IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

IMPACT OF STORAGE RINGS ON ELEMENTARY PARTICLE PHYSICS

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I. Introduction

It is well known that new experimental discoveries often closely follow the development of new technology. There is hardly a better example of this than the close coupling between new discoveries in the frontiers of elementary particle physics and the development of the art and science of making high-energy accelerators. It is almost twenty-five years since the construction of the Bevatron made possible the discovery of the antiproton; and, since that time our knowledge and understanding of particle physics has made enormous strides in step with new developments in both the accelerator and the detector arts. It is therefore with pleasure and gratitude that I, a particle physicist, attempt here to document how intimately many of the recent advances have been tied to your success in the development of storage rings and colliding beams.

The history of the development of storage rings is something you know much better than I. As far as I know, the earliest particle physics results from storage rings were tests of quantum electrodynamics obtained in 1965 by the Stanford-Princeton Collaboration on its 300 × 300 MeV e^-e^- storage ring. Hadron production in e^+e^- collisions became the topic of primary interest in electron-positron storage rings shortly thereafter and was investigated at medium energies by machines at Orsay and Novosibirsk and at higher energies by Adone, CEA, and then SPEAR and DORIS. The next generation of e^+e^- machines is just beginning to impact particle physics, the PETRA turn-on having occurred some months ago, and the turn-on's of PEP and CESR being due to occur later this year.

In parallel, the large proton-proton intersecting storage ring (ISR) at CERN opened its window onto ultra-high-energy hadron-hadron collisions in 1970 and has since continuously contributed to the understanding of particle physics. The next generations of hadronic-collision machines will be the "modest" $p\bar{p}$ colliding-beam facilities at CERN and Fermilab in the early 1980's, and the large storage ring ISABELLE at Brookhaven a little later.

The expected and perhaps unexpected achievements of the new machines, including those turning on now or in the very near future will be the subject of subsequent talks by Bjorken and Richter. I just want in this talk to describe a few physics breakthroughs made possible by storage ring operations over the last few years. My time does not permit anything like a complete survey, and I shall only be able to mention a few highlights. Since a complete list of references would have to be very lengthy and my space is limited, I shall give no references. I extend appropriate apologies to those groups whose work is quoted here.

II. Physics from the ISR

I start with pp colliding-beam results. The primary raison d'être of the pp storage ring is its ability to reach, with large luminosities, the highest possible energies for given cost (this advantage may eventually belong to the $p\bar{p}$ storage rings, but I am talking about present rather than future facilities). Such a machine can then be used to extend the study of known phenomena to the highest possible energies and to look for totally new things. Unfortunately no new thresholds have been observed at the ISR, but the detailed study of various aspects of hadron collisions at high energy has proved extremely interesting.

The early ISR work was primarily concerned with what is often referred to as "log s" physics (by convention $s \equiv$ total c.m. energy squared), because many of the gross properties of hadron interactions such as total cross section, multiplicities, etc. have logarithmic energy dependences. Only large energy jumps can have much impact when such slow variations are involved; indeed, at the time of initial turn-on, the ISR provided a c.m. energy increase by a factor of about 8 over the PS and AGS, enough to permit significant tests of ideas developed earlier and to observe substantial departures from some of these predictions. It is fair to say that as Fermilab came on, the energy advantage of the ISR for this kind of physics became reduced in view of such disadvantages as the inability to vary the initial state, the difficulty of detecting particles in the forward direction, etc. More recently the ISR emphasis has tended to be more what one might call quark and lepton physics for which the high energy still provides unique capabilities.

An early surprise from the ISR was the discovery of a rising pp total cross section at high energy. There had been hints, for example, a small rise in the K^+p cross section measured at Serpukhov and suggestive results from cosmic rays, but nevertheless the ISR result was a surprise. More recent work from Fermilab subsequently confirmed with impressive precision that total cross sections increase with energy for practically all hadron-hadron systems. The total cross section gives the imaginary part of the forward scattering amplitude. The real part has now also been measured both at Fermilab and for the highest energies at the ISR (a tour-de-force by the CERN-Rome Group, since the technique involves Coulomb interference at very small angles for which one has to place detectors perilously close to the full circulating beam). The results are shown in Fig. 1.

