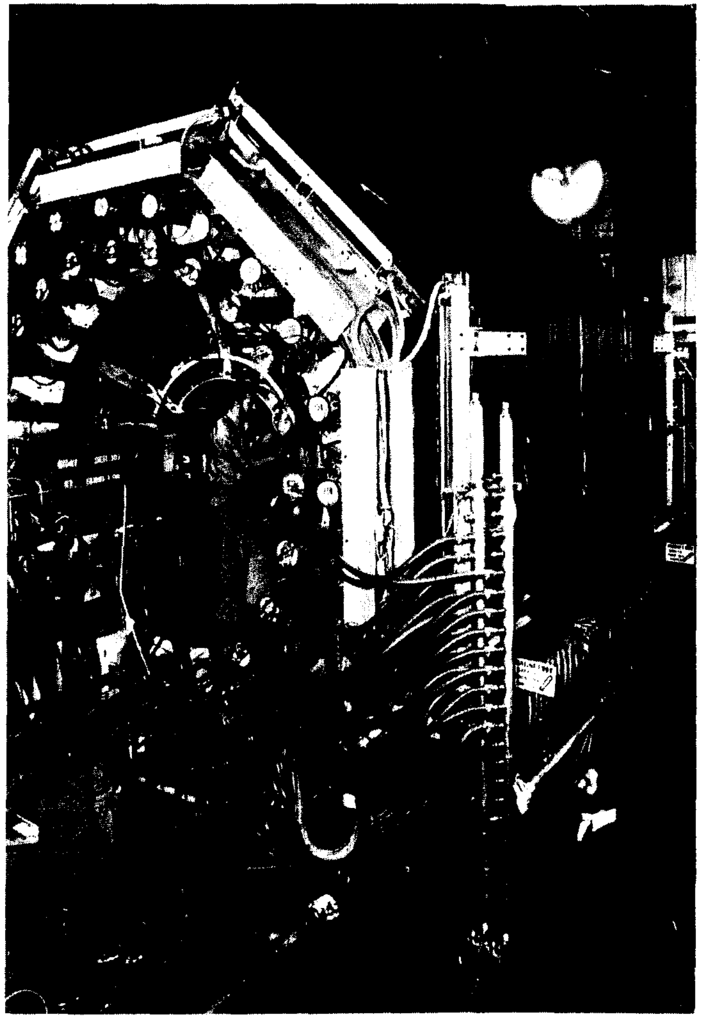

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Figure 4: The Mark I magnetic detector.

The first results from SPEAR[7] confirmed the results of ADONE and CEA (Figure 5). The dashed line on the figure shows what I might call an experimenters fit to the data; the simplest possible curve that represents it. My first talks about these results mention such things as constant cross sections, rising R, hadronic cores to the electron, etc.

There was a considerable degree of disarray in the theory community at that same time. The ADONE results had started many people thinking about how to make R big, and the SPEAR results generated much work more along this line. Experimenters probably enjoy confounding their theoretical colleagues more than proving their models to be correct, and I am no different from others in this respect. I particularly enjoyed John Ellis' rapporteur talk at the London High Energy Physics Conference[8] summarizing the theoretical results on the electron-positron cross section. Figure 6 reproduces a table from Ellis' talk that shows the predicted values of R which range from 0.36 to infinity.

It all began to clear with what has come to be called the November Revolution. That was the time when the Mark I collaboration found the ψ particle[9] and Sam Ting's group found the J particle.[10] At a wonderful meeting in Pief's office on November 11, Sam and I discussed each other's data and it was clear that we had discovered the same thing. Figure 7 shows the November data from SPEAR. What is depicted here is an incredibly narrow resonance in all channels — the hadron production cross section increases by a few hundred, the mu pair cross section goes up by a factor of 30, and the e^+e^- elastic scattering cross section goes up by a factor of 5 or 6, all in an energy region of a few MeV.

If there is one narrow resonance it is a natural question to ask whether there are more. At SPEAR we quickly modified the control system of the storage ring to turn it into a scanning device and started our hunt. At about 5:00 A.M. on November 21st, the second narrow resonance turned up — the ψ'. Eventually the entire energy region accessible to SPEAR from 3 GeV to 7.4 GeV was scanned and no other narrow states were found.

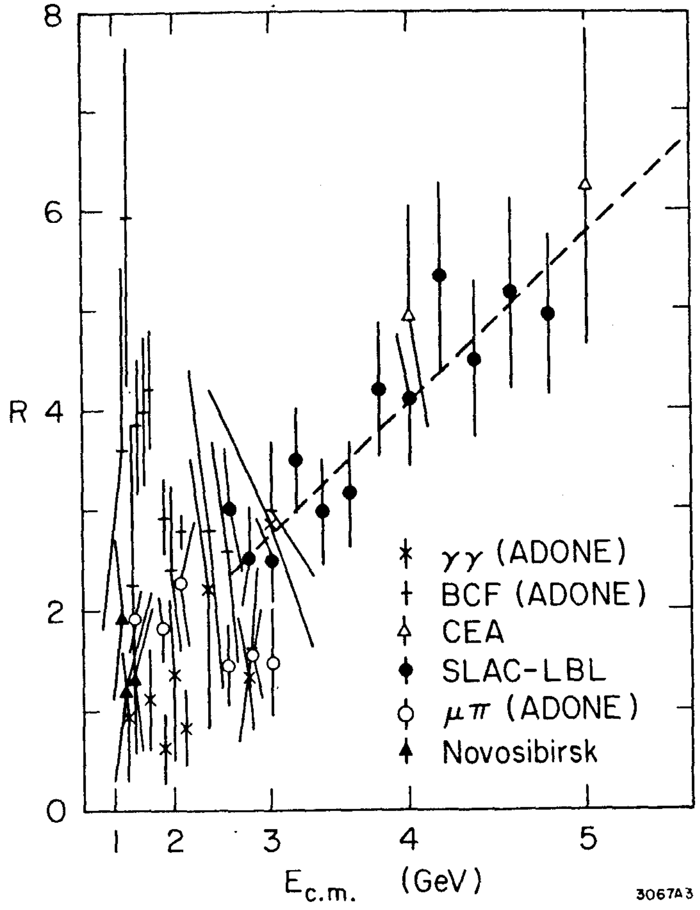

Figure 5: A summary of the data on R as a function of center-of-mass energy at the time of the 1974 London Conference on High Energy Physics. The dashed line is an experimenter's eyeball fit to the data.

