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THE FIRST YEAR OF MARK-J:

Physics With High Energy Electron- Positron Colliding Beams

MASTER

by the Mark-J Collaboration

(the AACHEN, DESY, M.I.T. NIKHEF, PEKING Collaboration)

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Abstract

This report reviews the experimental investigation of high energy e^+e^- interactions by the MARK J collaboration at PETRA, the electron-positron colliding beam accelerator at DESY in Hamburg, West Germany. The physics objectives include studies of several purely electromagnetic processes and hadronic final states, which further our knowledge of the nature of the fundamental constituents and of their strong, electromagnetic and weak interactions. Before discussing the physics results, the main features and the principal components of the MARK J detector are discussed in terms of design, function, and performance. Several aspects of the online data collection and the offline analysis are also outlined. Results are presented on tests of quantum electrodynamics using $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$, on the measurement of R , the ratio of the hadronic to the point-like muon pair cross section, on the search for new quark flavors, on the discovery of three jet events arising from the radiation of hard noncollinear gluons as predicted by quantum chromodynamics, and on the determination of the strong coupling constant α_s .

1) INTRODUCTION

This article reviews the experimental program of the MARK J collaboration using PETRA at DESY in Hamburg, West Germany. PETRA is the world's highest energy electron-positron colliding beam storage ring now in operation. There have been four groups (JADE, MARK-J, PLUTO and TASSO) using PETRA since 1979. Their results are supportive and complementary to each other.

Electron-positron collisions provide a particularly clean way to study the nature of the fundamental constituents of matter and their interactions because of the point-like nature of leptons. Experiments at PETRA are thus free of the complications that arise in studies of hadron-hadron or lepton-hadron collisions, where the hadrons themselves have a complex internal structure which must be understood in detail before new information on the large q^2 interactions of the constituents can be extracted.

The MARK J detector was proposed during the spring of 1976. The detector employs calorimetry to measure hadronic and electromagnetic energy flow. Large-area arrays of drift chambers together with the large magnetized iron toroids which form the main body of the detector distinguish hadrons from muons and determine the muon momenta. A compact inner detector is used to measure the vertex and the directions of charged tracks. The major components of the detector are constructed using simple technology, so that the apparatus has operated with negligible down-time.

The relative simplicity of the detector made possible the installation of the major part of the detector, as well as the associated electronics and data acquisition hardware, over a period of only six months from May-October 1978. The MARK J was thus ready for data-taking at the start of physics runs at PETRA in October, 1978 and its first

preliminary physics results were presented at DESY by the end of 1978.

PETRA has run with beam energies ranging from 6 to 16 GeV, and the MARK J has collected more than 90% of the time-integrated luminosity made available during physics runs, a total of 3.5 pb^{-1} . The high degree of operating efficiency is due to the relative insensitivity of the inner shower counter and calorimeter elements to synchrotron radiation and other low energy background. This has led to a low trigger rate, and minimal dead time during data taking.

The general features of the PETRA machine and its performance are given in Section 2. The MARK J experiment is discussed in Sections 3.1-3.3, starting with an overall view of the goals of the physics program in Section 3.1. The principal components of the detector are introduced in Section 3.2, where the design and function of the particle detectors, luminosity monitor, fast-electronics and microprocessor-based triggers, and the online data acquisition and monitoring systems are discussed. Section 3.3 deals with aspects of the offline analysis: the algorithms used to measure energy flow in the detector, the data reduction and event selection procedures for each of several e^+e^- final states, the computer simulation of a variety of e^+e^- reactions both as they are produced and as they appear in the MARK J detector, and the methods used to compute the luminosity. Sections 4.1-4.3 review the MARK J physics results. Tests of quantum electrodynamics (QED) and of the universality of the charged leptons are presented in Section 4.1. The hadronic event selection criteria, the measurement of R , the ratio of the cross section for hadron production to the cross section for point-like muon pair production, and the use of the R measurement to search for new quark flavors are discussed in Section 4.2. Section 4.3 focuses on jet analysis: the interpretation of the topo-

logical features of the events in terms of jets of particles which are formed by the fragmentation of quarks and gluons in the framework of QCD... Several methods of characterizing the overall event shape are described, and the methods are applied to sensitive searches for the top quark contribution to the hadronic continuum. The detailed analysis of the event topology which led to the discovery by the MARK J of three jet events arising from the radiation of hard non-collinear gluons, and the determination of the strong coupling constant α_s , are also discussed.

Section 5 closes the report with a summary of the physics conclusions.

2) EXPERIENCE AT PETRA

PETRA [1] (Positron Elektron Tandem Ringbeschleuniger Anlage) began operation in the fall of 1978 as the world's highest energy e^+e^- colliding beam machine. Since its commissioning, PETRA beams have been available for physics runs 60% of the time, with the remaining time being devoted to machine development and maintenance periods [2].

The ring, with a circumference of 2.3 kilometers, has eight long straight sections of which two are reserved for the RF accelerating cavities. At present only four of the experimental areas are occupied. The remaining two experimental areas are reserved for second generation experiments.

FIGURE 1.

The layout of PETRA e^+e^- Storage Ring at DESY.

The original injection scheme utilized both of the existing DESY facilities, DESY and DORIS. Electrons, initially accelerated in LINAC I (see Fig. 1) are injected into DESY (Deutsches Elektronen Synchrotron) where they are further accelerated to 6 GeV and injected into PETRA. Positrons follow a somewhat more complicated path: after initial acceleration in LINAC II, positrons are injected via DESY into DORIS (Doppel-Ring-Speicher), where they are accumulated at an energy of 2.2 GeV. Stored positron bunches in DORIS are then transferred back to DESY for further acceleration to 6 GeV, the minimum PETRA injection energy.

With the discovery of the upsilon (Υ) resonance in 1977 at FNAL [3] and the confirmation in e^+e^- interactions [4], the need to operate DORIS as a storage ring independent of PETRA was realized. Consequently, in the fall of 1977 the decision was made to construct a Positron Intensity Accumulator (PIA) [5] to free DORIS for physics runs. In this new injection scheme, positrons are accumulated in PIA after acceleration in LINAC II. Twenty successive LINAC bunches are injected into PIA, compressed in phase space, and transferred to DESY for acceleration and injection into PETRA. PIA was assembled in record time and since the summer of 1979 has served as the injector for both DORIS and PETRA.

The average luminosity is $2 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$ at beam energies of 15 GeV. It is expected that the luminosity will increase in the near future with more operational experience.

In the first year of operation, PETRA has run from an energy of 12 GeV to 31.6 GeV. It has run reliably with very little failures. The stability of the machine was the major reason why all groups at PETRA have been able to perform their experiments satisfactorily.

3) THE MARK J EXPERIMENT

3.1 Physics Objectives

The MARK J detector [6], which identifies and measures the energy and direction of muons, electrons, charged and neutral hadrons with close to uniform efficiency and with $\sim 4\pi$ acceptance, is capable of fulfilling a broad range of physics objectives. Some of the prime physics goals of the experiment are:

1) To study the various QED processes shown in Fig. 2 and to study the universality of the known charged leptons in their electromagnetic interactions. At PETRA the available c.m. energy is $\sqrt{s} = 32 \text{ GeV}$ (q^2 up to 1000 GeV^2). Since first order QED processes exhibit a $1/s$ cross section dependence the MARK J can probe the validity of QED with an order of magnitude greater sensitivity than that previously available in earlier colliding beam experiments performed at storage rings at SLAC, DESY, ADONE and CEA in the range of $q^2 \lesssim 50 \text{ GeV}^2$.

FIGURE 2.

Electron, muon and tau pair production in lowest order.

2) To search for new quark flavors by studying the energy and angular distributions of inclusive muon production in hadronic events (Figure 3 a).

3) Using the distributions of μe and μh final states shown in Fig. 3b to search for the existence of new charged leptons heavier than the tau.

FIGURE 3.

- a. Diagram for production and decay of heavy quarks in e^+e^- annihilation.
 b. Diagram for production and decay of heavy leptons in e^+e^- annihilation.

4) To measure the total hadronic cross section (Fig. 4) and thereby the structure and energy dependence of the total cross section, in order to search for new thresholds in the hadronic final state continuum, and to search directly for more J-like particles which appear as sharp resonances.

FIGURE 4.

The reaction $e^+e^- \rightarrow \text{hadrons}$ in lowest order.

5) To study the topology of hadronic events by measuring the direction and energy of charged and neutral particles. In particular, at PETRA energies, the fragmentation of hard gluons emitted in association with quark-antiquark pairs leads to the creation of additional gluons and quarks, resulting in the production of multi-jet events. Study of the properties of these jets enables us to make a direct comparison with the predictions of QCD [7]. The rate of 3-jet events relative to 2-jet events enables us to measure directly the strong interaction coupling constant α_s .

6) To measure the charge asymmetry expected from the interference of weak and electromagnetic interactions in the production of $\mu^+\mu^-$ pairs. As shown in Fig. 5, diagrams in which a virtual photon is exchanged or in which a Z^0 vector boson is exchanged both contribute to $\mu^+\mu^-$ production.

FIGURE 5.

First order electromagnetic and weak processes contributing to the reaction $e^+e^- \rightarrow \mu^+\mu^-$

The interference can be understood in terms of a variety of models based on the weak interaction Lagrangian

$$L_{\text{int}} = i\bar{\mu}\gamma^\tau (g_V - g_A \gamma^5) \mu Z_\tau.$$

In the simple V-A model for example, one assumes $g_V = g_A = g$, where $g^2/M_Z^2 = G/\sqrt{2}$, and where G is the Fermi coupling constant. In the now standard Glashow-Weinberg-Salam (GWS) model the couplings are expressed in terms of the single parameter θ_W , the Weinberg angle:

$$g_V = 1/4 g \cos \theta_W (3 \tan^2 \theta_W - 1), \text{ and } g_A = 1/4 g \sec \theta_W.$$

In order to distinguish between theoretical hypotheses, we can use the forward-backward charge asymmetry $A \equiv \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+}$, where σ_- (σ_+) corresponds to the μ^- (μ^+) appearing in the forward hemisphere. At $\sqrt{s} = 30$ GeV, with a total time-integrated luminosity of 10^{38} cm^{-2} , one obtains $\sim 10^4$ events in a 4π detector, leading to a 10 standard deviation asymmetry effect in the V-A model and a 5 standard deviation effect in the GWS model [6].

Because the expected asymmetry is small and because higher order QED processes also produce sizable charge asymmetry at small angles, the measurement of asymmetry requires attention in reducing and understanding systematic errors in the detector design.

One notes that before the direct observation of the Z^0 , the precise determination of the charge asymmetry arising from weak-electromagnetic interference is the most important verification of the idea of the unified electromagnetic and weak theory.

3.2 The Detector

a) Overview

The MARK J detector is shown in Figs. 6-10. It is designed to distinguish charged hadrons, electrons, muons, neutral hadrons and photons and to measure their directions and energies. It covers a solid angle of $\phi = 2\pi$ and $\theta = 12^\circ$ to 168° (θ is the polar and ϕ is the azimuthal angle). The detector, which consists of five magnetized iron toroids built around a non-magnetic inner detector complemented by end caps, was designed to be insensitive to the effects of synchrotron radiation. Particles leaving the interaction region first pass through a five millimeter thick aluminium beam pipe, with an outer diameter of 190 mm. The aperture of the beam pipe is large enough so that the synchrotron radiation produced in the final PETRA bending magnets and quadrupoles will pass unobstructed through the entire detector. Two thick copper absorbers are located symmetrically around the interaction region, at a distance of 1 meter, to trap synchrotron radiation reflected back towards the interaction region by collimators just in front of the last PETRA quadrupoles.