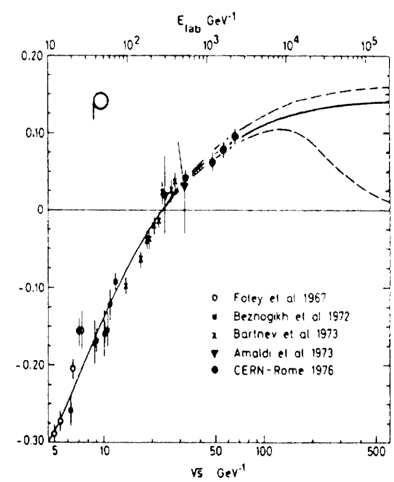

Fig. 1. Ratio of real to imaginary part of forward proton-proton scattering amplitude.

Fits to these data as well as the cross-section data coupled to dispersion-relation calculations provide the best indications about the behavior of the cross sections at even higher energies, and suggest that the rise continues up to very high energies.

I now want to mention briefly the study of general multiparticle processes which represent the bulk of inelastic interactions at high energy. If one considers an inelastic process creating particles of mass m, emitted with momentum P (longitudinal and transverse components P_L and P_T relative to the beam line), it is convenient to replace the variable P_L by the longitudinal

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rapidity y,

$$y \equiv \frac{1}{2} \log \left(\frac{E + P_L}{E - P_L}\right) ,$$

where E is the total energy of the particle. Under Lorentz transformations along the beam direction, y is just translated by a constant amount. Consider a Lorentz frame at rest with respect to one of the two incident protons in a pp collision. The behavior of the cross sections for creating given types of particles at a fixed value of P_T as functions of this rapidity y, from a compilation of various ISR experiments, is shown in Fig. 2. The data in this figure cover a large variety

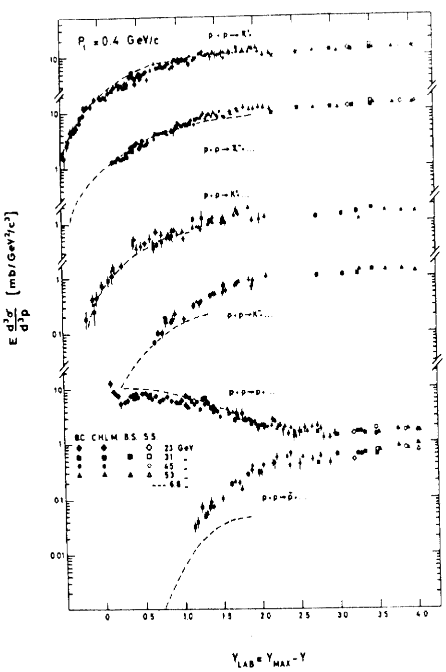

Fig. 2. Cross sections for pion, kaon and proton production versus laboratory rapidity.

of incident energies and exhibit some remarkable regularities:

1) The cross sections are roughly independent of total incident energy. This is in good accord with the ideas of scaling or limiting fragmentation put forward earlier by a number of theorists, but testable only with ISR energies.

2) For rapidities larger than about 2 units, the spectra become nearly flat (this is often called the central plateau). Note that the maximum rapidity range for fixed total c.m. energy $\sqrt{s}$ in GeV is about equal to log s and that, because of the pp symmetry, the distributions at any one energy are symmetric about the mid-value of rapidity. Figure 2 just extends over one half of the total rapidity range corresponding to the highest energy. The expectation is that at yet higher energies the only change would be an extension of the central plateau to the higher rapidities available.

The data in Fig. 2 represent behavior of a single outgoing particle, after integration over all other particles. Much work has also gone into the study of particle correlations. Figure 3 shows a contour map of the two-particle rapidity correlation function as measured by a Pisa-Stony Brook collaboration. Strong correlations are associated with close values of rapidity, and a correlation distance of about 2 units seems appropriate. These observations illustrate the importance of short-range correlations in rapidity, one of the major results of the early ISR work.

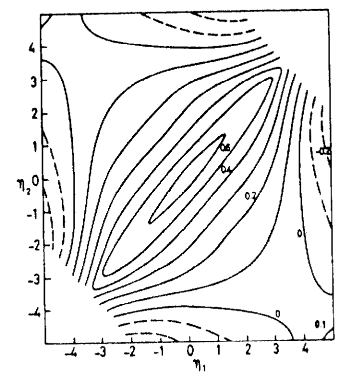

Fig. 3. Contours of constant two-particle correlation in the $\eta_1 - \eta_2$ plane at a total energy $\sqrt{s} = 62$ GeV. Here η is almost the same quantity as the rapidity y defined in the text.