Figure 6

Table of Values of R from the Talk by J. Ellis at the 1974 London Conference(8)
(References in Table from Ellis's Talk)

Value	Model	
0.36	Bethe-Salpeter bound quarks	Bohm *et al.*, Ref. 42
2/3	Gell-Mann-Zweig quarks	
0.69	Generalized vector meson dominance	Renard, Ref. 49
~ 1	Composite quark	Raitio, Ref. 43
10/9	Gell-Mann-Zweig with charm	Glashow *et al.*, Ref. 31
2	Colored quarks	
2.5 to 3	Generalized vector meson dominance	Greco, Ref. 30
2 to 5	Generalized vector meson dominance	Sakurai, Gounaris, Ref. 47
3-1/3	Colored charmed quarks	Glashow *et al.*, Ref. 31
4	Han-Nambu quarks	Han and Nambu, Ref. 32
5.7 ± 0.9	Trace anomaly and ρ dominance	Terazawa, Ref. 27
$5.8^{+3.2}_{-3.5}$	Trace anomaly and ϵ dominance	Orito *et al.*, Ref. 25
6	Han-Nambu with charm	Han and Nambu, Ref. 32
6.69 to 7.77	Broken scale invariance	Choudhury, Ref. 18
8	Tati quarks	Han and Nambu, Ref. 32
8 ± 2	Trace anomaly and ϵ dominance	Eliezer, Ref. 26
9	Gravitational cut-off, Universality	Parisi, Ref. 40
9	Broken scale invariance	Nachtmann, Ref. 39
16	$SU_{12} \times SU_{12}$ gauge models	Fritzsch and Minkowski, Ref. 34
35-1/3	$SU_{16} \times SU_{16}$ gauge models	
~ 5000	High Z quark	Yock, Ref. 73
70,383	Schwinger's quark	
∞	∞ of partons	Cabibbo and Karl, Ref. 9 Matveev and Tolkachev, Ref. 35 Rozenblit, Ref. 36

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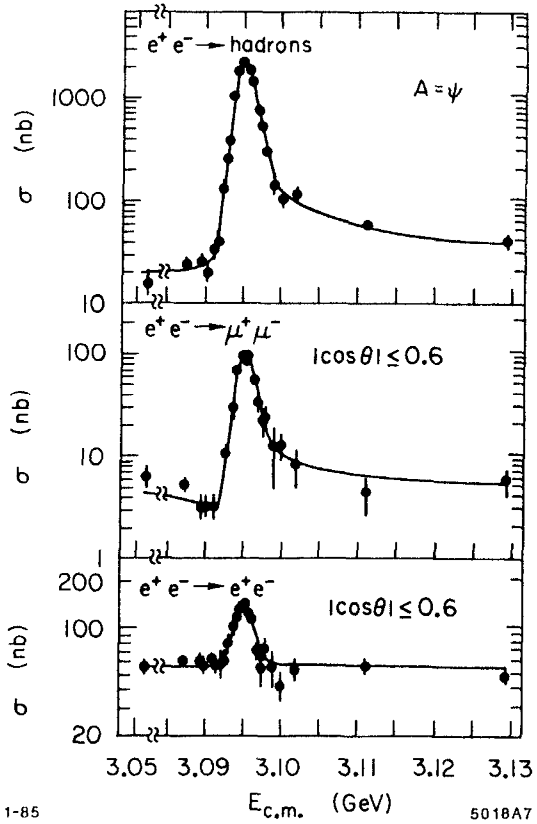

Figure 7: Cross-section for various channels versus center-of-mass energy, showing the remarkably sharp rise and narrow width of the ψ resonance.

With the help of the theorists, and in particular, with help from the theory workshop run here by J. D. Bjorken, the many initial hypotheses about what was going on quickly came down to three. The first was that these states were particles with color. The second was that they were the Z^0 (the mass limits on the Z^0 were considerably lower then). The third was that they represented a new quark-antiquark bound state. Over the next six months or so a series of experiments at SPEAR ruled out the color and the Z^0 hypotheses. The ψ and the ψ' seemed to be the bound states of a fourth quark and its antiquark. If that were so, the system was much like positronium (it was called "charmonium" after the name of the quark) and there should be other states observable in the decay of the ψ and the ψ'.

Experiments at SLAC and at DESY were done to sort out these states. The final word on the radiative transitions in ψ and ψ' decay comes from the data taken by the Crystal Ball collaboration.[11] The Crystal Ball, a sodium iodide sphere about 1.5 meters in diameter, was finely segmented and had good energy resolution. Figure 8 shows their data on the gamma ray transitions in which all of the allowed transitions are seen.

If the ψ particles were bound states of a new quark and antiquark, then mesons should exist which contained the new quark plus one of the old quarks. Detailed measurements of R showed a complicated structure in R at around 4 GeV mass (see Figure 9) but it was not easy to find the particles containing these new quarks. About a year and a half went by before Gerson Goldhaber found these new mesons in a subtle analysis of the SPEAR data and showed also that they violated parity conservation in their decay.[12]

This is a good point to pause and look at what had been learned by these experiments. Discovery of the ψ/J, the measurement of the energy levels of charmonium, and the discovery of the D mesons had proved that there was a fourth quark, the charmed quark, involved in the strong interactions. There were now two firmly established doublets of quarks, the up and the down and the