FIGURE 6.
The MARK J detector in a side view.

MARK J - DETECTOR

(Cross Section)

- (A) (B) (C) SHOWER COUNTERS
- (D) TRIGGER COUNTERS
- (DT) DRIFT TUBES
- (Q) DRIFT CHAMBERS, MEDIAN
- (P) (R) DRIFT CHAMBERS, OUTER
- (S) (T) DRIFT CHAMBERS, INNER

- (1) BEAM PIPE
- (2) MAGNET IRON
- (3) AL - RING
- (4) MULTIPLIERS

WEIGHT (total) : ~ 400t
MAGNETIC FIELD: 1.8 T

PARTICIPANTS:

RWTH - Aachen
DESY - Hamburg
MIT - Cambridge
NIKHEF - Amsterdam
HEPI - Peking

FIGURE 7.

The MARK J detector in end view. Beam pipe (1), drift tubes (DT), shower counters (A,B,C), inner drift chambers (S,T), calorimeter counters (K), outer drift chambers (Q,P,R), and magnetized iron (2).

FIGURE 8.

The MARK J detector showing the outer drift chambers.

FIGURE 9.

Aerial view of the MARK J showing movable cable supports.

FIGURE 10.

End view of the MARK J showing the inner chamber and calorimeter.

The detector layer structure is best understood by referring to Fig. 11.

FIGURE 11.

The layer structure of the MARK J detector as seen by a particle emerging from the interaction point at a right angle to the beam axis.

During the first nine months of operation, a ring of 2 x 16 lucite Cerenkov counters each covering an azimuthal sector of 22.5° and a polar-angle region from $9^\circ < \theta < 171^\circ$ surrounded the beam pipe. These counters are divided at $\theta = 90^\circ$ to permit a crude determination of the momentum balance between the forward and backward hemispheres. The counters are insensitive to the effects of synchrotron radiation and can be used to separate charged from neutral particles.

In the latter part of 1979 the lucite counters were replaced by a four-layer inner track detector composed of 992 drift tubes. Each tube is 300 mm long and 10 mm wide and has a spatial resolution of 300 microns. The tubes, which are arranged perpendicular to the beam line, distinguish charged from neutral particles in the angular range $30^\circ < \theta < 150^\circ$ and reconstruct the position of the event vertex along the beam line to an accuracy of two millimeters. The distribution of event vertices obtained using the drift tubes is shown in Fig. 12. The observed r.m.s. width of 1.27 cm is compatible with that expected from the known bunch length of the machine.

Particles then pass through 18 radiation lengths of shower counters used to identify and measure the energy of electrons, photons, charged and neutral hadrons. This inner calorimeter is divided into three layers of shower counters (labelled A, B and C in Fig. 6). Each counter is constructed of 5.0 mm thick pieces of scintillator alternated with lead plates of equal thickness. The A and B counters are each 3 radiation lengths thick, while the C shower counter is a total of 12 radiation lengths thick (measured normal to the surface of the counter).

The twenty A shower counters are each 2 m long and cover the angular region of $\theta = 12^\circ$ to 168° . The 24 B counters are constructed identically to the A counters and cover an angular region from $\theta = 16^\circ$ to 164° .

FIGURE 12.

Distribution of event vertices along the beam direction
reconstructed using drift tube tracks.

Since every shower counter is viewed by one phototube at each end, the longitudinal (z) position of particle trajectories can be determined by comparing the relative pulse heights from each end of the counter. Timing information provides another measure of the longitudinal position. The trajectory location determined by this method was found to be in excellent agreement with the data from the drift tubes (see Section 3.3a).

Twelve planes of drift chambers (labelled S and T) measure the angles of particles penetrating the inner electromagnetic calorimeter. Each of the sense wires is connected to its own amplifier and time digitizer. Both

end cap regions are covered by an additional ten planes of drift chambers (labelled U and V) of similar construction. These chambers are protected from beam backgrounds from the interaction region by the shower counters A, B and C. The energy sampling elements of the calorimeter K, shown in Fig. 6, are 192 scintillation counters arranged in four layers. The main body of the calorimeter is composed of the magnetized iron plates which are also used to momentum-analyze muons. These plates range in thickness from 2.5 to 15 cm. Hadrons penetrating the inner shower counter layers, and secondary particles produced by hadronic showers initiated in the inner layers, deposit most of their remaining energy in the calorimeter K. The energy sampled by the K counters is thus used to help distinguish hadrons from electrons, and to help identify minimum-ionizing particles.

Muons are identified by their ability to penetrate the iron of the hadron calorimeter. The low-momentum cut-off is about 1.3 GeV/c at normal incidence. The initial muon trajectory is measured in the S and T (U and V) chambers and in the drift tubes.

The bend angle and position of muons exiting from the calorimeter are measured in 10 planes of drift chambers, labelled R and P in Fig. 6. The total thickness of the iron is 87 cm and it has a bending power of approximately 17 kG-meters. The typical bend angle for a 15 GeV muon is 30 mrad.

An additional 2 layers of drift chambers (Q chambers) are situated amidst the iron layers to measure the muon tracks in the bending plane. Adjacent to these chambers are the 32 muon trigger counters marked (D) used to trigger on single and multiple muon events and to reject cosmic rays. Each of these counters is 30 cm wide and 450 cm long and has a phototube at each end. The timing difference between real dimuon events and cosmic rays is about 10 ns. These counters have a timing resolution of 400 ps.

Covering each of the end cap regions are the E counter hodoscopes. Each of these counters has dimensions 80 cm x 450 cm x 1 cm and they are used to trigger on muons produced in the forward and backward directions as well as to reject cosmic rays and beam-gas background.

One of the prime goals of the MARK J experimental program (see section 3.1) is to measure the charge asymmetry in the angular distribution of muon pairs produced in e^+e^- annihilation to an accuracy of $\sim 1\%$. This goal can only be achieved if small systematic effects due to variations in chamber efficiency and counter gains, and slight asymmetries in the construction of the magnet and the positions of particle detectors in space, do not influence the overall charge asymmetry measurement. In order to isolate and subsequently eliminate the effects of these systematic errors in the measurement, the supporting structure is designed so that the entire detector can be rotated azimuthally about the beam line by $\pm 90^\circ$ and 180° about a vertical axis. The rotation about the vertical axis maps θ into $180^\circ - \theta$, and is therefore most useful in checking the measurement of the front-back charge asymmetry. The azimuthal rotation, which is used to check for beam polarization, can also be used to aid in the charge asymmetry measurement in the presence of polarized beams.

For the data in this report detectors E and R were not used.

b) The Luminosity Monitor

The luminosity monitor consists of two arrays of twenty-eight lead glass blocks [8] (labelled G in Fig. 6), each with dimensions of 8 cm x 8 cm x 70 cm located 5.8 m from the interaction point. They are designed to measure Bhabha events at small scattering angles (~ 30 mrad). Scintillators (F) in front of the lead glass define the acceptance and the lead glass counters measure the energy of the electron pairs.

For on-line luminosity measurements, only the signals from the lead glass are used. The trigger demands signals in both the forward (i.e. in the direction

of the electrons) and backward hodoscopes with a minimum of 20% of the beam energy detected in each counter array.

In the off-line analysis, the signals from the lead glass are used in connection with those coming from sixteen acceptance-defining scintillation counters paired to form eight monitoring stations.

Each luminosity monitoring station consists of a small (60 mm x 30 mm x 5 mm) scintillator behind which a larger counter (80 mm x 50 mm x 5 mm) is centered. Every F counter is glued to a thin aluminum finger tilted so that the counters are perpendicular to particles originating from the interaction region. The larger scintillator is viewed by a XP2230/B phototube via an air light guide; the smaller scintillator is viewed by a separate tube of the same type via an air-lucite hybrid light guide. Care was taken so that the large scintillator does not lie in the shadow of the lucite light guide of its companion. Four monitoring stations are mounted in the forward region and four in the backward region such that opposite pairs of counters lie in the horizontal or vertical plane.

The size of the small scintillators was chosen to give an acceptable counting rate given the machine luminosity and the scattering angle. The typical singles counting rate in each of the monitoring stations is 100 kHz. The dimensions of the large scintillator were then chosen to minimize the radiative corrections (see section 3.3d) The scintillators were machined with a diamond cutting tool to a tolerance of ± 50 microns and the machined surface did not require polishing. After machining, the sizes of the scintillators were measured to an accuracy of ± 5 microns.

Because the Bhabha cross section at small scattering angles is proportional to θ^{-4} it is necessary to know as precisely as possible the positions of the scintillators with respect to the beam direction. Crawford et al., [9] have

shown, however, that if scintillators on opposite sides of the beam line are mounted such that their separation remains fixed, first order effects due to displacements and angular rotations of monitor counters with respect to the beam line cancel out. This was realized in this instance by mounting all four of the monitoring stations at one end of the detector on a common frame. The separation between opposite monitoring stations was then measured using a precision table and a height gauge with an intrinsic setting error of 20 microns. The position of the frame in the experimental hall can then be measured to an accuracy of 200 μ . Details of the calculation of the radiative corrections for this monitor are given in Section 3.3d.

c) The Drift Chambers

The design of the drift chambers was dictated by the need for mechanical simplicity and strength together with the necessity to cover a very large solid angle [10]. Previous to the experiment at PETRA, chambers of identical construction had been used successfully over a period of three years in an experiment [11] at the CERN Intersecting Storage Rings. On the basis of the experience gained at CERN, the MARK J chambers for PETRA were constructed in several configurations: twelve layer (S and T) or ten layer (U and V) chambers to measure tracks before they enter the magnetized iron, very large chambers with ten layers (P) or sixteen layers (R) to measure the tracks after leaving the iron, and two layer sampling chambers (Q) to measure the tracks in the bending direction halfway through the iron. For this application the chambers used had to be large and rigid with little dead space occupied by structural elements. The amount of material in the chamber along the path of the particles was not a consideration, since it is negligible compared with the material in the iron. The solution was to construct chambers with 10 cm cells formed by two field-shaping I-beams

(which provide the structural strength) glued with insulators between two aluminium ground plates. A coordinate is measured by a double layer of such cells, with the second layer displaced by half a cell width from the first to resolve the left-right ambiguity. This double layer is normally glued to another double layer formed by I-beams running in the perpendicular direction, which add additional strength as well as measuring the perpendicular coordinate. Because the electric field in the drift chamber cell is non-uniform, and the relation between time and position is not linear for inclined tracks, the positions must be corrected for angle during track reconstruction.

Individual cells have been tested to give a resolution of 0.4 mm for perpendicular tracks. In our system of 5000 wires with individually calibrated TDC's we find that for all angles of incidence the average resolution is about 0.6 mm. This is much smaller than the spread resulting from multiple scattering in the iron.