The value of the ISR in such studies is clearly indicated in Fig. 2 by the extremely limited input that excellent PS data, shown by the dashed curves, could provide. The ISR doubled the rapidity range kinematically available. This was crucial because it made this total rapidity range large compared to the typical two-unit correlation distance in rapidity space implied by the data of Fig. 2 and Fig. 3.

I now move away from the "log s" processes to those which have been at the forefront of recent interest in the study of hadron collisions. They involve the study of various manifestations of the basic constituents of hadrons. Just as Rutherford studied massive point-like constituents of the atom (namely nuclei) by observing rare large-angle α-particle scatterings, one now looks for effects of point constituents in hadrons by studying those rare collisions in which particles are produced with high transverse momenta. Data from electron, muon and neutrino experiments (one place where fixed target accelerators are crucial) suggest that these constituents are quarks. I have listed in the Table the presently-known quark flavors. The protons in the ISR

Presently Observed Quark Flavors

Symbol	Charge	s	c	b
$u,\bar{u}$	± 2/3	0	0	0
$d,\bar{d}$	∓ 1/3	0	0	0
$s,\bar{s}$	∓ 1/3	∓ 1	0	0
$c,\bar{c}$	± 2/3	0	± 1	0
$b,\bar{b}$	∓ 1/3	0	0	∓ 1

Notes: (a) Baryon number is ± 1/3 for all quarks.
(b) Baryons are qqq (e.g., uud, udd, etc.) combinations. Mesons are $q\bar{q}$ (e.g., $u\bar{d}$, $d\bar{u}$, etc.) combinations.
(c) Each quark flavor comes in three colors.

circulating beam (or in our bones) each consist of two u and one d valence quarks carrying in total about half the proton momentum, a so-called "sea" of $q\bar{q}$ pairs of all varieties carrying very little momentum, and a collection of gluons which transmit the forces between quarks (just as photons transmit forces of electromagnetism) and carry the other half of the momentum. The assumed mechanism for the production of high-transverse-momentum particles is schematically shown in Fig. 4. If in one of the high-P_T jets (labeled (c) in the figure) most of the transverse momentum is concentrated in a

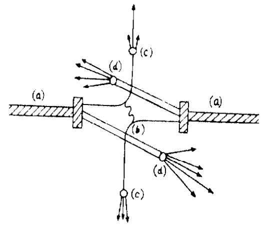

Fig. 4. Possible mechanism for high P_T particle production. (a) Incoming protons. (b) Large angle quark-quark scattering by gluon exchange. (c) Fragmentation of scattered quarks into hadrons. (d) Fragmentation of spectator quarks into hadrons.

single particle, the detection apparatus is triggered. The terminology "jet" in this context is intended to describe a group of hadrons of relatively high energy, with transverse momenta relative to the direction of the total momentum of order of a few hundred MeV/c. If the longitudinal momentum of each of the particles in the jet is much greater than this, they become highly correlated in direction, hence the name. The natural interpretation of such jets, if indeed one observes them, is that they arise from quarks or perhaps gluons which "dress" themselves into hadrons. Thus the study of events with high transverse momentum jets is in a real sense a study of the scattering of the basic constituents of hadrons. As mentioned above, the trigger for such events has usually been the presence of a single particle with high P_T.

Figure 5 shows the results of recent measurements

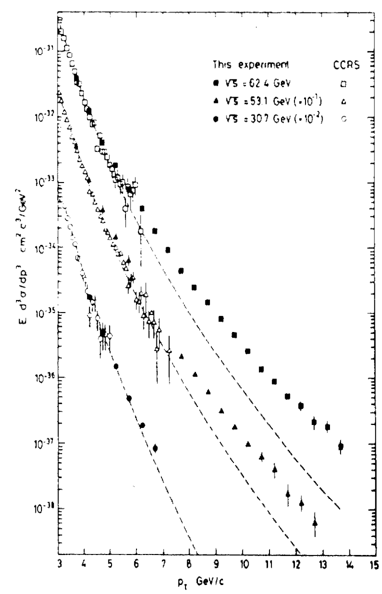

Fig. 5. Cross sections for the reaction $p+p \to \pi^0 +$ anything versus P_T. The cross-section scale corresponds to the data at $\sqrt{s} = 62$ GeV. For $\sqrt{s} = 53.1$ and 30.6, the data have been divided by factors of 10 and 100 respectively.

of the P_T distributions of neutral pions by the CERN-Columbia-Oxford-Rockefeller Collaboration. The following points are particularly noteworthy:

(a) The measurements extend to P_T of 14 GeV/c, a cross-section drop of about 12 orders of magnitude from the data shown in Fig. 2. This sort of sensitivity is made possible by the ingenuity and longevity of the experimenters, and the excellent luminosity of the ISR.