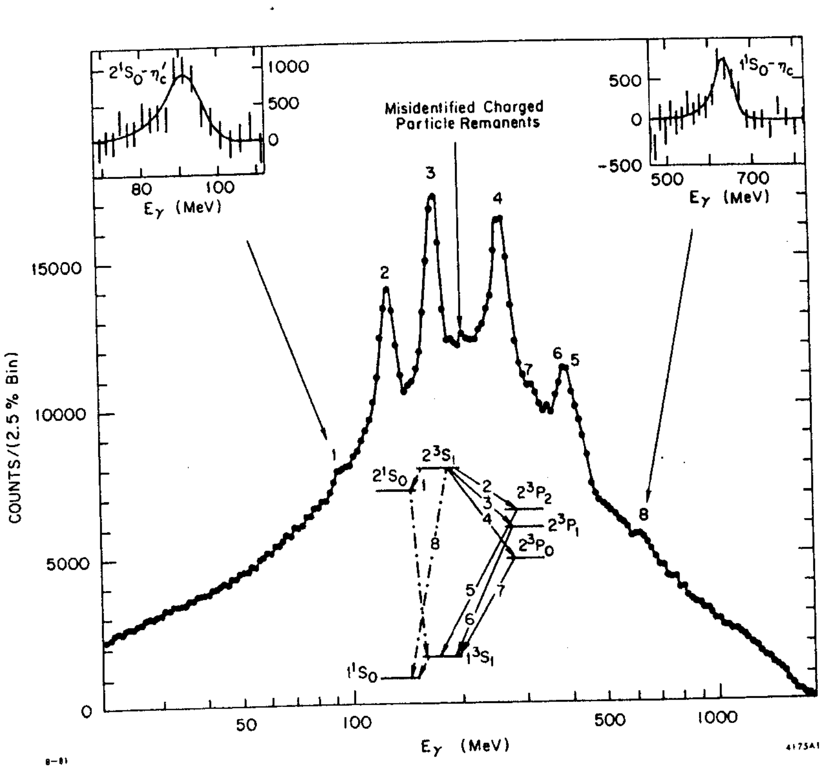

Figure 8: Data from the Crystal Ball group at SPEAR showing the inclusive photon spectrum in ψ' decay versus photon energy. The various transitions are identified on the energy level diagram.

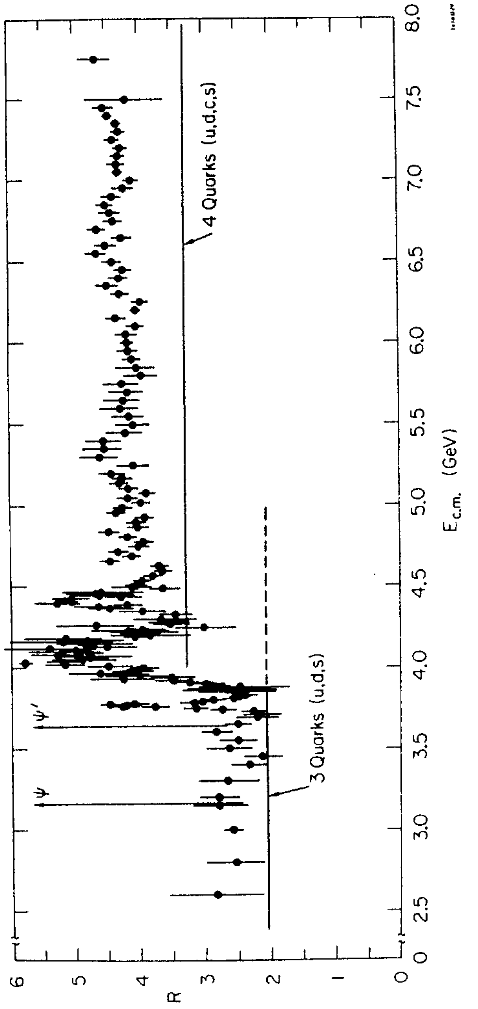

Figure 9: Data from the Mark I detector at SPEAR showing R versus center-of-mass energy from below the ψ to well above the threshold for charmed meson production. The arrows at about 3.1 and 3.7 GeV show the location of the very large and very narrow ψ and ψ' resonances.

charmed and the strange, that restored a certain symmetry to the fundamental constituents of matter, for we had had for years two doublets of leptons, the electron and its neutrino and the muon and its neutrino. There was then — and still is — a great mystery about why the fundamental constituents of matter seemed to come in families: e, ν_e, u, d; and μ, ν_μ, c, s at that time. The quark model explained the old ADONE measurements for, according to the quark model, R should be equal to 3 (for the color factor) times the squares of the quark charges and at the ADONE energy only three of the quarks could be produced (u, d, and s) and R should be about 2. We should have known it all the time if only we had really believed in the quark model. The SPEAR results could be explained by the production of the fourth quark with an effective mass about 1.5 GeV, which gave rise to the ψ/J and ψ' narrow resonances and all of the charmonium states. The complicated structure at around 4 GeV in the center-of-mass could be explained as crossing of the threshold for the production of charmed mesons and in this model R should have settled down to be $3\frac{1}{3}$ after the threshold region for charmed meson production had been passed. But it wasn't $3\frac{1}{3}$ it was $4\frac{1}{3}$. Why?

This problem was solved by Martin Perl through his analysis of the SPEAR data. Perl found a class of events which consisted only of electrons, muons, and missing energy.[13] There was no sign in these events of any extra photons or of any strongly interacting particles. The only way to explain these events was by the production of a pair of new leptons still heavier than the muon which decayed weakly into electrons or muons and the appropriate neutrinos. It took a couple of years of work to prove conclusively that Perl's events were really the sign of a new heavy lepton with a pair production threshold between the mass of the ψ' and the threshold for the production of charmed meson pairs. The DASP group at DESY and the DELCO group at SLAC pinned down the threshold for the production of this new lepton,[14] the τ, and the DELCO data gave the final conclusive proof that the new particle was a lepton with spin $\frac{1}{2}$. The DELCO excitation curve is shown in Figure 10 and its shape is characteristic of a spin $\frac{1}{2}$