The drift chambers contain 50 cubic meters of a gas mixture composed of 75% argon and 25% isobutane. To reduce the gas consumption for this large volume we have installed a partially recirculating gas system. This circulates the entire gas volume through the chambers every four hours. Water is removed by a molecular sieve filter and oxygen is removed by a catalytic converter fed with a small amount of hydrogen. Other contaminants are removed by replacing 10% of the gas with fresh gas each circulation cycle. The isobutane content of the gas is monitored continuously by an infrared gas analyzer and maintained at $(25.0 \pm 0.1)\%$. The oxygen is monitored by a fuel cell and kept below 20ppm in the return gas from the chambers. The gas is also analyzed automatically every two hours by a Hewlett-Packard 5840A programmable gas chromatograph so that water, nitrogen, light hydrocarbons and other contaminants can be monitored. The nitrogen is not removed by the purification system and thus provides a means of estimating the amount of contamination from air, either through leakage,

diffusion through the plastic supply lines, or from its presence in the gas supply. The nitrogen content normally remains below 500ppm.

d) The Trigger

The trigger is arranged in two stages. The first stage is a fast loose trigger generated from the counter hit information with the following requirements:

i) For electron pairs we require at least 0.5 GeV total energy deposited in opposite quadrants of the A and B counters.

ii) For muon pairs we require at least two A and two B counters in coincidence with a pair of D counters which are coplanar within 50° .

iii) For single muon events we require at least two A, two B, two C and one D counters to be triggered.

iv) For hadrons we require at least four A and three B counters; each triggered quadrant must be in coincidence with the opposite quadrant.

All triggers are required to be in coincidence with the beam crossing signal.

After the fast trigger, a second stage imposes two more selections depending on event type. For electron pairs and hadron events the total energy deposited in the inner calorimeters A, B and C is determined by measuring the pulse area of linearly added signals. We require at least 13% of the total C.M.S. energy for hadrons and at least 10% for electron pair events. For muon pairs, single muon and hadron events, a microprocessor (Section 3.2f) applies a loose track requirement demanding at least three pairs of wires to be hit in the S or T chambers.

e) Detector Calibration

In a detector of this type in which event identification and energy measurement depends on the detailed response of calorimeter counters, it is essential that the behavior of counter packages be investigated in particle beams of various types and energies. Thus, one quadrant of the complete A, B, C and K assembly was reassembled at CERN and set up on a movable table in a test beam. The response of the counters to electrons, pions and muons of various energies, incident angles and positions was measured. The incident beam was defined by three small scintillation counters and collimated to a size of 2 cm x 2 cm on the counters. Electrons and pions were discriminated by two Cerenkov counters filled with helium or air, and muons were identified by their penetration of additional iron absorbers. All phototube gains were adjusted by normalizing the pulse height to that obtained from muons injected normally at the center of the counter. A total of 200 spectra covering a range of beam momenta from 0.5 to 10.0 GeV and the angular ranges $15^\circ \leq \theta \leq 90^\circ$, $0^\circ \leq \phi \leq 45^\circ$ were measured. Pulse height and timing of each phototube were recorded on magnetic tapes and analyzed offline. The response of the A, B, C and K arrays was then assessed by combining their pulse heights with proper weights chosen to optimize the energy resolution.

To relate the pulse height in the phototubes of each counter of the A, B and C arrays to the deposited energy, the signals of the two tubes are added, and the light attenuation in the scintillator is taken into account. The attenuation length is measured to be 102 cm for A and B counters and 109 cm for C counters. Within the acceptance of C counters, linearity for both incident electrons and incident pions improves slightly at smaller θ angles due to the increase of the effective thickness of the calorimeter, while no clear degrading of the resolution is observed. The hit position in the counter can be reconstructed

from both the timing difference and pulse height asymmetry of the phototubes at each end of the counter. The r.m.s. position resolution of both A and B counters is 2.5 cm from timing measurement and 6 cm from pulse height measurement. Combination of the two measurements gives an angular resolution better than 5° for the full acceptance of A and B counters.

f) On-line Data Collection and Data Monitoring

The experimental data from the detector are read in through two main CAMAC branches (Fig.13). Branch A includes two crates of scalers which monitor 300 singles rates from the counters, and 100 coincidence rates and high voltages in the counter power supplies. This branch is time driven; it is read and cleared every 100 seconds. Branch B is trigger driven; it consists of fifteen CAMAC crates divided into three sub-branches which are connected to the main branch through three branch selectors of the CERN type. On this branch, all the counter TDC's, ADC's, and the drift tube and chamber TDC's are read out.

The above two branches A and B are interfaced to the online computer via two separate microprogrammable branch drivers (MBD), each of which is a complete software programmable microprocessor.

For branch B, the microprocessor is used to preselect event candidates and to suppress spurious information, as described briefly in section 3.2d. The master trigger signal, corresponding to the logical OR of the five fast electronics triggers described earlier, is sent to a CAMAC input register, and it initiates the microprocessor. The microprocessor first reads the data from the drift chamber time-digitizer electronics into its own memory, and then reads an input register to see which kind of trigger has occurred. If it is either a luminosity monitor or electron pair trigger, it directly reads

FIGURE 13.

Schematic of online computer and peripherals configurations.

in and writes out all the CAMAC data to the online computer. If the trigger is a single muon, muon pair or hadron trigger, a wire pair test is carried out in the microprocessor. That is, it scans through the drift chamber data stored in its memory and tests to determine the number of double planes in the inner detector which have adjacent hits. If the number is less than three, the event is rejected. Otherwise, it is read into the computer. The flow diagram of this program is shown in Fig. 14.

FIGURE 14.

Block diagram showing microprocessor program logic for trigger handling.

As the microprocessor reads in the counter information, it decides whether each data word is useful; whether it is greater than the pedestal value in the case of the ADC's, or whether it is less than the overflow value in the case of the TDC's. Only when the data are valid are they written into the computer. Thus, the average length of a trigger is only about 400 16-bit words. This also decreases the deadtime due to data transfer. For triggers which are accepted the deadtime is about 30 msec. For those rejected it is typically 3 msec.

The online computer is a PDP 11/55 (Fig. 13). In addition to writing data to magnetic tape, selected quantities are histogrammed and displayed online on color video monitors. The histograms are also printed out in hardcopies for record. Selected coincidence rates are monitored constantly. If any of them is out of preset limits, warning messages are displayed.

At a beam luminosity of $1 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$, depending on the beam conditions, the typical trigger rate from the fast electronics is 5 Hz. After microprocessor preselection, the data rate written on magnetic tape is 2 Hz. The resulting deadtime is about 5%.

In addition to the purely online functions the PDP11 is used between runs and during shutdowns for calibrating the time-digitizing electronics for the drift chambers and counters, and the pulse height digitizing electronics for the counters.

3.3 Off-line Analysis

This section gives a brief description of the methods used to calculate the energy and direction of the particles seen by the detector and of the procedures used to select the events of interest. In addition we discuss the Monte Carlo simulation of the observed processes, and radiative corrections applied to the experimental data.

a) Direction and Energy Measurements

The A, B, C and D counters (Figure 6) have a phototube at each end. The position of the track along the z direction of the counter can thus be determined by use of the pulse height (ADC) and time (TDC) differences measured by these tubes. Combined with the position of the intersection region, this gives the polar angle θ of the track. The attenuation length of the counters, which is needed for the ADC position measurement, was measured in the test beam as described in Section 3.2e. It is ~ 100 cm for the A, B, and C counters and ~ 180 cm for the D counters. The position deduced from the TDC measurement uses a light propagation speed of ~ 16 cm/nsec. This was also determined from test beam data. Corrections for the dependence of the TDC output signal on input pulse height and for time of flight are applied. A weighted average of the two position measurements is then taken. These position estimates have also been checked with the recently installed drift tubes. An example is shown in Figure 15a, where the difference between the position of the hit in the A counters as determined from ADC and TDC, and the position expected from the more precise tracks fitted in the drift tubes is plotted for 30 GeV Bhabha events. As can be seen, the r.m.s. position resolution obtained from the counters is ~ 2.5 cm.

FIGURE 15.

Counter resolution for large angle Bhabha scattering at $\sqrt{s} = 30 \text{ GeV}$.

- a. Position of hits deduced from TDC and ADC information (z_{ctr}) in the A counters compared to extrapolated tracks (z_{tub}) observed in drift tubes.
- b. Polar angles of reconstructed counter tracks compared to tracks fitted with drift tube information.
- c. Observed energy spectrum for large angle Bhabha scattering.

The azimuthal angle ϕ is determined by the position of the counters in space. The segmentation of the counter layers corresponds to a resolution of $\sim 7^\circ$ in ϕ for an individual hit.

Counter tracks are constructed with a vector energy flow computed from the pulse height and position information of the groups of hits occurring within a cone of 20° opening angle, emanating from the interaction point. In Figure 15b we show a comparison of the polar angle of the counter track, obtained from this combination of shower information, with that of the track fitted in the drift tubes. As can be seen, the resolution is $\sim 3^\circ$.

The energy corresponding to the pulse height recorded in the shower counters and calorimeter counters is computed by taking a weighted sum of the ADC values. The appropriate weight for each layer of counters has been determined from the analysis of the test beam data described in Section 3.2e. The weights are different for hadronic and electromagnetic showers. Figure 15c shows the energy measured in this way for electrons observed at large scattering angles in $e^+e^- \rightarrow e^+e^-$ at 30 GeV. For hadronic events the r.m.s. resolution in the total observed energy is $\sim 20\%$ as can be seen in Figure 16a. From counter tracks the total missing energies in the directions parallel and perpendicular to the beam, which are used in the event selection, may be computed. The observed distributions of these quantities are shown in Figures 16b and 16c for high energy hadron events.

FIGURE 16.

Energy measurement at $\sqrt{s} = 30$ GeV. The solid curves are predictions of Monte Carlo computations.

a. Visible energy spectrum for hadronic events.

b. Energy imbalance $E_{\perp}$ in the direction transverse to the beam.

c. Energy imbalance $E_{\parallel}$ in the beam direction.

b) Off-Line Data Reduction

The data are reduced in a series of three passes. Diagrams representing the general arrangement of the data reduction process and illustrating two of these passes are shown in Figure 17. The first pass is a fast filter for hadron and muon events. For hadron events, the energy is calculated roughly, and a cut at 25% of the center of mass

FIGURE 17.

Block diagram of offline data reduction by pass 1 and pass 2 filters.

energy is made. A balance cut is also made, excluding events which have most of the energy deposited in only one detector quadrant. Approximately 1.8% of the original events are accepted by the hadron filter.

The muon filter requires a possible track in the outer drift chambers and applies timing cuts. Signals in at least one A or B counter must be in time with the beam gate along with at least one signal in D counters which are shielded by 42 cm of iron. In addition, if there is more than one D counter with a signal, the time difference between counters is used to reject cosmic rays. Approximately 0.7% of the original events pass these cuts, so that the overall pass 1 output is 2.5% of the raw data.

The pass 2 filter is much more refined. The energy calculation described in Section 3.3a is used, and the total energy, E_{vis} , is required to be $> 35\%$ of the center of mass energy. The events must also be balanced to within 50% of E_{vis} . In addition, an angle-dependent cut on the energy deposited in the latter part of the calorimeter (K in Figure 6) is made for hadronic events. This cut is used to distinguish Bhabhas and $e^+e^- \rightarrow \gamma\gamma$. The drift tubes and the inner chambers are used to make a cut on the longitudinal vertex position and a multiplicity cut which also reduces the Bhabha background. The end result of these cuts is a sample of hadron candidates that is typically 0.03% of the original raw data sample.

The final selection of hadron-, muon-, and large angle Bhabha events is made by scanning the candidates, selected in the pass 2, on a video screen. This is done by physicists with the use of an interactive display program. The program can plot the detector components and energy deposited in different projections and magnifications. Fits through the hits in the drift chambers and the counters can be made on-line. The counter tracks can be rotated in space to study the event shape.

c) Monte Carlo Simulation

A large part of the analysis effort for the MARK J detector is devoted to the development and use of Monte Carlo programs.