(b) The energy-scaling properties of data like those of Fig. 5 are of particular interest to theorists since they can be interpreted in terms of mechanisms of the type shown in Fig. 4.

If one had a 4π detector of perfect efficiency one would detect for each high-P_T trigger all four of the jets shown in Fig. 4. There are several problems with this: (i) typical detectors though complex and sophisticated do not cover the full solid angle; (ii) the jets have a sizable angular extent and their separation from each other at ISR energies cannot be completely clear. Considerable work in the last few years has concentrated on demonstrating the presence, in association with a high-P_T particle, of both of the high P_T jets labelled (c) in Fig. 4. Typical results are shown in Figs. 6 and 7 both

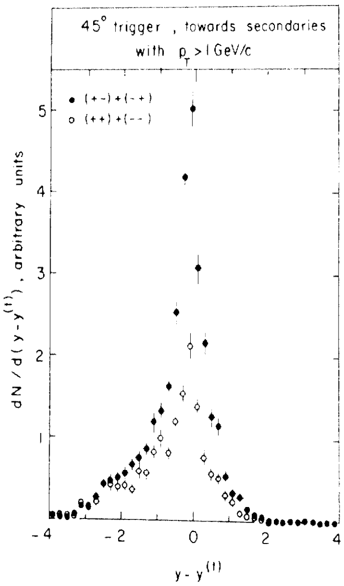

Fig. 6. Rapidity distribution of same-side secondaries (P_T > 1 GeV/c) relative to the trigger rapidity.

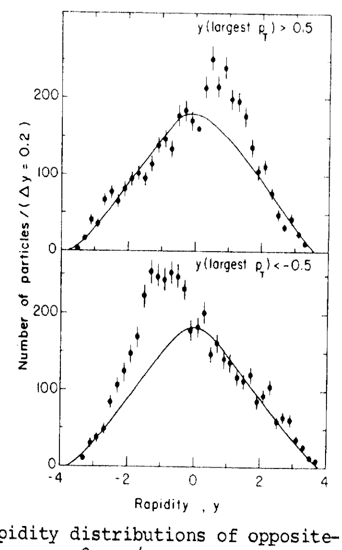

Fig. 7. Rapidity distributions of opposite-side secondaries with $P_T > 0.8$ GeV/c from events in which the opposite-side particle with highest P_T (the "pseudo trigger" which is not included in the figure) has $P_T > 1.0$ GeV/c: (a) The pseudo trigger has rapidity $y > 0.5$. (b) The pseudo trigger has rapidity $y < -0.5$.

from the work of the CERN-College de France-Heidelberg-Karlsruhe Collaboration. Figure 6 shows the strong rapidity correlations between the triggering particle and other particles in the same region of azimuth. Figure 7 shows correlations on the opposite-side between the highest P_T particle and others. Considerable quantitative experimental work has now been done which supports the pictorial indications of jet structure seen in Figs. 6 and 7. More recently, the spectator jets (see

Fig. 4) have also been observed and studied. In general the results support the picture implied by Fig. 4. I have no time here to go into further detail, but I should note that both the ISR and Fermilab are now strongly contributing to this area although, judging from the rapporteur's report of last summer's High Energy Conference, most of the data still seem to be from the ISR. I should mention that another area of quark physics, namely the production of lepton pairs (presumably through $q\bar{q}$ annihilation) has prominently figured in the ISR program, but I simply have no time to discuss it here.

In assessing the impact of the ISR as seen now, one has to say that in practically all of the areas to which it has contributed, Fermilab has also provided important, although in many cases complementary, inputs. When the ISR first turned on, Fermilab was still in construction and its energy jump was a major one which gave it a unique position for the first few years. Subsequent to the Fermilab turn-on, the ISR's limited energy advantage in the log s physics was somewhat balanced by a Fermilab advantage of greater flexibility in the initial state. However the energy advantage of even a factor of two (in the c.m.) coupled with powerful and flexible detectors has enabled it to keep contributing an important share of the high P_T and dilepton physics.