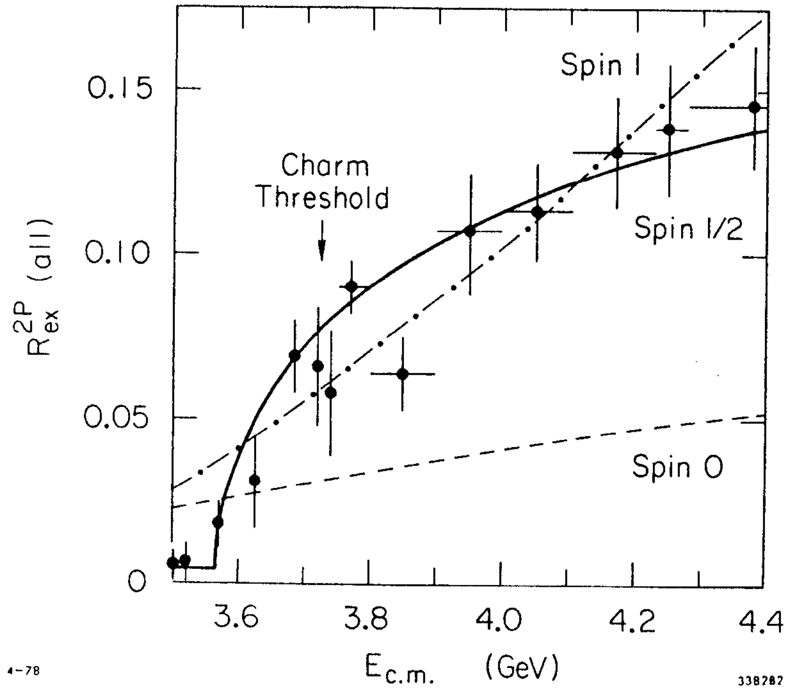

Figure 10: Data from the DELCO experiment at SPEAR showing R for final states where electrons are accompanied by other particles versus center-of-mass energy. The curves show the expected shape of the excitation function for different spins of pair produced particles. This data fixes the spin of the τ lepton as 1/2 and the mass of the τ as 1782 ± 2 MeV.

particle.

The discovery of the τ was a complete surprise to the physics community. *Tau* pair production added one unit of R to what one expected to see in e^+e^- annihilation experiments and so solved the problem of the value of R being $4\frac{1}{3}$ above the charmed meson pair production threshold. However, the lovely symmetry between quarks and leptons which had been restored by the discovery of the charmed quark was now destroyed by the discovery of the τ lepton. Before the discovery of charm, we had four leptons and three quarks. There were theoretical speculations that there should be a fourth quark to restore quark-lepton symmetry and to solve certain problems which existed in the weak decays of K mesons. Charm was found and all was well. The discovery of the τ left us with six leptons (certain experiments on τ decays indicated that the τ had to be associated with its own neutrino distinct from those associated with the muon and the electron and only four quarks). Our newfound symmetry was gone before we had had much chance to appreciate its beauty.

We hardly had time to speculate over this destruction of quark-lepton symmetry when it was partly restored by the discovery by Lederman and collaborators in an experiment at Fermilab of a narrow resonance (they named it the υ) that decayed into muon pairs and had a mass of around 9 GeV.[15] After the physics community had been through the ψ/J story and what followed from it, everyone was quite sure that this signalled the production of a fifth quark (the b quark) and subsequent experiments at the DESY storage ring, DORIS, and the Cornell storage ring, CESR, have found the same kind of level structure in the b–$\bar{b}$ quark bound state as was seen earlier in the c–$\bar{c}$ bound quark system. While the sixth quark, already named t, has not yet been found, everyone is quite certain it will be and the only question is its mass.

While all of this was going on, other results were coming from the storage ring that put the quark model on an even sounder footing. It is now taken for granted that in e^+e^- annihilation an evanescent state of a quark-antiquark pair is produced and that it is these quarks which turn into the hadrons that we see in the final state. As illustrated in Figure 11 the then developing model of quantum chromodynamics (QCD) predicted that the final state hadrons should be produced with limited transverse momentum with respect to the directions of the parent quarks. Thus, there should be collimated jets of mesons produced in e^+e^- annihilation. These jets were searched for and found at SPEAR.[16] Jets are trivial to observe at the higher-energy e^+e^- colliders like PEP and PETRA, for the higher energy of these machines compared to SPEAR implies smaller angles of the final state hadrons with respect to the parent quark direction. Figure 12 shows a typical two-jet event from the Mark II detector at PEP. There is no question that these particles come off in highly-collimated jets, but it was a considerably more difficult job to prove that such jets existed at the lower SPEAR energies.

The experiment that convinced me that quarks were more than a convenient mathematical fiction was done at SPEAR with polarized beams of electrons and positrons. Under certain conditions, synchrotron radiation produced as the beams circulate in the storage ring can transversely polarize the beams and, if the beams are polarized, it is possible to have an azimuthal asymmetry of the particles produced in e^+e^- annihilation. The asymmetry is different depending on whether the particles produced are bosons or fermions. Figure 13 shows the azimuthal asymmetry of the jet axis in e^+e^- annihilation.[16] This asymmetry is characteristic of the patterns expected for the production of a fermion-antifermion pair in spite of the fact that all of the particles in the final state are bosons. Even a skeptic like me had to believe that quarks were real based on this result.

THE PRESENT — A TIME OF CONSOLIDATION

The last few years have been spent in more detailed studies of the products of electron-positron annihilation reaction. Two new colliding beam storage rings, PEP at SLAC and PETRA at DESY, have come into operation at high energy;

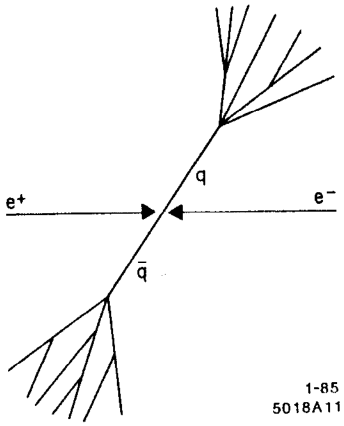

Figure 11: Schematic of how hadronic jets are produced in electron-positron annihilation.