This simulation of events proceeds in three steps.

1. Event generation
2. Detector simulation
3. Event coding

The event generators produce simulated events for a wide variety of e^+e^- reactions. The momenta, masses, charges, and the spatial distribution of the final state particles are generated according to the physics hypothesis appropriate to each process.

Hadron production by e^+e^- annihilation

$$e^+e^- \rightarrow \text{hadrons}, \quad (1)$$

is treated in the framework of quantum chromodynamics (QCD), where the final state hadrons are viewed as composite particles made up of quarks (and antiquarks) bound by a force mediated by gluons. Process (1) proceeds through the production of a quark-antiquark ($q\bar{q}$) pair, accompanied by the possible final state radiation of one or two gluons (denoted by g or gg) or in rare cases by the production of an additional $q\bar{q}$ pair. The quarks and gluons then fragment, meaning that they pull additional $q\bar{q}$ pairs from the sea with limited P_t with respect to the quark or gluon directions, forming jets of hadrons. Reaction (1) thus includes the following sub-processes:

$$e^+e^- \rightarrow q\bar{q} \rightarrow \text{hadrons} \quad (1a)$$

$$e^+e^- \rightarrow q\bar{q}g \rightarrow \text{hadrons} \quad (1b)$$

$$e^+e^- \rightarrow q\bar{q}gg \rightarrow \text{hadrons} \quad (1c)$$

$$e^+e^- \rightarrow q\bar{q}q\bar{q} \rightarrow \text{hadrons} \quad (1d)$$

As an example, Figure 18 shows a $q\bar{q}g$ final state, accompanied by radiation of an initial state photon, which leads to multi-jets.

FIGURE 18.

Gluon bremsstrahlung from the final state of e^+e^- annihilation into quark antiquark pairs.

For the MARK-J search for the existence of new heavy quark flavors such as the top quark t , the reaction

$$e^+e^- \rightarrow t\bar{t} \rightarrow \text{hadrons} \quad (1e)$$

is simulated as a special case of process (1a-1d)

Pair production of the charged leptons, through the reactions

$$e^+e^- \rightarrow e^+e^- \quad (2)$$

$$e^+e^- \rightarrow \mu^+\mu^- \quad (3)$$

$$e^+e^- \rightarrow \tau^+\tau^- \rightarrow \text{hadrons and leptons} \quad (4)$$

is also simulated. The analysis of computer generated final states for reactions (2)-(4) is a major part of the QED tests discussed in Section 4.1.

Other processes simulated include

$$e^+e^- \rightarrow \gamma\gamma \quad (5)$$

and the "two photon processes"

$$e^+e^- \rightarrow e^+e^-e^+e^- \quad (6)$$

$$e^+e^- \rightarrow e^+e^-\mu^+\mu^- \quad (7)$$

and
$$e^+e^- \rightarrow e^+e^- + \text{hadrons} \quad (8)$$

Event types (1a)-(1e) are generated using a slightly modified version of the computer program recently implemented by A. Ali, E. Pietarinen, G. Kramer, and J. Willrodt [12], which provides a detailed model of hadron production by e^+e^- annihilation in the framework of QCD. In general, $q\bar{q}$ pairs are produced in fractions proportional to the square of the quark charges for flavors up, down, strange, charm, and bottom (denoted u, d, s, c, and b respectively). The fragmentation procedure used to transform quarks into hadrons is similar to that used by Feynman and Field [13]. The fragmentation functions used are $zD(z) = (1 - z)^2$ for u, d, and s quarks and $zD(z) = \text{constant}$ for c and b quarks, where z represents the fraction of the quark momentum carried away by the hadron formed at each stage of the fragmentation process [see Ref. 13].

Heavy quarks (c and b) are allowed to decay weakly according to the usual six quark model [14], and the light quarks produced in the decay sometimes fragment independently, forming additional jets.

Since gluon fragmentation functions are unknown, gluons simply fragment to quark pairs which in turn fragment according to the normal procedure.

The $q\bar{q}g$ events in which hard non-collinear gluons are radiated (see Fig. 18) are generated according to the perturbative QCD matrix elements which includes the effects of non-zero quark mass [15]. Events of this type are required to have a thrust (Section 4.3a) less than 0.95 before fragmentation in order to avoid the singularity for soft or collinear gluon emission [12]. We have checked that our results do not depend strongly on the value of this cut.

Events from the higher order QCD processes $q\bar{q}gg$ and $q\bar{q}q\bar{q}$ are treated in a similar way to those from $q\bar{q}g$. The principal difference is that instead of applying the thrust cut, the requirement of acoplanarity greater than 0.05 is imposed, where acoplanarity is defined as

$$A = \min_i \frac{\sum_i |\vec{E}_i \cdot \hat{n}_3|}{\sum_i |\vec{E}_i|}$$

and $\vec{E}_i$ is the vector energy and $\hat{n}_3$ is chosen to minimize A.

This implies that none of the four partons can be soft and that no two are collinear. It does, however, reject planar events which are not near a singularity in the matrix element. We have also used a $t\bar{t}$ generator [15] which proceeds in the same way as for other heavy quarks, to study the effects that will be useful in searching for the top quark.

All of the first four event generators use a simple (QED) radiative correction generation [16] which assumes that only initial state photon emission is important and that all of these photons go along the beam direction with a momentum spectrum given by the equivalent photon-approximation.

Bhabha scattering, μ pair production, τ pair production and $\gamma\gamma$ events are currently generated according to lowest order distributions and radiative corrections are applied externally using the programs of Berends et al. [20], (see Section 3.3d). Two-photon event generation for $e^+e^- \rightarrow e^+e^-e^+e^-$ and $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$ is done using the program of Vermaseren [17] which is exact to order α^4 in the cross section.

The output of the Monte Carlo generators is in a format that can be conveniently used by the detector simulation program. This latter program proceeds in the following way. Particles are tracked through the detector and intersection points with counter and chamber planes are computed. The amount of energy in each hit counter is determined from tables that give the dependence on penetration depth, angle, and particle energy. Energy

resolution and longitudinal shower fluctuations are also simulated using tabulated information. The above-mentioned tables were generated from the test beam data taken with electrons and pions at energies from 0.5 to 10 GeV, from experimental calorimeter studies [18] and from shower Monte Carlo programs [19].

Hits in the drift chambers and drift tubes are digitized. The chamber performance is simulated in detail including background, inefficiency, multiple hits, cross talk and δ -rays. The full chamber survey information is used as provided on an input file. The somewhat complicated drift distance versus drift time function is also reproduced [Section 3.2c].

Finally the counter ADC and TDC information is digitized. Pulse heights are corrected for attenuation in the scintillator and times are corrected for particle flight time, scintillation light transit time and time slewing due to varying pulse height. Multiple hits are also treated.

To summarize, the detector is simulated in detail so that Monte Carlo events can be treated in the same way as actual data. To complete this process, the information described above is then coded into a form that resembles the raw data format. These events are stored on tape or disk so they may be read by the various analysis programs. This is useful for many purposes such as calculation of acceptance for a process, computation of background, and determination of detector effects on measured quantities. In particular, we use Monte Carlo simulation of the MARK J detector, and the appropriate event generator, to produce expected distributions in variables that can be compared to data.

d) Radiative Corrections for Luminosity Monitoring and Tests of QED

The luminosity in the MARK J intersection is monitored by measuring the rate of Bhabha events in the central A counters [Figure 6] and the small angle luminosity monitor, described earlier. We assume that at present energies and small q^2 the absolute rate of the Bhabha scattering process is well described by QED and it may thus be used as an absolute monitor. The large q^2 Bhabha scattering covered by the A counters as described in Section 4.1a is also well described by QED and can be used as an independent monitor. Nevertheless, care must be exercised to take proper account of radiative corrections which may be as large as 20% for some final state configurations in our detector.

The measured rate for Bhabha scattering (reaction (2)) receives contributions from all orders in the perturbation expansion of QED. Furthermore, given the finite energy and position resolution of the detector, some events in which a hard photon is radiated

$$e^+ e^- \rightarrow e^+ e^- \gamma \quad (9)$$

are also detected and attributed to Bhabha scattering.

It is therefore necessary to evaluate the contribution to the total Bhabha scattering cross section to order α^3 . Higher order corrections are difficult to compute and have not yet been calculated exactly. Fortunately, they are small since the result of the α^3 correction is already only a few percent.

The calculations described below were first carried out by Berends and Gastmans [20], and we use the most recent version of their computer program modified for our detector. We write the cross section for Bhabha scattering as

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} (1 + \delta[\theta, \phi])$$

where $d\sigma_0/d\Omega$ is the lowest order (α^2) cross section and δ represents the radiative correction to order α^3 . Following the notation of Berends, we write

$$\delta = \delta_b + \delta_v,$$

where δ_b is due to real bremsstrahlung and receives contributions from the eight diagrams in Figure 19a and δ_v is due to virtual bremsstrahlung which is the contribution of the interference between the lowest order

FIGURE 19.

Radiative correction diagrams for the process $e^+e^- \rightarrow e^+e^-$.

diagrams and the diagrams in which one closed loop occurs (due to virtual photons, virtual electron-positron pairs, $\mu^+\mu^-$ or $\tau^+\tau^-$ pairs) shown in Figure 19b.

Renormalization removes the ultraviolet divergence of δ_v , and one is left with an infrared divergence which is exactly cancelled by the infrared divergence occurring in δ_b ; δ is then finite.

A further correction which could have been included in δ_v is the hadron contribution to vacuum polarization. It can be thought of as quark-antiquark loops occurring in the photon propagator and is similar to lepton loops. Those contributions have been calculated by Berends and Komen [16] using experimental knowledge of R , the ratio of the cross section for $e^+e^- \rightarrow \text{hadrons}$ to the cross section of the point-like process $e^+e^- \rightarrow \mu^+\mu^-$. At 90° with respect to the beam axis the contribution from quark loops to δ is of the order of +4% at $\sqrt{s} = 17$ GeV and slowly increases with energy.

i) Small Angle Radiative Corrections

The radiative corrections for the small angle Bhabha scattering require careful treatment since the differential cross section is strongly peaked in this region. Ripken [22] has overcome the technical difficulties of numerical computation in the small angle region by using Gaussian integration techniques, and he has applied his program to the case of the MARK-J using a matrix element provided by Berends [16, 20]. At angles smaller than 5° with respect to the beam axis, all electron muon and tau loop diagrams and the hadronic contribution to vacuum polarization are small and are neglected.

In the small angle luminosity monitoring stations, as described in Section 3.2b, pairs comprising one small scintillator and one opposite large scintillator define the acceptance. The geometry of these counters has been incorporated into the radiative corrections in the following fashion. For the hard-photon part of the cross section electron-positron-photon triplets are generated where one of the leptons is within the acceptance of a small scintillator and the other lepton is required to pass within the boundaries of the large scintillator diametrically opposite. The soft photon part is incorporated analytically. These corrections are very sensitive to the relative position of the small scintillator with respect to the larger one. The residual uncertainty in the positions of the scintillators contributes a relative systematic error in the calculation of δ of about 30%. Since the value of δ is -8%, the radiative corrections contribute an error of 2.5% to the total luminosity measured in the small angle monitor.

ii) Large Angle Radiative Corrections

For large angle Bhabha scattering the phase space for real bremsstrahlung can be experimentally characterized by two simple boundaries:

E_{th} : an energy threshold for the outgoing
electron and positron

ξ : a limit on the angle in space between the electron
direction and the direction at 180° to the positron
direction (acollinearity cut).