III. Electron-Positron Physics

In his remarks to a similar conference a few years ago, Professor Leon Lederman talked about the relative advantages of storage rings and fixed-target accelerators. The storage rings in question at that time were pp rings and there was hardly mention of e^+e^-. This was in the summer of 1974, and the physics revolution in which e^+e^- collisions were to play so important a role came just a few months later. In my discussion today I can easily confine myself to vast areas in which total experimental ignorance has been transformed to detailed quantitative understanding solely with data from e^+e^- storage rings which would have been unobtainable in any other known way.

The reason for this remarkable situation has to do with the dominant e^+e^- annihilation mechanism, schematically represented in Fig. 8. The electron-positron

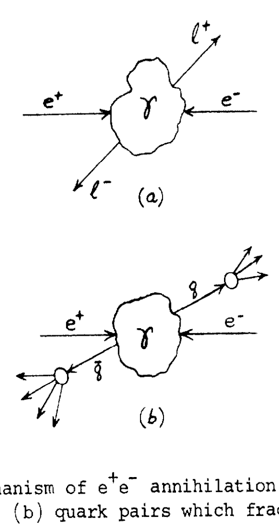

Fig. 8. Mechanism of e^+e^- annihilation to produce (a) lepton pairs, (b) quark pairs which fragment to hadrons.

system transforms into a massive photon; i.e., an object which has all the properties of the usual photon, except for the fact that it is at rest and has a mass equal to twice the beam energy. This photon almost immediately transforms into the final-state particles. The beauty of this process is that nature's basic objects, the quarks and leptons, are all charged particles; and, as such, are coupled in a well-known way to the electromagnetic field and hence to the photon. Thus the storage ring, by giving the experimenter an intense source of virtual photons of precisely controllable mass, provides the ability to manufacture at will quark-antiquark ($q\bar{q}$) or lepton-antilepton pairs of whatever mass nature has provided up to nearly the maximum available energy of each beam. Indeed one can even make $q\bar{q}$ bound states with the quantum numbers of the photon by operating at the appropriate total c.m. energy, and study the properties of such bound states with a degree of detail unavailable with any other technique.

Although e^+e^- work at Orsay and Frascati had already provided useful inputs on $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ bound states which complemented what was principally bubble chamber spectroscopy work, the technique really came into its own in the fall of 1974 with the electromagnetic production of the charmed quarks c and $\bar{c}$. While the lowest-lying spin-one bound state of $c\bar{c}$, the J/ψ, was first seen in the MIT-BNL experiment at BNL and independently observed by the SLAC-LBL collaboration at SPEAR, its properties as well as those of its higher mass ψ' brother, namely mass, width, spin, parity, isotopic spin, and many decay-mode branching ratios came entirely out of SPEAR, DORIS and ADONE experiments.

The extraordinarily narrow widths of the J/ψ and ψ' are explained by the fact that their masses are too low to permit the normal decay modes into the lowest-lying charmed mesons. At masses just above that of the ψ', such decays become possible and the typical widths become the tens or hundreds of MeV usual for hadronic resonances. The spectrum of $c\bar{c}$ states with the same quantum numbers as those of the photon (i.e., producible via the process of Fig. 8) has been studied by measurement of the annihilation cross section. Results at energies above the mass of the ψ' from four laboratories are shown in Fig. 9.

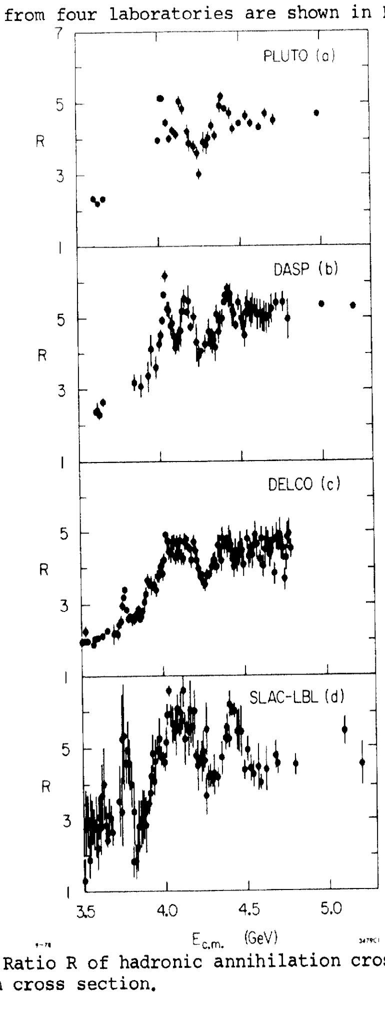

Fig. 9. Ratio R of hadronic annihilation cross section to dimuon cross section.