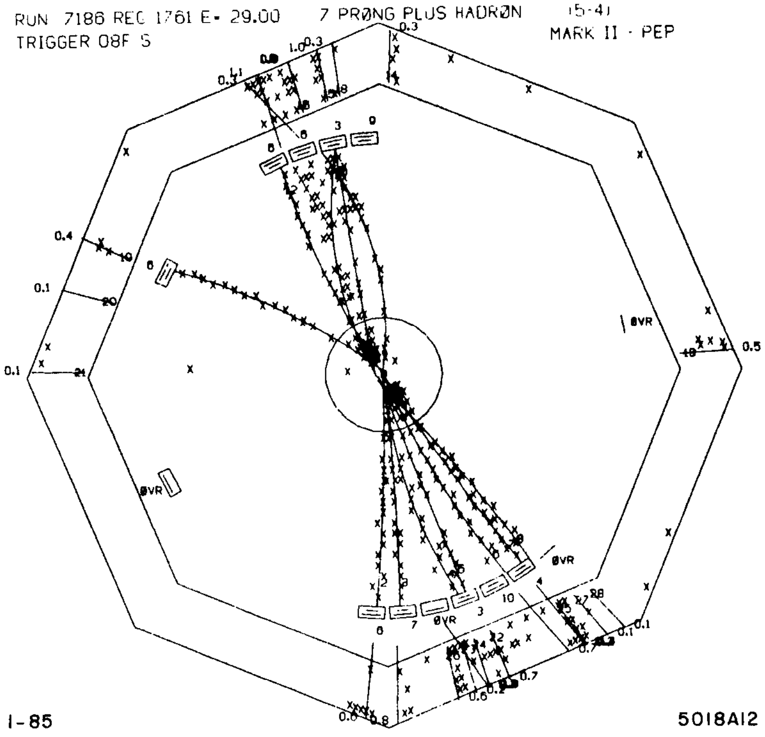

Figure 12: A two-jet event from the Mark II detector at PEP. This event was obtained at a center-of-mass energy of 29 GeV.

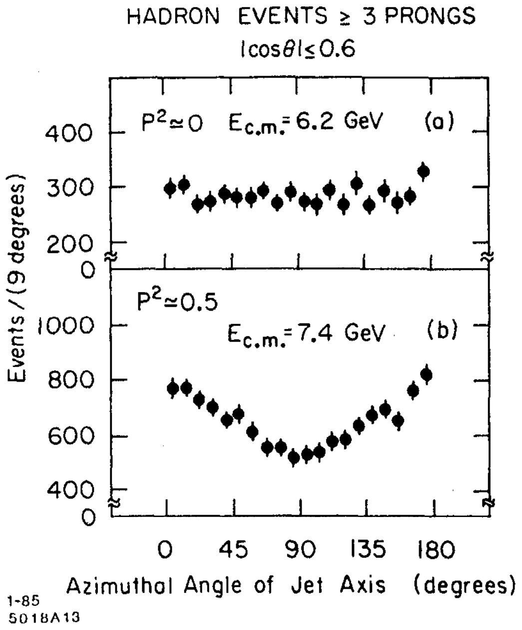

Figure 13: Jet production with transversely polarized beams from the Mark I detector at SPEAR. (a) Shows the azimuthal angular distribution of the jet axis at an energy where *no* transverse polarization of the beams is expected. (b) Shows the azimuthal distribution at an energy where the beams are 70% polarized. The cosine-like nature of the distribution in (b) is characteristic of the production of a pair of spin $\frac{1}{2}$ particles.

the CESR storage ring at Cornell covers the intermediate energy region; and a re-built DORIS storage ring gives relatively high luminosity at the υ resonance. The work has concentrated on measurements pertaining to quantum chromodynamics (the theory of the strong interactions), determinations of the strong interaction coupling constant, searches for new particles, studies of lifetimes, and weak electromagnetic interference phenomenon. There have also been indepth studies of the spectroscopy of the bound b–$\bar{b}$ quark system and considerably more work on the ψ system. No spectacular discoveries have been made like those from the past generation of storage rings, but is early yet and there may be more to come.

The first results from the big machines confirmed the existence of the "gluon" (the carrier of the strong interaction)and determined its spin. As mentioned earlier, the theory of QCD predicts that hadron production in e^+e^- annihilation reaction proceeds by the production of a virtual quark-antiquark pair which then evolve through a shower of gluons and quarks into the final state particles that we see. The theory says that sometimes a gluon can be radiated by a quark at large angles to the quark direction and that that gluon can turn into a jet well-separated from the parent quark jets. The first observations[17] were made by Mark J and TASSO at DESY. Figure 14 is an illustration of data from the Mark J apparatus where Ting and collaborators confirmed the existence of the gluon by using a method called "energy flow." Imagine that you're looking at the end of the Mark J apparatus. The beam direction is perpendicular to the paper and the figure shows the energy deposited in the Mark J apparatus as a function of azimuthal angle. A characteristic three-lobe pattern is seen showing that three jets are produced in the final state. The picture is a bit clearer in the tracking detectors than in the calorimetric detectors like Mark J, and Figure 15 shows a three-jet event from the Mark II running at PEP. There is no question that three well-collimated bunches of particles exist.