Figure 20 shows δ plotted as a function of θ over the A counter acceptance at $\sqrt{s} = 27.4$ GeV for various combinations of the cuts.

FIGURE 20.

Radiative corrections δ as a function of the scattering angle θ for different acceptance cuts.

The cuts used to define the sample for the MARK J luminosity measurement at large angles are:

$$E_{th} = 0.3 E_{beam}$$

$$\xi = 50^\circ$$

The energy threshold cut is chosen to be well below the tail of the energy resolution curve with its r.m.s. width of $\sim 10\%$ so that the resolution correction is not very sensitive to this cut.

With the knowledge of δ one may integrate the differential cross section over the detector acceptance to find the Bhabha rate expected in the central detector. Knowledge of the acceptance at the end of the counters is especially important since the Bhabha cross section is strongly peaked at small angles and most of the contribution to the total rate comes from the end region of the counters. Near the edge of the acceptance the

FIGURE 21.

Efficiency function at the end of the A shower counters.

radiative corrections become large and negative as more photons of lower energy can cause one of the outgoing electrons to recoil outside the counter limits. Because of the spread of the electromagnetic shower and because of back scattered showers from neighboring counters, the acceptance does not drop sharply at the end of the A counters but shows a tail beyond the geometrical end of the counters (see Figure 21). The efficiency of the A counters near their ends is computed using the Monte Carlo simulation described in section 3.3c, and the specialized Monte Carlo program EGS (Electron Gamma Shower) developed at SLAC which provided detailed information on electromagnetic showers [21].

The results of the calculation of the cross section over the A counters, including the radiative corrections, are shown in Figure 22.

FIGURE 22.

The calculated cross section $e^+e^- \rightarrow e^+e^-$ integrated over the solid angle covered by the A shower counters.

We find that the luminosity measurement with the central detector agrees within $\sim 3\%$ with the measurement made with the small angle luminosity counters (see Figure 23).

FIGURE 23.

Luminosity measured with the central detector (L_C) and with the luminosity monitor (L_G) during energy scan.

4) PHYSICS RESULTS

4.1 Test of Quantum Electrodynamics and of Universality for Charged Leptons

There have been many experiments testing quantum-electrodynamics (QED) with electrons, muons and photons at electron-positron storage rings. Notable experiments [23] were done by Alles-Borelli et al., Newman et al., Augustin et al., O'Neill et al., and by our group at PETRA [24] up to a center of mass energy of 17 GeV. For a comprehensive review of QED work, see Brodsky and Drell [25]. Much has been learned about the properties of the heavy lepton tau since the original search began at ADONE on $e^+ + e^- \rightarrow \mu e + \dots$ [26]. The discovery of the τ lepton at SLAC [27] and its subsequent confirmation at DESY [28] has inspired further studies. We know it is a spin 1/2 particle which decays weakly [29] and whose properties are very similar to the muon.

In this experiment we study the reactions $e^+ + e^- \rightarrow \ell^+ + \ell^-$ for all the known charged leptons ($\ell = e, \mu, \tau$) by measuring the dependence of the cross section on center of mass energy or scattering angle over a wide range of PETRA energies. These measurements enable us to compare the data with predictions of quantum electrodynamics; to test the universality of these leptons at very small distances, and to set a limit on the charge radius of these particles. Up to the present time the reactions:

$$e^+ + e^- \rightarrow e^+ + e^- \text{ (Bhabha scattering)} \quad (2)$$

$$e^+ + e^- \rightarrow \mu^+ + \mu^- \quad (3)$$

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \quad (4)$$

$\rightarrow (h's \text{ or } e) + \nu's$
 $\rightarrow \mu + \nu's$

have been measured at the center of mass energies $\sqrt{s} = 12, 13, 17, 22, 27.4, 30$ and 31.6 GeV.

a) Bhabha Scattering

The Bhabha events are identified by requiring two back-to-back showers in the A, B and C counters which are collinear to within 20° in ϕ and θ and with a measured total shower energy greater than $1/3$ of the incident beam energy. Photons emitted close to either electron are included in the electron momentum. From the measurement of the acollinearity angle $\Delta\theta$, and the acoplanarity angle $\Delta\phi$, we observe that most of the events are in the region $\Delta\theta < 4^\circ$, $\Delta\phi < 4^\circ$. Because there are few events near the 20° cuts in $\Delta\theta$ we conclude that the background to Bhabha scattering is negligible.

To eliminate most background from hadron jets, the energy in the K counters was required to be less than 7% of the total energy. Because the QED test is most sensitive to background in the large angle region, all events having θ larger than 60° were scanned on graphic displays

which showed the distribution of counter hits. On the basis of a Monte Carlo study of hadron events, we conclude that the background from this source is less than 1% of the events. As mentioned above, the acceptance for $e^+e^- \rightarrow e^+e^-$ was computed using Monte Carlo techniques and is defined by the geometry of the first shower counter array A. Both energy and acceptance losses in the corners were found to be small.

The first order QED photon propagator produces an s^{-1} dependence in the $e^+e^- \rightarrow e^+e^-$ cross section. Thus when radiative corrections have been taken into account in the data, the quantity $s \frac{d\sigma}{d\cos\theta}$ vs $\cos\theta$ should be independent of s . This distribution is plotted for the data at $\sqrt{s} = 13, 17$ and 27.4 Gev in Figure 24. Excellent agreement with QED predictions is seen. To express this agreement analytically, we compare our data with the QED cross section in the following form (since charge is not distinguished here) [30]:

$$\begin{aligned} \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s} \left\{ \frac{q^4 + s^2}{q^4} |F_s|^2 + \frac{2q^4}{q^2 s} \text{Re}(F_s F_T^*) + \frac{q^4 + q^4}{s^2} |F_T|^2 \right. \\ \left. + \frac{q^4 + s^2}{q^4} |F_s'|^2 + \frac{2q^4}{q^2 s} \text{Re}(F_s' F_T'^*) + \frac{q^4 + q^4}{s^2} |F_T'|^2 \right\} \{1 + C(\theta)\}, \end{aligned}$$

where

$$F_s = 1 + q^2 / (q^2 - \Lambda_{s\pm}^2)$$

is the form factor of the spacelike photon,

FIGURE 24.

The differential cross section $s \frac{d\sigma}{d\cos\theta}$ for $e^+e^- \rightarrow e^+e^-$ at $\sqrt{s}$ of 13, 17, and 27.4 GeV.

$$F'_S = 1 + q'^2 / (q'^2 - \Lambda_{S\pm}^2),$$

$$F'_T = 1 + s / (s - \Lambda_{T\pm}^2)$$

is the form factor of the timelike photon, $q'^2 = -s \cos^2(\theta/2)$, $q'^2 = -s \sin^2(\theta/2)$, Λ is the cut-off parameter in the modified photon-propagator model [31] and $C(\theta)$ is the radiative correction term as a function of θ .

The radiative correction to the e^+e^- elastic scattering process was calculated using the program of Berends for these particular event selection criteria [20].

In order to establish lower limits on the cut-off parameters a Monte Carlo program was used to generate e^+e^- pairs which were then traced through the detector with the inclusion of measured θ , ϕ resolutions. A χ^2 fit to all of the 13, 17 and 27.4 GeV data is then made using the Monte Carlo generated angular distribution. The normalization is treated in two ways: (1) the total number of Monte Carlo events in the region $0.90 < \cos\theta < 0.98$ was set equal to the total number of measured events in the same region, (2) the minimum- χ^2 for the entire data sample determined the normalization. The two methods agree with each other to within 3% and give essentially the same result in the cut-off parameter Λ . The lower limits of Λ at 95% confidence level under various assumptions are shown in Table I. The JADE and PLUTO groups have also analyzed their QED reactions and have obtained similar conclusions with regard to the validity of QED at small distances. (see section 4.4).

TABLE I
Cut-off parameters in GeV for photon form factors from Bhabha scattering.

Λ	$1 - \frac{q^2}{q^2 - \Lambda^2}$	$1 + \frac{q^2}{q^2 - \Lambda^2}$
Λ_s	52	55
Λ_T	60	52
$\Lambda_s = \Lambda_T$	65	64

b) Muon and Tau Pair Production [32]

The MARK J detector is designed to distinguish muons from electrons and hadrons and to distinguish back-to-back muon pairs from cosmic ray muons. Muon identification is also aided by the short decay path allowed to hadrons before reaching the shower counters. In addition to the cuts described in Section 3.3b, single muons are identified as particles which:

- i) are reconstructed in the inner drift chambers to come from the interaction region;
- ii) leave minimum ionizing pulse heights in the A, B, C, K, and D counters, a total of seven layers;
- iii) leave a track in the outer drift chambers (P) and thus fall into an angular range $45^\circ < \theta_\mu < 135^\circ$.

In addition back-to-back muon pairs from reaction (3) are distinguished from cosmic rays by the requirement that:

- i) the D counter timing signals are coincident with one another (and not relatively off time as in the case for cosmic rays traversing the detector),
- ii) the muons should be collinear and coplanar, and they should pass through the intersection region.

A Monte Carlo study shows that the $\mu^+\mu^-$ acceptance, which is dominated by the geometrical acceptance of the P drift chambers, is $41\% \pm 3\%$ independent of beam energy.

Tau leptons from reaction (4) are identified by detecting μ -hadron and μ -electron final states. The cross section is determined using the known branching ratio of $\tau \rightarrow \mu \nu \bar{\nu}$ (16%) and $\tau \rightarrow (e, \text{hadron or multihadrons}) + \nu$ (84%) [29]. The muons, hadrons and electrons are identified as described previously. The total deposited energy of hadrons (or electrons) is required to be greater than 2 GeV.

The major background to reaction (4) is the two-photon process:

$$e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \mu^- \quad (7)$$

This process becomes important at high energies since the total cross section grows as $\ln(\sqrt{s}/m_e)^2 \ln(\sqrt{s}/m_\mu)$ with increasing beam energy in contrast to reaction (3), the rate for which falls as $1/s$. The observed cross section for the two-photon process is suppressed by a factor $\sim 10^3$ relative to the total cross section by momentum cuts on the muons and by energy and angle cuts on the electrons, but rates of the accepted events remain significant.

In Figure 25 we show the calculated cross section in our detector when the observed particles are

- (a) two μ 's only,
- (b) only one μ and one e and,
- (c) two μ 's and one e .

The cross sections for each of these configurations were computed using the Monte Carlo integration program of Vermaseren [17]. The computations were compared to the cross sections measured for reaction (7) using the following cuts:

$$168^\circ \geq \theta_e \geq 12^\circ$$

$$E_e \geq 2 \text{ GeV}$$

$$135^\circ \geq \theta_{\mu_1} \geq 45^\circ$$

$$P_{\perp \mu_1} \geq 1.5 \text{ GeV (first muon)}$$

$$147^\circ \geq \theta_{\mu_2} \geq 33^\circ$$

$$P_{\perp \mu_2} \geq 0.8 \text{ GeV (second muon)}$$

The measured cross sections, also shown in Figure 25, agree well with the calculations in all cases.

FIGURE 25.

The observed cross sections of $e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \mu^-$ in our detector as functions of $\sqrt{s}$: when the observed particles are:

- a. two μ 's
- b. one μ and one e
- c. two μ 's and one e

The solid lines are Monte Carlo calculations of the yield from two photon diagrams and the points are the measurements.