The quantity R plotted in the figure is actually the ratio of hadronic annihilation cross section to muon pair cross section. The considerable structure shown in the figure will have to be understood in terms of a theory of $q\bar{q}$ forces. There are differences between the results of the various experiments; these reflect the systematic uncertainties connected with trigger and other biases and represent one of the major problems of particle physics at storage rings.

Going to higher energies, the lowest-lying $b\bar{b}$ bound states, the Υ and Υ', which were discovered in a beautiful experiment by the Columbia-Fermilab-Stony Brook group at Fermilab, have now been seen with more than an order of magnitude resolution improvement at DORIS (see Fig. 10) and it is clear that further information will

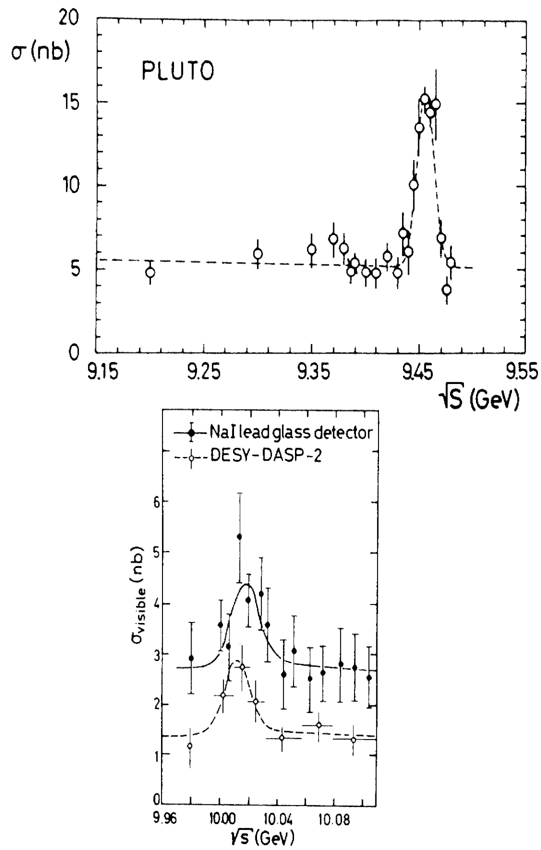

Fig. 10. Annihilation cross section in the neighborhood of the Υ and Υ' as measured at DORIS.

have to come from e^+e^- experiments.

While those $q\bar{q}$ bound states whose quantum numbers are the same as those of the photon manifest themselves directly as annihilation cross-section resonances, others with different quantum numbers can be detected through secondary decays. Thus, if we denote such $c\bar{c}$ states by the symbol X, typical processes in which the X's have been detected are the following,

$\psi' \to X + \gamma$

$\quad \vert\!\to \gamma\psi$

$\quad\quad \vert\!\to e^+e^-,\ \mu^+\mu^-$

$\quad \vert\!\to$ hadrons .

With substantial runs at the ψ' energy, one can discover and study the properties of such X states. The spectroscopy of $c\bar{c}$ states below the ψ' (i.e., states of narrow width) is shown in Fig. 11. It can be noted that while J/ψ, ψ', Υ, Υ' can be straightforwardly detected in fixed-target experiments because of their prominent decay modes into lepton pairs (for which there is relatively little background), the X's which decay in more complicated ways are extremely difficult to detect in such experiments in the midst of a prodigious general hadron background.

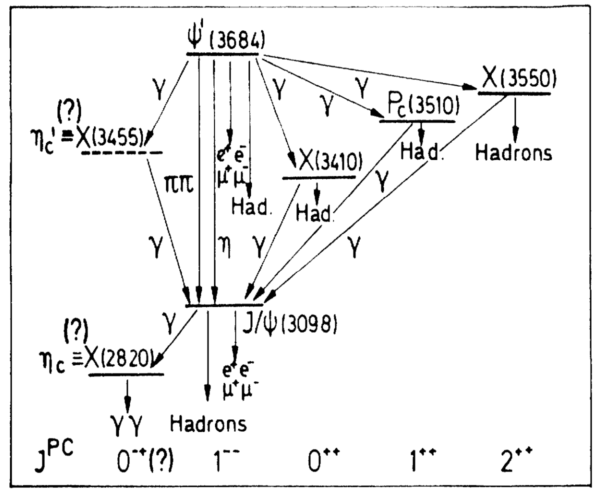

Fig. 11. Charmonium ($c\bar{c}$) level diagram as of October 1977.