The strong coupling constant, α_s, has been determined in a variety of ways. The process by which the parent quarks turn into the final hadrons involves

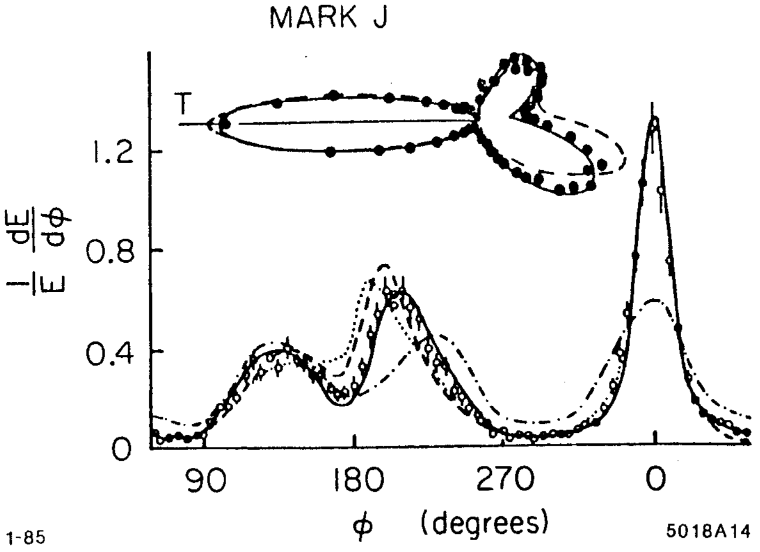

Figure 14: Energy-flow diagram from the Mark J detector at PETRA showing the characteristic three-lobe pattern which would be expected to occur in the production of a gluon jet together with a quark jet and an anti-quark jet.

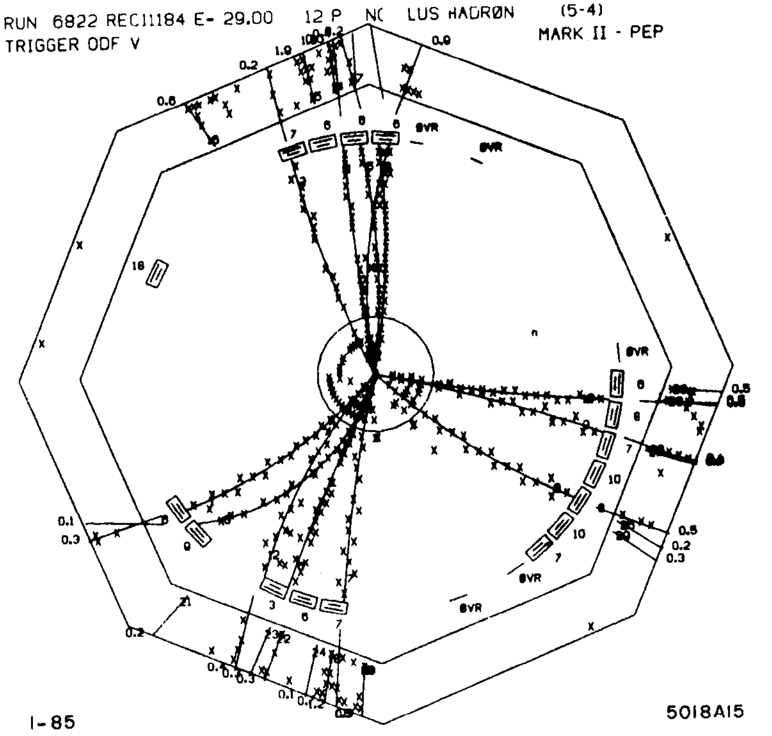

Figure 15: A three-jet event from the Mark II detector at PEP at an energy of 29 GeV in the center-of-mass.

gluon radiation from quarks, pair production of quarks by the gluons, more gluon radiation, etc. Particle distributions within a jet, particle correlations within a jet, correlations between jets, energy asymmetries in jets, and energy moments in jets all are related to the strong coupling constant. All of these methods have been used but there is still some uncertainty about the value of α_s. While the experimental results are clear, the theory is not so clear, for there are higher order corrections to the determination of the strong coupling constant and the value of α_s determined by each of the experiments is somewhat model dependent. We know now that in the center-of-mass energy range between 30 and 40 GeV the value of the strong coupling constant is somewhere between 0.12 and 0.19 and better precision than this determination requires more theoretical work rather than more experimental work.

Many searches for new particles have been done at PEP and PETRA. The best lower bound on the mass of the lower top quark comes from experiments at PETRA which give a limit of 23 GeV. Free quarks have been searched for in a dedicated experiment at PEP, and as a by-product of more general studies using the JADE detector at DESY and the TPC at SLAC. Presently the best limit comes from the TPC because of the precision measurements on ionization that can be done with that device. The limit on the production of free quarks is something like 10^{-3} or 10^{-4} of muon pairs for q–$\bar{q}$ production and about 10^{-2} of mu pairs for q–$\bar{q}$ production accompanied by a number of other particles. No pointlike short-lived bosons have been found for masses up to 15 GeV, and no long-lived ones (analogs of the muon) have been found up to 20 GeV. Excited leptons have been looked for and none found with masses up to around 15 GeV. No new charged leptons like the τ have been found up to about 14 GeV; thus there is no sign of a fourth generation of quarks and leptons. No heavy neutral leptons have been found up to about 15 GeV. Free monopoles have been looked for and none found to a limit of about 10^{-3} of the mu pair cross section for masses up to about 15 GeV. No supersymmetric electrons have been produced. Thus the PEP/PETRA energy region seems devoid of exotic new particles.

Some of the most dramatic and interesting results reported recently from the high energy storage rings have to do with the measurements of lifetimes of the τ lepton and of mesons containing b quarks. Two methods have been used. The first, used for the measurement of the τ lifetime, projects the tracks of the decay products of the τ back to the point where the decay occurred and then measures the distance of that decay vertex from the known position of the beams where the τ had to be produced. This is illustrated in Figure 16a. The τ lifetime is measured to be $(2.86 \pm 0.16) \times 10^{-13}$ seconds. The precision of this measurement is sufficient to indicate that the weak interactions of the τ are very much like the μ and to indicate that the lower bound on the mass of a right-handed W boson is several hundred GeV.

The second method is called the impact parameter method and is illustrated in Figure 16b. This method is useful when the unstable particle is accompanied by other particles which are produced at the primary vertex. In this method a particle such as a lepton known to come from the decay that one is interested in is projected back and the distance by which this track misses the known beam positron is used as a determinant of the particle lifetime. Jaros has summarized the measurements in a talk given earlier at this symposium[18] and while the errors on the measurement are still large the b lifetime seems to be larger than about 10^{-12} seconds. This is a very long lifetime for a particle as heavy as the b and the measurement has given very tight constraints on the weak couplings of all of the quarks and a lower bound on the top quark mass, if our present theory is correct, of around 30 GeV.