The cross section for case (a) above is much larger than that for the process

$$e^+ + e^- \rightarrow \tau + \bar{\tau} \rightarrow \mu^+ + \mu^- + 4\nu,$$

and the $\mu^+ \mu^-$ events from the two processes are hard to distinguish.

We therefore exclude case (a) from the sample of $\tau\bar{\tau}$ candidates.

In case (b) the electron from the two-photon process is strongly peaked in the small angle region. Typically, $\frac{d\sigma_{\mu e}}{d(\cos\theta_e)}$ decreases by two orders of magnitude from $\cos\theta_e = 0.98$ to 0.80. Furthermore, the observed muons and electrons tend to be coplanar because of conservation of transverse momentum. By requiring $30^\circ < \theta_e < 150^\circ$ for the $\tau\bar{\tau}$ sample, and by requiring that the final state μe be collinear within 30° , we were able to reduce the two-photon contribution to a negligible level ($< 10^{-3}$ picobarns). The rate for case (c) is small and can be readily separated from the τ events.

The fact that the μ -hadron events produced by reaction (4) in our energy region are almost collinear can also be used to distinguish reaction (4) from μ -hadron events produced by the semi-leptonic decay of particles with c (charm) or b (bottom) quantum number. In the latter cases the muon is accompanied by hadrons emitted close to the muon direction.

The measured muon momentum and hadron energy for the $\tau\bar{\tau}$ candidates is in agreement with calculations based on the known decay properties of the τ lepton [29].

The acceptance is calculated using a Monte Carlo method to generate $\tau\bar{\tau}$ production from reaction (4) including radiative corrections. We obtain a detection efficiency of $\sim 10\%$ for τ pairs at various energies, when requiring one decay muon to be detected in association with a single electron, or one or more hadrons.

The resultant $e^+e^- \rightarrow \mu^+\mu^-$ and $\tau\bar{\tau}$ cross sections as a function of s are plotted in Figures 26 and 27 together with the QED prediction.

FIGURE 26.

Observed cross section for the reaction
 $e^+ e^- \rightarrow \mu^+ \mu^-$ compared to predictions of QED.

FIGURE 27.

Observed cross section for the reaction
 $e^+ e^- \rightarrow \tau^+ \tau^-$ compared to predictions of QED.

We see that from $q^2 = s = 169$ to $q^2 = 999 \text{ GeV}^2$ the data agree well with the predictions of QED for the production of a pair of point-like particles. In particular, Figure 27 represents the first evidence that the τ lepton is a point-like particle over a large range of q^2 , and demonstrates that it belongs in the same family as the electron and muon. To parametrize the maximum permissible size (radius) of the particles, we use a form factor:

$$F_\ell = 1 + \frac{q^2}{q^2 - \Lambda_{\ell\pm}^2} \quad (\ell = e, \mu, \tau).$$

By comparing our data with the cross sections including this form factor we find lower limits on the cut off parameters, at the 95% confidence level, summarized in Table II.

TABLE II

Cut-off parameters in GeV for e^+e^- , $\mu^+\mu^-$ and $\tau^+\tau^-$ production using leptonic form factors.

ℓ	electron	muon	tau
Λ_-	95	114	69
Λ_+	74	116	118

Thus, from Heisenberg's Uncertainty Principle, all the known charged leptons are point-like particles in their electromagnetic interactions, with characteristic radii $< 2 \times 10^{-16} \text{ cm}$.

4.2 Hadronic Final States

a) Hadron Identification

As described in section 3.3, the final selection for hadrons is made by scanning the events on an interactive graphics system after a preselection which includes energy and momentum balance cuts. In this scanning, hits observed in the drift tubes and in the drift chambers allow an easy determination of the event vertex. Thus beam gas events which do not come from the interaction region are readily recognized. The charged multiplicity observed in the drift tubes and the shower envelope in the counters is used to reject events of electromagnetic origin. For events which have low multiplicity both in the tubes and the counters, we require that a minimum fraction of the total energy is deposited in the hadron calorimeter (K in Figure 6) to further discriminate against purely electromagnetic final states.

The energy spectrum of the events passing the cuts is shown in Figure 28. For the analysis of hadronic final states we employed an additional energy cut of $E_{vis} > 0.5\sqrt{s}$ for measurement of total cross section (Section 4.2b), for most of the thrust analysis (Section 4.3a) and the study of inclusive muons in hadron events (Section 4.3c). This additional cut also reduces the contamination from beam-gas events, from two-photon processes [33] and $e^+e^- \rightarrow \tau^+\tau^-$ events which yield hadrons in the final state [34].

For reasons discussed in Section 4.3d we employed an even more restrictive cut of $E_{vis} > 0.7\sqrt{s}$ for study of gluon effects in thrust distributions (Section 4.3a), for jet analysis using Fox-Wolfram moments (Section 4.3b), for the discovery of 3-jet events (Section 4.3d) and determination of the strong coupling constant α_s (Section 4.3e). Both of these cuts are indicated by arrows in Figure 28.

FIGURE 28.

Energy distribution of hadron events satisfying the cuts described in Section 4.2a.

b) Total Hadronic Cross Section [35, 36, 37].

The total cross section for $e^+e^- \rightarrow \text{hadrons}$ was measured over a wide range of center of mass energies from 12 to 31.6 GeV, including results obtained by extended periods of running at a fixed beam energy and by a fine energy scan covering the range of 29.92 to 31.46 GeV. The results are expressed in terms of R:

$$R = \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-).$$

In the naive quark-parton model, the cross section for the hadron production process is simply given by the sum over flavors of the point-like $q\bar{q}$ pair cross sections. Using this picture with spin 1/2 massless quarks, and with three colors gives

$$R = 3 \sum_q e_q^2,$$

where e_q is the charge of the quark with flavor q . Considering the five known quark flavors (u, d, s, c and b), and correcting the naive model for gluon emission as predicted by QCD, we expect $R \approx 4$, over the entire PETRA energy range, with only a slight decrease in R with increasing beam energy.

The MARK J results for R are shown in Figure 29 along with the QCD predictions. The data consist of a total of 1812 hadron events corresponding to 3.5pb^{-1} . The results are summarized in Table III. Figure 29 shows that the data agree with the QCD predictions for five quark flavors (represented by the lower dashed line), and that there is no sign up to 31.6 GeV of a threshold in the hadron continuum corresponding to a new heavy quark of charge 2/3 such as the top quark (the upper line).

FIGURE 29.

The total relative hadronic cross section $R = (\sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-))$ at all energies by this experiment. Note that the point at 27.5 GeV corresponds to data taken over the range of 27.4 to 27.7 GeV, and the point at 30.7 GeV represents the energy scan from 29.9 to 31.5 GeV.

TABLE III

Results of R measurement. The errors are statistical only.

$\sqrt{s}$ [GeV]	R+ Δ R (statistical)
12.0	4.03 $\pm$ 0.28
13.0	4.1 $\pm$ 0.5
17.0	4.4 $\pm$ 0.6
22.0	4.7 $\pm$ 0.7
27.57 *)	3.8 $\pm$ 0.3
30.0	4.2 $\pm$ 0.3
29.90-31.46	4.33 $\pm$ 0.17
31.6	4.0 $\pm$ 0.5

*) = combination of 27.4 and 27.7 GeV data

The experimental R-values in Figure 29 have been corrected for initial-state radiative corrections ($\Delta R \approx -0.3$), for contamination of the sample by hadronic events produced by the two photon process $e^+e^- \rightarrow e^+e^- + \text{hadrons}$ ($\Delta R \leq -0.1$), and for the contribution of $e^+e^- \rightarrow \tau^+\tau^- \rightarrow \text{hadrons} + \text{leptons}$ (ΔR typically = -0.3). In addition to the statistical errors shown, there is an additional systematic uncertainty due to model dependence of the acceptance of 10%. The accuracy in evaluating the contributions of the two photon and tau-pair contributions to the hadronic event sample is limited by the lack of detailed experimental data on the high energy, high multiplicity states arising from these sources.

In addition to the $t\bar{t}$ contribution to the hadronic continuum, the toponium system should form one or more bound states, with the number of such states depending on the shape of the binding potential [35]. Interpretation of the vector mesons ρ , ω , ϕ , J , ψ' , T , T' , and T'' , as nonrelativistic $q\bar{q}$ bound states, or "quarkonia" leads to the prediction that the gap between the lowest bound state and the continuum is probably ~ 1 GeV, and very likely < 2 GeV.

In order to check for the existence of $t\bar{t}$ bound states lying below 31.6 GeV, the energy scan mentioned earlier was performed in 20 MeV center of mass energy steps (matching the r.m.s. energy spread of PETRA), with an average of $\sim 25\text{nb}^{-1}$ per point. The overall hadron event sample for the scan consists of 807 hadronic events corresponding to a time-integrated luminosity of 1945nb^{-1} . The results of the scan are

FIGURE 30.

R values measured during the energy scan between 29.9 and 31.5 GeV.
The line represents the predictions of QCD.

shown in Figure 30, along with the results obtained earlier at 30.0 and 31.6 GeV. The figure shows that the data are entirely consistent with the predictions of QCD for u, d, s, c and b quarks, that is, with a constant value of R over the whole range. No single point lies $\geq 3\sigma$ above the QCD line, and there is no indication of an upward slope with increasing energy signaling the onset of a new contribution to the continuum. The value of R averaged over the energy range of the scan is 4.33 ± 0.17 .

In order to set a quantitative upper bound on the possible production of a narrow resonance, the data in Figure 30 were fitted by a constant plus a gaussian:

$$R = R_0 + R_v e^{[-(\sqrt{s} - M)^2 / 2\Delta_w^2]}$$

where R_0 represents the non-resonant continuum, M is the mass of the resonance, Δ_w is the r.m.s. machine energy width, and R_v is the peak value of the resonant contribution. The largest value of R_v consistent with the data was determined by trying fits with M, the center of the gaussian, fixed at all the center of mass energies at which data were taken. The largest value of R_v was obtained at 31.32 GeV, corresponding to an upper limit on the resonance strength

$$\Sigma_v \equiv \int \sigma_v(w) dw, \text{ where } w = \sqrt{s},$$

of 33 MeV-nb at the 90% confidence level. Using the relation between the resonance strength, the width into e^+e^- (Γ_{ee}), the hadronic width (Γ_h),

the total width (Γ), and the hadronic branching ratio ($B_h \equiv \Gamma_h/\Gamma$):

$$\Sigma_v \equiv \int \frac{3\pi}{M^2} \frac{\Gamma_{ee} \Gamma_h}{(w-M)^2 + \Gamma^2/4} dw = \frac{6\pi^2}{M^2} B_h \Gamma_{ee}$$

we obtained

$$B_h \Gamma_{ee} < 1.3 \text{ KeV (90\% C.L.)}.$$

This upper limit excludes the production of a vector particle consisting of a $q\bar{q}$ bound state where the quark has charge $2/3$. On the basis of the experimental fact that Γ_{ee}/e_q^2 is approximately constant for the vector meson ground states ρ , ω , ϕ , J and T , as is predicted by duality arguments [35], one expects $\Gamma_{ee} \sim 5 \text{ KeV}$ for the lowest mass meson in the toponium family. Effects due to radiative corrections and the energy spread of the machine which influence the shape of the cross section have been taken into account in this analysis. Our results are in good agreement with results obtained by different methods from other PETRA groups, JADE, PLUTO and TASSO. (See section 4.4).