The next remarkable feature of the production of new heavy quarks arises from the fact that they can decay to lighter quarks only in a very slow weak interaction. Thus the lightest bound states of a c with lighter quarks (such as u, d, s or $\bar{u}$, $\bar{d}$, $\bar{s}$) must be nearly stable. It was indeed this feature applied to s quarks which led to their discovery (or more precisely to the discovery of the strangeness quantum number which they carry) just about 30 years ago. The bound states of c with $\bar{u}$ or $\bar{d}$ quarks are called D^0 and D^+ mesons, and they are produced fairly copiously in the structured region above the ψ' in Fig. 9. Indeed the peak at 3770 MeV seen in the DELCO and SLAC-LBL data arises from a $c\bar{c}$ state which decays almost exclusively to $D^0\bar{D}^0$ or D^+D^- pairs. The D's decay further into hadrons and manifest themselves as effective mass peaks as seen in Fig. 12, taken from the work of the Lead Glass Wall Collaboration at SPEAR. The present state of knowledge of these D

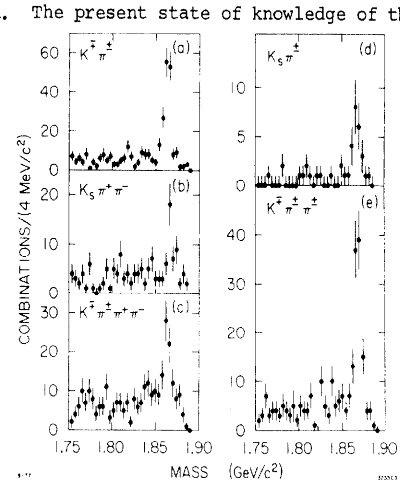

Fig. 12. D^0 and D^+ signals in various effective-mass plots.

mesons gleaned almost entirely from SPEAR data includes their masses, lowest excited states D^*, spins, the demonstration of the weak nature of their decay and of the fact that they cannot be manifestations of normal hadronic resonances. DORIS experiments have also found clear evidence for the existence of bound states of c with $\bar{s}$ quarks (the F mesons).

It is fair to note that charmed particles have also been observed in fixed-target neutrino and photoproduction experiments. However, in my opinion, those data which demonstrated the existence of particles carrying nonzero values of the quantum number charm in a manner so conclusive as to allow no credible alternative interpretation were those obtained at SPEAR in the last few years.

As I said earlier the strength of the e^+e^- storage ring is its ability to make quark-antiquark and lepton-antilepton pairs, but so far I have only talked about the quarks. The leptons which have long been known are the electron and muon with their associated neutrinos. The existence of two objects like the electron and muon with just the same interactions and differing in all their properties only in consequence of their mass difference has long been an outstanding puzzle. A natural question is whether yet heavier objects in this sequence exist. Such objects are much more difficult to detect since their lifetime is expected to be short ($\lesssim 10^{-12}$ sec); and, unlike muons, they will be too massive to be the decay products of other common long-lived objects. The process of Fig. 8 solves this difficulty of production provided that the lepton mass be substantially lower than the maximum beam energy. The problem of detection has been solved through use of the fact that such a lepton would decay copiously into both $e\nu\bar{\nu}$ and $\mu\nu\bar{\nu}$ final states. The simultaneous detection of a high energy electron and an oppositely-charged muon with no detectable associated particles is then a good signature, remarkably free of most backgrounds. Indeed a signal of a few such $e^{\pm}\mu^{\mp}$ events was detected at SPEAR about four years ago. There is no time to tell the whole story, but further experiments at DORIS and at SPEAR confirmed the original indications, and there is now extremely compelling evidence for the $\tau^{\pm}$, a new charged lepton with its own associated neutrino, of mass 1.78 GeV/c^2, differing from its lighter brothers only through the kinematical consequences of its higher mass. Because the τ decays largely into final states with only one charged particle, the process $e^+e^- \to e^{\pm}$ + one charged particle (not electron) is a copious source of τ's. Figure 13 shows the cross section for