Work is continuing on the υ system at DESY and Cornell and on the ψ system at the SPEAR storage ring at SLAC. Large quantities of data are being accumulated and are being used to search for such exotica as glueballs (bound states of two gluons), charged conjugation even states produced in radiative decays, etc. One of the most interesting observations is that of the Mark III detector at SPEAR where a state that is very narrow with a mass of 2.2 GeV may have been found in radiated ψ decay. More data are needed to confirm this result.

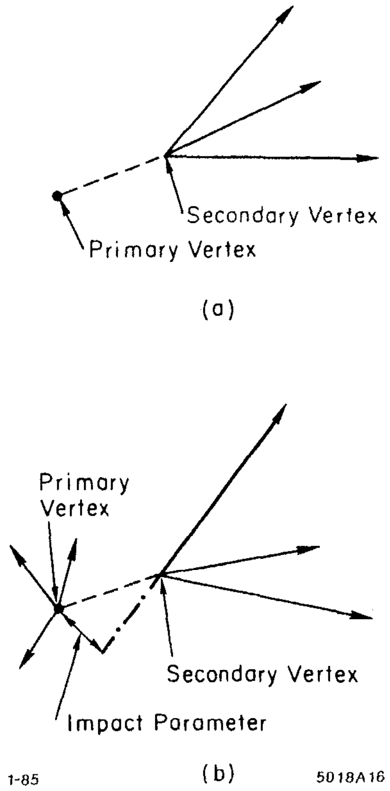

Figure 16: (a) A schematic of the secondary vertex reconstruction method of determining a lifetime. (b) A schematic of the impact parameter method of determining a lifetime.

There are many other interesting experiments that could be reported on, but time is short. I can summarize this period by observing that the results have been such as to pin down many of the important details of the theoretical models which we are currently using. It is an evolutionary period rather than a revolutionary one like the 1970s. That is not to say that there may still not be a revolution in the offing, for afterall, Ting's discovery of the J occurred on one of the oldest of the high energy physics accelerators.

THE NEAR FUTURE 1986 to 1996

Prognostication is a dangerous game, but I will play it anyway. I think that the decade from 1986 to 1996 will be a new era of discovery, for in that era we will have four new e^+e^- machines with which to experiment. TRISTAN at KEK will begin operation in 1986 with a maximum center-of-mass energy of 60 to 70 GeV. Also in 1986 the SLC will turn on with a maximum center-of-mass energy of 100 Gev. LEP I will begin operation in 1989 with a maximum center-of-mass energy of 120 GeV, and LEP II, the 200 GeV version of LEP I, will probably begin working in 1992. Using these tools we expect to be able to study the bound states of the top quark system, Z^0 decays, and to untangle some of the strange things that are hinted by current data from UA-1 and UA-2 at the CERN proton-antiproton collider. The electron-positron annihilation channel with its very low background, simple angular distribution and sharply defined center-of-mass energy will, I think, lead to simple and unambiguous understanding of any new phenomena that turn up in this energy range.

Let me first discuss the top quark system. Recently the UA-1 group at CERN has reported preliminary evidence[19] that the top quark may have a mass between 35 and 50 GeV, placing the mass of the "toponium" system at between 70 and 100 GeV. Thus, if this evidence turns out to be correct, toponium will be within the reach of the SLC and LEP, and if the mass is low enough, within the reach of TRISTAN as well. The top quark is much heavier than the others, and the binding of the t–$\bar{t}$ is much tighter than that of the other q–$\bar{q}$ systems. In theory, this looks like a much richer field than *b-onium,* for example, for there are many more bound states to study. However, the energy resolution of the machines is such that most of these states will be unresolvable. Figure 17 shows the expected level structure of toponium with the energy resolution of LEP superimposed on the figure (I choose LEP I for this example, for the very large radius of LEP gives it the best energy resolution in this region). One can see that it is unlikely that any more than the two lowest $^3S_1$ states will be resolvable. Thus, we will not see the wealth of detail that we have seen before, but we probably don't need to answer the most critical questions about the q–$\bar{q}$ potential. There are four popular q–$\bar{q}$ potentials that are now used to fit the charmed quark and bottom quark systems with equal success. However, these potentials differ markedly at small radii, and the large mass of the t–$\bar{t}$ system makes the small distance region relatively much more important than it is in either the c–$\bar{c}$ or b–$\bar{b}$ systems. A simple measurement of the spacing between the first two levels of toponium gives us the ability to distinguish between candidate potentials.

The richest field of experimentation will be the Z^0 region available to both the SLC and LEP. When these facilities run at their designed luminosity, there will be millions of Z^0 decays to study per experiment per running year. Such questions as the number of generations, the existence of light supersymmetric particles, the existence of light Higgs bosons, etc., can be studied with ease. The physics of Z^0 decays has been extensively discussed in a large number of meetings, and I will not go into it here. Suffice it to say that a large number of events, coupled with the availability of longitudinally polarized beams and apparatus capable of measuring lifetimes, will, we all believe, contribute enormously to understanding the structure of matter and the forces of nature.