4.3 Jet Analysis

a) Thrust Distributions

Data at lower energies from SPEAR [38] have shown that the final state hadrons from the process $e^+e^- \rightarrow \text{hadrons}$ are predominantly collimated into two back-to-back "jets" in agreement with the expectations of simple models in which the time-like photon materializes initially into a quark antiquark pair. It is thus necessary to develop kinematic quantities which describe the jet-like nature of the MARK-J hadronic events.

A jet analysis of the hadronic events has been devised using the spatial distribution of the energy deposited in the detector. For each counter hit, a vector $\vec{E}^i$ (the energy flow) is constructed, whose direction is given by the position of the signal in the counter, and whose magnitude is given by the corresponding deposited energy. A parameter thrust (T) is defined as [37]

$$T = \max \sum |E_{||}^i| / E_{\text{vis}}$$

where $E_{||}^i$ is the parallel component of $\vec{E}^i$ along a given axis, and the maximum is found by varying the direction of this axis, and where the sums are taken over all counter hits. The resultant direction is thus the direction along which the projected energy flow is maximized.

For events in which the spatial distribution of energy is isotropic, T is expected to approach 0.5. This would be the situation if, for example, the virtual photon materializes into two very heavy quarks, each with a mass close to the beam energy. Such quarks would be produced almost at rest. On the other hand, pairs of light quarks would move at high speed and the Lorentz boost of their hadronic fragmentation products would result in the hadrons being produced in narrow jets collimated around the initial quark directions. Higher beam energies would result in narrower jets, so that T should approach the value 1. Thus, thrust measurements can be used as a sensitive method to detect the presence of a new threshold due to new heavy quarks.

These expectations are illustrated qualitatively in Figure 31 in which the thrust distribution expected just below and just above the

threshold for production of a new heavy quark is shown. Production of a new heavy quark would also result in lowering the average T as the energy is raised and the threshold is passed.

The normalized thrust distributions $\frac{1}{N} \frac{dN}{dT}$ for 13, 17, 22, and the combination of 27.4 and 27.7 GeV data (labelled 27 GeV combined) are shown in Figures 32 a-d along with the Monte Carlo predictions of a quark-parton model with u , d , s , c , and b quarks and no gluon emission.

NEW QUARK FLAVOR

FIGURE 31.

A sketch showing the qualitative change in the thrust distribution expected when the energy is increased and the threshold for production of a new quark flavor is crossed.

FIGURE 32.

Thrust distribution observed at $\sqrt{s} =$ a) 13, b) 17, c) 22, d) 27 GeV (see text). The solid line is the quark model prediction for u, d, s, c and b quarks with no gluon emission.

(The individual distributions at 27.4 and 27.7 GeV are in agreement with each other). As expected for production of final states with two jets of particles, the distributions become narrower and shift towards high thrust with increasing energy.

Figure 33 shows the normalized thrust distributions for combined data between 29.9 and 31.6 GeV where the measured energy of the selected events is at least 70% of $\sqrt{s}$. The curves show the Monte Carlo predictions with and without inclusion of gluons. As can be seen, these data lend support to the necessity of including gluons in the Monte Carlo program. The data is also compared with a Monte Carlo calculation which includes a charge $2/3$ t quark produced as described previously. For thrust smaller than 0.75, the QCD model with a top quark predicts 283 events. The QCD model without top quark predicts 79. We find 68. We thus conclude that there is no evidence for production of a new heavy quark with charge $q = \frac{2}{3}e$.

Figure 34 shows the average thrust $\langle T \rangle$ plotted at the six energies. The solid curves are from Monte Carlo calculations which include u , d , s , c and b quarks with gluon emission. The energy dependences of the data are smooth and show none of the steps which would have appeared at new quark thresholds.

Similar results are obtained by the JADE, PLUTO and TASSO collaborations on searches for new flavor production. (See section 4.4).

FIGURE 33.

The thrust distribution with a 70% energy cut for $\sqrt{s} \sim 30$ GeV.
The curves are predictions for various models as described in the text.

FIGURE 34.

Average value of thrust as a function of $\sqrt{s}$ together with the QCD prediction (solid line). The values expected from a phase space distribution and from a QCD model with a top quark are also shown.

b) Jet Analysis Using Fox-Wolfram Moments

Another method of jet characterization has been proposed by Fox and Wolfram. The simplest observables characterizing the three-dimensional shape of the energy distribution in a hadronic event are the Fox-Wolfram moments [39].

$$H_{\ell} = \sum_{i,j} \frac{|\vec{E}_i| |\vec{E}_j|}{E_{vis}^2} P_{\ell}(\cos\theta_{ij}), \text{ where } P_{\ell} \text{ is } \ell\text{th Legendre polynomial}$$

and

$$\pi_1 = \sum_{i,j,k} \frac{|\vec{E}_i| |\vec{E}_j| |\vec{E}_k|}{(E_{vis})^3} (\hat{E}_i \cdot \hat{E}_j \times \hat{E}_k)^2$$

The H 's parametrize the shape of the energy distribution by measuring the correlation between pairs of energy flow elements in terms of spherical harmonics. For cigar-shaped events expected from the process $e^+ + e^- \rightarrow q + \bar{q}$ the even moments H_2 and H_4 tend to be large, while they take relatively low values for events broadened on one side by the radiation of a hard non-collinear gluon ($e^+ + e^- \rightarrow q + \bar{q} + g$). Less significant differences are exhibited by the odd moments. The moment π_1 , involving a three-particle angular correlation, is sensitive to the planarity of events expected from gluon bremsstrahlung.

Since all these quantities are invariant against a split-up of the particle energy vector E into separately measured components $\vec{E}'_n$ ($\sum_n \vec{E}'_n = \vec{E}_1$) having a small angular spread, they are well suited for detectors not identifying individual particle tracks. Since they are also rotationally invariant, they are easily calculable and do not involve the definition of an event axis by a maximization process.

Figures 35 and 36 show the distributions $\frac{1}{N} \frac{dN}{dH_2}$ and $\frac{1}{N} \frac{dN}{dH_4}$ of the combined data taken at high energies ($\sqrt{s} > 27$ GeV). They are compared to predictions of QCD and of the quark-parton model with $\langle P_t \rangle = 225$ MeV/c, where P_t refers to the quark transverse momentum in the fragmentation process. The experimental distributions are in excellent agreement with QCD and clearly rule out the simple quark model at this particular $\langle P_t \rangle$. The same is true for the differential distribution $\frac{1}{N} \frac{dN}{d\pi_1}$, shown in Figure 37. The predictions of the quark model for these shape parameters are, however, sensitive to the $\langle P_t \rangle$ chosen, so that compatibility with the measured data can always be achieved at very high $\langle P_t \rangle$.

An unambiguous proof for the existence of hard non-collinear gluon bremsstrahlung necessitates therefore the use of observables less sensitive to the details of hadron jet development.

All moments and especially H_2 show strong kinematic correlations with thrust (see Section 4.3a) which also shows the above mentioned $\langle P_t \rangle$ dependence. The use of these variables thus does not provide a distinct advantage over the conventional analysis based on thrust.

FIGURE 35.

The distribution of the combined high energy data ($\sqrt{s} > 27$ GeV) in the Fox-Wolfram moment, H_2 compared to the prediction of QCD at $\alpha_s = 0.23$ and the quark model with $\langle P_t \rangle = 225$ MeV.

FIGURE 36.
The Fox-Wolfram moment H_4 distribution.

FIGURE 37.

The Fox-Wolfram moment π_1 distribution.

c) A Study of Inclusive Muons in Hadronic Events

In the framework of the six quark model for the weak decays of heavy quarks, (c, b and t) copious muon production is expected from the cascade decays $t \rightarrow b \rightarrow c$ [14,15]. The onset of production of a new heavy lepton would also lead to an increase in muon production. Thus, in addition to indications based on thrust and R measurements, a measurement of inclusive muon production in hadronic final states should provide a clear indication of the formation of top quarks or new leptons. All the hadron data for $\sqrt{s}$ from 12 to 31.6 GeV has therefore been analyzed and scanned in a search for muons. The sample of events used in the inclusive muon survey is a subsample of that used to measure R.

The main sources of muons in the hadron sample are decay products of bottom and charm quarks. Background contributions to the muon signal, arising from hadron punch through and decays in flight of pions and kaons have been calculated using the Monte Carlo simulation (Section 3.3c) to be $\sim 2\%$ at these energies. The contribution of $\tau^+\tau^-$ events to the μ^+ hadron sample becomes negligible when the total energy cut and the energy balance cut are applied.

Table IV. summarizes the results for the relative production rate of hadronic events containing muons. The table demonstrates once again the absence of new heavy mesons up to 31.6 GeV. For $\sqrt{s} \geq 30$ GeV the observed rate of $3.75 \pm 0.57\%$ agrees with the Monte Carlo predictions for five quark flavors, but is approximately 5 standard deviations away from the prediction which includes the top quark.

TABLE IV

Monte Carlo predictions and data for hadronic events which include muons.

E_{cm}	Luminosity nb^{-1}	Number of Hadron Events	Number of Muon Events	% of Muon Events	Monte Carlo (no top) %	Monte Carlo (with top) %
12	97.7	239	2	0.8 ± 0.6	1.1 ± 0.3	
13	53	95	1	1.05 ± 1.0	1.25 ± 0.3	
17	60	67	2	3.0 ± 1.7	2.0 ± 0.3	
27.4	414	188	11	5.85 ± 1.8	3.3 ± 0.4	
30 to 31.6	2804	1147	43	3.75 ± 0.57	4.5 ± 0.5	7.8 ± 0.5

Figure 38 shows the thrust distribution of the hadronic events containing muons compared to a QCD calculation containing five quark flavors. There is very good agreement between the data and the Monte Carlo prediction. The scarcity of events at low thrust in the figure also rules out the existence of the top quark.

d. Discovery of Three Jet Events

In this section we review the detailed topological analysis which was used by the MARK J to unambiguously isolate the 3-jet events arising from the emission of hard non-collinear gluons [40]. Examination of the azimuthal distribution of energy around the thrust axis was used to obtain a sample of planar events. An analysis of the spatial distribution of the energy flow for the planar event sample established the underlying 3-jet structure in agreement with the QCD predictions for $e^+e^- \rightarrow qqg$.

FIGURE 38.

The thrust distribution of high energy hadron events ($\sqrt{s} > 27$ GeV) containing at least one muon. The data (solid points) are compared to the prediction of QCD with five quark flavors.

In the reaction $e^+ + e^- \rightarrow \text{hadrons}$, the final states have many appearances: spherical, 2-jet like, 3-jet like, 4-jet like, etc. Events which fall into each of these visual categories can be produced by a variety of underlying processes:

$$e^+ + e^- \rightarrow \text{a phase space like distribution of hadrons}$$

$$e^+ + e^- \rightarrow q + \bar{q} \text{ (quark } \langle P_t \rangle = 200 - 500 \text{ MeV)}$$

$$e^+ + e^- \rightarrow q + \bar{q} + \text{gluon}$$

$$\text{and } e^+ + e^- \rightarrow q + \bar{q} + 2 \text{ gluons}$$

These alternatives make any conclusions which may be drawn from the jet-like appearance of individual events of little value in distinguishing between the models, nor can such an appearance provide information about the nature of the basic final-state constituents. Neutral particles carry a large fraction of the total energy. When the statistics are limited it is important to measure both charged and neutral particles. For a consistent analysis, one must collect a statistically significant number of events in a given kinematic region and compare the number of events in the region with specific model predictions on a statistical basis. A meaningful comparison with models must take into account the uncertainties in the models such as the quark P_t distributions, fragmentation functions, etc. Before conclusions can be drawn, background contributions from other processes must be understood and be kept small [41].