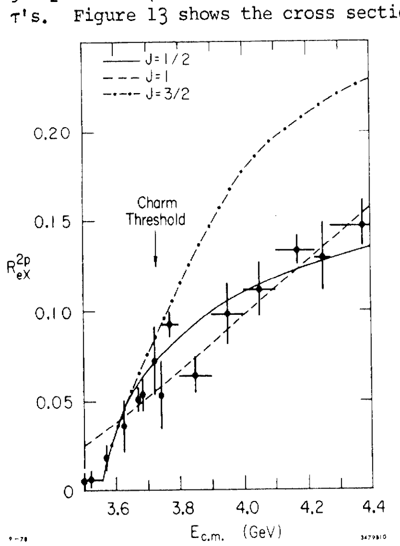

Fig. 13. Cross section for the process $e^+e^- \to e^{\pm}$ + anything except $e^{\mp}$.

this process (relative to $e^+e^- \to \mu^+\mu^-$), as measured by the detector DELCO at SPEAR. This figure beautifully shows the production near threshold of this new lepton. From these data come a very precise mass measurement and clear demonstration that the spin of the object is 1/2 as expected. There are many other data to demonstrate that indeed the particle whose threshold is exhibited in Fig. 13 has all the attributes expected for a heavy muon.

To finish my brief discussion of e^+e^- results, I come back to the process we started with, namely $e^+e^- \to \gamma \to q\bar{q}$ and note that as shown in Fig. 8 the quarks dress themselves as hadrons (just as in our discussion of high P_T at the ISR). At high enough energy, the hadrons will come off as two opposite jets of highly correlated particles. There are predictions for the cross section and angular distributions of the quark pairs which should be reflected in the hadrons. Suffice it to say here that these predictions are borne out by experiment and that further one can relate the dressing of the quarks in this process to that which takes place in high P_T hadron reactions. Thus a self-consistent picture which interrelates many different phenomena in terms of the behavior of basic constituents is emerging.

It is not uncommon to hear particle physicists refer to the "November Revolution," alluding thereby to the discovery of the J/ψ at BNL and SPEAR in November 1974. What in large measure however made these discoveries the threshold of a new period of rapid progress was the incredible productivity of the storage rings SPEAR and DORIS and the flexible detectors in their interaction regions.

IV. Concluding Remarks

I want to conclude with a few general comments about the impact of storage rings on physicists and the way they do physics. Before I do so however, let me emphasize that in spite of my enthusiasm for storage rings, I have to admit that much crucial physics can only be done with fixed targets. Hadron collision experiments with pions or kaons permit interesting changes in the quark content of the initial state. Neutrino beam experiments are our major way of exploring weak interactions. Furthermore many kinds of experiments may be more easily done in the rest frame of one of the colliding objects than in the center of mass. I have every reason to believe that the Tevatron will be an immensely valuable tool.

I now come back to the interaction of physicists and storage rings, and make a few points specific to doing physics at storage rings:

(1) Detectors are very complex and costly, and tend to be built to perform simultaneously many different types of measurements rather than be focused on a single narrow objective. The factors pushing in this direction involve the optimizing of data rates, the maximizing of solid angle to study correlation effects, and, in general, the desire to learn as much about each event as possible.

(2) There is very intimate coupling between the apparatus and the storage ring, and also closer coupling of the various experimenters to each other than is common in a fixed-target machine. This means greater demands on the reliability of the equipment, and more rigorous adherence to schedules. The fact that all experiments run at the same energy again pushes towards building detectors of great flexibility which can dig out useful physics for almost any set of running conditions (as long as there is beam). Furthermore there has to be close interplay between experimenters and the physicists and engineers running and developing the machine.

(3) The sociology of physics groups changes. Experiments in storage rings are mostly done by large groups and require very large commitments in terms of equipment, people and time. Collaborations are usually large, and there often tends to be specialization with different components of a complex instrument being the responsibilities of well-defined subgroups of the collaboration. Thus there can be few experiments simultaneously set up, but each employs a vast group of scientists. The team approach to doing physics research reaches one of its most extreme manifestations.

These characteristics, good or bad, are almost unavoidable. The payoff is the most exciting adventure in research that I can imagine having.

This work is supported in part by the U. S. Department of Energy.