During the latter part of this ten-year period LEP II will be available with energies of up to probably 200 GeV in the center-of-mass. The energy increase will be accomplished by replacing the conventional RF cavity of LEP with superconducting ones now under development. This higher energy region is where

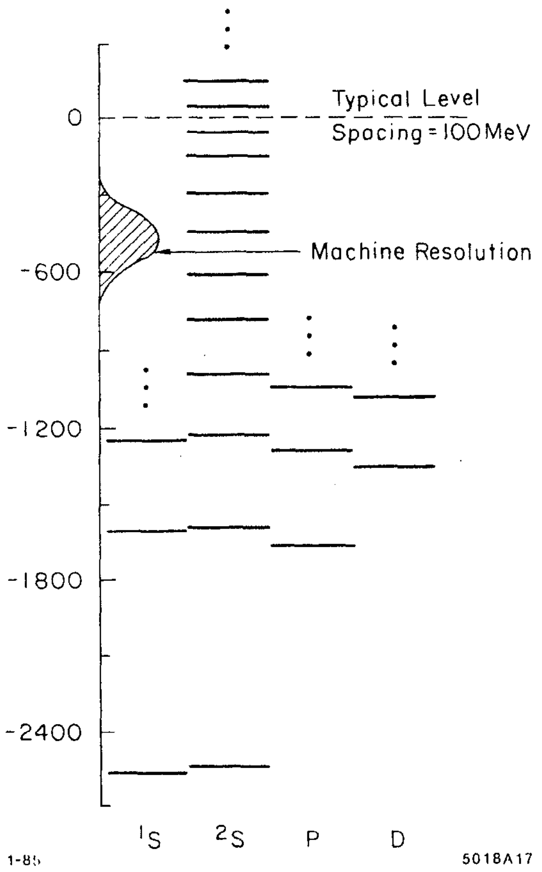

Figure 17: The expected level structure of toponium. The vertical scale gives the binding energy in MeV and the hatched curve shows the expected energy resolution of LEP at 80 GeV in the center-of-mass.

the UA-1 and UA-2 experiments on the CERN proton-antiproton collider hint that new things are occurring. At this symposium, the UA-1 collaboration has reported on their monojet events, and the UA-2 collaboration has reported on a small bump in the jet-jet mass distribution at around 150 GeV and on some unusual events containing leptons which also seem to have their origin at around 150 GeV. This energy range is easily accessible to LEP II, and I look forward eagerly to CERN getting there, for once again I think that the electron-positron annihilation technique with its low background and its well-designed center-of-mass energy, will allow us to sort out what is going on there.

THE FAR FUTURE: 1996 to 2001

The title of this section is something of a fraud. I doubt that anyone can predict what the specific physics questions will be twelve to seventeen years from now. I will use this instead as an excuse to make some general remarks and then end with an exhortation.

We have made remarkable progress in the last decade in understanding the structure of matter and the forces of nature. We have a picture of interactions between the elementary constituents, the quarks and the leptons, through three forces: an electro-weak force, a strong force, and gravity. We can calculate a lot more than we could ten years ago and that is a source of some satisfaction. Yet with our deeper understanding has come a proliferation of fundamental entities and a certain complexity that is the source of considerable dissatisfaction. Here are some of the things that bother me.

We seem to have at least thirty-seven fundamental entities in our system. There are eighteen quarks (six flavors times three colors), six leptons, eight gluons, three weak bosons, one photon, and one graviton. This seems a bit much.

The Weinberg-Salam model has given us what appears to be a unified picture of the weak and electromagnetic interactions. This model is the simplest possible scheme that allows such a unified picture, and it seems to work well. Its most recent triumph has been the discovery of W and Z at CERN as predicted. Yet, we don't understand the breaking of electro-weak symmetry and we have to invent a scalar interaction (Higgs) to explain it. We also need roughly twenty, apparently arbitrary constants (Cabibbo angles, for example) to cover all of the phenomenology.

In the strong interactions, we have QCD that allows us to make good calculation of high momentum transfer processes, but the low momentum transfer processes can't be handled by the perturbation techniques of QCD, and so are ignored by most of us. Our attitude is much like that toward the job of calculating the electronic energy levels of a heavy atom — the principles are known and the calculations are difficult so why bother? Maybe that's all it is, but maybe not.

The first attempt to unify the strong interactions with the electro-weak using the simplest scheme that can accommodate such a unification (SU-5) has been proved wrong by experiments on the proton lifetime that have set significant lower bounds on the decay rate of the proton to a positron plus π^0. It's too bad it failed, for grand unification is such an intriguing idea. Will it ever work?

Gravity is understood only in the classical limit. There is no satisfactory quantum gravity, and while the gravitation interaction is weak at present mass densities and accessible energies, it becomes comparable in strength to the other forces at very small distances or high energy densities. It must be dominant in the early universe if our picture of the Big Bang is correct, yet we can't do anything with it.

Many are trying to bring further simplification and deeper understanding to our present picture of the physical world through both theory and experiment. On the theoretical side, we hear about such things as guts, supergravity, technicolor, supersymmetry, horizontal gauge symmetries, compactified higher dimensional spaces, etc. The theoretical picture reminds me of the situation in the late 1960s and early 1970s when many theoretical models were contending with the then-known facts to give us a deeper insight into nature. That situation changed drastically with the discovery of the weak neutral currents and the November Revolution, and it is perhaps appropriate every decade or so to remind ourselves of the obvious — physics is an experimental science.

What is needed now is a new generation of experiments. In the coming decade we will have as new tools for experimentation SLC, LEP, HERA, and Tevatron I. Experiments with these accelerators may point us again in the right direction to make the next great advance in understanding our physical universe, but there is a general consensus that we will have to go higher in energy to make the mass region up to about 1 TeV accessible before the phenomena will become manifest that will clear up the present, murky theoretical situation. We will get there, but if the past is any guide, it is extremely unlikely that all our questions will be answered by experiments on that mass scale and what will be needed is new accelerators to allow us to go further.

A start has been made by a few of the people in high energy physics on new accelerator techniques that will allow the problems of 1996 to 2001 to be solved by experiments. The first linear collider will run in a couple of years. Technology is being developed to push conventional linacs to very high energy. Such exotica as wake-field accelerators, laser accelerators, free-electron laser power sources, plasma accelerators, etc. are being worked on by a handful of people.

I close with my exhortation. More people are needed to work on the advanced accelerators that will be required if we are to keep our science evolving towards its ultimate goal of an understanding of the physical universe. The problems of the accelerators are more difficult than the problems of doing experiments with the existing accelerators and we need some of our best minds to work on the new machines. This is a fitting note on which to close this lecture in honor of W. K. H. Panofsky, for he has always known that, and it would do well for the rest of us to keep it firmly in our minds as well.

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