In order to exclude events where leading particles have escaped down the beam pipe, or where part of a broad jet is missed, we select only those events for which $E_{\text{vis}} > 0.7 \sqrt{s}$. This cut also eliminates two-photon events and events where a hard photon is emitted in the initial state. The drift tubes enable us to separate more distinctly the distribution of charged particles from neutrals. Since neutral particles carry away a large portion of the total energy, they will not only affect the axes of the jets, but will also affect the identification of individual jets.

The jet analysis of hadronic events and the search for 3-jet events is based on a determination of the three dimensional spatial distribution of energy deposited in the detector. This method is quite different from the pioneering method used by the PLUTO and TASSO groups [42]. The characteristic features of hard non-collinear gluon emission in $e^+e^- \rightarrow q\bar{q}g$ are illustrated in Figure 39. Because of momentum conservation the momenta of the three particles have to be coplanar. For events where the gluon is sufficiently energetic, and at large angles with respect to both the quark and anti-quark, the observed hadron jets also tend to be in a recognizable plane. This is shown in the upper part of the figure where a view down onto the event plane shows three distinct jets; distinct because the fragmentation products of the quarks and gluons have limited P_t with respect to the original directions of the partons. The lower part of the figure shows a view looking towards the edge of the event plane, which results in an apparent 2-jet structure. Figure 39 thus demonstrates that hard non-collinear gluon emission is characterized by planar events which

FIGURE 39.

A schematic view of the process $e^+e^- \rightarrow q\bar{q}g$, and the three resulting hadron jets showing the axes used to describe the event.

may be used to reveal a 3-jet structure once the event plane is determined.

The spatial energy distribution is described in terms of three orthogonal axes called the thrust, major and minor axes. The axes and the projected energy flow along each axis T_{thrust} , F_{major} and F_{minor} are determined as follows:

(1) The thrust axis, $\vec{e}_1$, is defined as the direction along which the projected energy flow is maximized. The thrust, T_{thrust} and $\vec{e}_1$ are given by

$$T_{\text{thrust}} = \max \frac{\sum_i |\vec{E}^i \cdot \vec{e}_1|}{\sum_i |\vec{E}^i|}$$

where $\vec{E}^i$ is the energy flow detected by a counter as described above and $\sum_i |\vec{E}^i|$ is the total visible energy of the event (E_{vis}).

(2) To investigate the energy distribution in the plane perpendicular to the thrust axis, a second direction, $\vec{e}_2$, is defined perpendicular to $\vec{e}_1$. It is the direction along which the projected energy flow in that plane is maximized. The quantity F_{major} and $\vec{e}_2$ are given by

$$F_{\text{major}} = \max \frac{\sum_i |\vec{E}^i \cdot \vec{e}_2|}{E_{\text{vis}}}; \quad \vec{e}_2 \perp \vec{e}_1$$

(3) The third axis, $\vec{e}_3$ is orthogonal to both the thrust and the major axes. It is found that the absolute sum of the projected energy flow along this direction, called F_{minor} , is very close to the minimum of the projected energy flow along any axis, i.e.,

$$F_{\text{minor}} = \frac{\sum_i |\vec{E}^i \cdot \vec{e}_3|}{E_{\text{vis}}} \sim \min \frac{\sum_i |\vec{E}^i \cdot \vec{e}|}{E_{\text{vis}}}$$

If hadrons were produced according to phase-space or a $q\bar{q}$ two-jet

distribution, then the energy distribution in the plane as defined by the major and minor axes would be isotropic, and the difference between F_{major} and F_{minor} would be small. Alternatively, if hadrons were produced via three-body intermediate states such as $q\bar{q}g$, and if each of the three bodies fragments into a jet of particles with $\langle P_t^h \rangle \sim 325$ MeV, the energy distribution of these events would be oblate (P_t^h refers to the final state hadrons). Following the suggestion of H. Georgi, the quantity oblateness, O , is defined as

$$O = F_{\text{major}} - F_{\text{minor}}$$

The oblateness is $\sim 2 P_t^{\text{gluon}} / \sqrt{s}$ for three-jet final states and is approximately zero for final states coming from a two-jet distribution.

Figure 40a shows the event distribution as a function of oblateness for the data at $\sqrt{s} = 17$ GeV where the gluon emission effect is expected to be small. The data indeed agree with both models, although the prediction with gluons is still preferred.

Figure 40b shows the event distribution as a function of oblateness for part of the data at $27.4 \leq \sqrt{s} \leq 31.6$ GeV as compared with the predictions of $q\bar{q}g$ and $q\bar{q}$ models. Again, in the $q\bar{q}$ model we use both $\langle P_t^h \rangle = 325$ MeV and $\langle P_t^h \rangle = 425$ MeV. The data have more oblate events than the $q\bar{q}$ model predicts, but they agree with the $q\bar{q}g$ model very well. Figure 40b also illustrates a useful feature of the oblateness: it is quite insensitive to the details of the fragmentation process.

To study the detailed structure of the events we also divided each event into two hemispheres using the plane defined by the major and minor axes, and separately analyzed the energy distribution in each hemisphere as if it were a single jet. The jet having the smaller P_t with respect to the thrust axis is defined as the "narrow" jet (n) and the other as a

FIGURE 40.

Differential oblateness distribution at a) $\sqrt{s} = 17$ GeV and b) at high energies (combined data) compared to the predictions of QCD (solid line) and quark model (dashed lines).

FIGURE 41.

Energy flow diagrams for two high energy hadronic events viewed in the major-thrust plane.

"broad" jet (b). In each hemisphere we calculate the oblateness, $O_n = 2(F_{\text{major}}^n - F_{\text{minor}}^n)$, and $O_b = 2(F_{\text{major}}^b - F_{\text{minor}}^b)$, and thrusts T_n and T_b .

One approach to analyzing the flat events for a possible 3-jet structure is illustrated by Figure 41. The figure shows the energy flow diagram for each of two high energy hadronic events, viewed in the event plane determined by the major and thrust axes. The energy flow diagram is a polar coordinate plot in which we summed the energy vectors E^i in 10° intervals. Each point in the plot represents the summed energy in an angular interval, with the radius given by the magnitude, and the azimuth given by the center of the angular interval in the event plane. The two events in the figure both show an apparent 3-jet structure.

As mentioned earlier, however, the examination of individual event appearances cannot be used to establish the underlying 3-jet structure characteristic of $q\bar{q}g$ final states. This is demonstrated by Figure 42, which shows two low thrust, planar events at 12 GeV center of mass energy. The events also show a distinct multi-jet structure. It should be noted that all the measured distributions at low energies (thrust, oblateness, etc.) are well described by a simple $q\bar{q}$ model, so that the suggestive event appearances are unrelated to gluon emission, but are dominated by fluctuations in the quark fragmentation process. The views of the events in the minor-thrust plane (looking at the edge of the event plane) also show that the events are planar.

FIGURE 42.

Energy flow diagram. Two events measured at $\sqrt{s} = 12 \text{ GeV}$ with the lines showing the direction and magnitude of energy deposited in the calorimeter displayed in two projections. The events appear to have a multi-jet structure in the thrust-major plane. The view in the thrust-minor plane shows the events are flat.

At the 1979 International Symposium on Lepton and Photon Interactions at Fermilab, all DESY groups (JADE, MARK J, PLUTO and TASSO) reported evidence for hard gluon emission. Following the conference each group published their findings [43]. The first statistically relevant results, establishing the 3-jet pattern from $q\bar{q}g$ of a sample of hadronic events were presented by the MARK J collaboration. These are shown in Figure 43 in which a sample of the events with low thrust and high oblateness, where the gluon emission effect is expected to be relatively large, is selected for detailed examination. The key feature of this figure is that it consists of the superposition of an entire event sample, and thus displays the average behavior of the energy flow for planar events at high energy. The event sample is composed of 40 events with $T < 0.8$ and $O_b > 0.1$ out of 446 hadronic events obtained up to the time of the Fermilab Conference in the energy range of 27-31.6 GeV.

In the energy flow plot, all events are rotated to lie in a plane; they are then oriented so that the longest jet is at 0° and the second longest is in the lower half plane. Therefore, all events contributing to the substantial third jet do have longer jets in the two other regions. In addition, it is clear that none of the events has substantial energy flow in the regions between the jets because the dips in these bins go nearly to zero because the energy is always positive. All of the events thus do have a three-jet structure. Furthermore, each event has been examined by physicists and found to be three jet like in appearance like those shown in Fig. 41.

The calculated Monte Carlo model predictions based on QCD in both the rate and shape of three jet events in the figure are compatible with the data with $\chi^2 = 67$ for 70 degrees of freedom. The accumulated energy distribution in the lower part of the figure, showing the view in the plane defined by the thrust and minor axes, exhibits a flat distribution consistent with the model predictions.

FIGURE 43.

- a. Energy distribution in the plane defined by the thrust and major axes for all events with $T < 0.8$ and $0_b > 0.1$ at $\sqrt{s} = 27.4, 30$ and 31.6 GeV obtained up to the time of the 1979 Fermilab Conference. The radial distance of the data points is proportional to the energy deposited in a 10° bin. The superimposed dashed line represents the distribution predicted by QCD.
- b. Measured and predicted energy distribution in the plane defined by the thrust and minor axes, which shows only 2-jets.

These results can be contrasted to those obtained with a simple phase space model. When viewed in the major-thrust plane, phase-space shows three nearly identical lobes due to the method of selection used. However, at $\sqrt{s} = 30$ GeV these lobes are different in appearance from the jets shown in Figure 43. In general, one expects the three jets from $q\bar{q}g$ to become slimmer and easier to distinguish from the phase-space distribution as the center-of-mass energy increases. Using a χ^2 fit of the phase-space energy distribution to the data we found that $\chi^2 = 222$ for 70 degrees of freedom. Therefore, phase-space is inconsistent with the data. Furthermore, large contributions of phase-space distributions are ruled out by our thrust distributions as shown in Figures 32-34.

For the analyses performed in the earlier part of 1979, as shown in Figures 40 and 43, we used a Monte Carlo model implemented by P. Hoyer et al. [44]. In the analysis discussed below, the Monte Carlo of Ali et al. [12] was adopted. As discussed in Section 3.3c, this model incorporates higher order QCD effects, the q^2 evolution of the quark and gluon fragmentation functions and the weak decays of heavy quarks. The QCD predictions presented in Figures 40 and 43 are not noticeably different for the two models.

Including the running in the latter part of 1979, the total number of hadronic events with $E_{vis} \geq 0.7 \sqrt{s}$ has increased to 1220 for $\sqrt{s} > 27$ GeV [45].

Figures 44 and 45 show the event distribution as a function of O_n and O_b , compared to the predictions of the QCD model [46] and of two quark-parton models with quark $\langle p_t \rangle = 300$ MeV and 500 MeV respectively [47]. Figure 44 shows that the narrow jet distribution agrees with the various models indicating that it comes from a single quark jet. Figure 45, however, shows that the quark-parton models severely underestimate the number of events with $O_b > 0.3$ while the QCD model correctly predicts the observed distribution.

FIGURE 44.

The narrow jet oblateness distribution $\frac{1}{N} \frac{dN}{dO_N}$ for all hadron events with measured energy $E_{vis} > 0.7 \sqrt{s}$. The data are compared to the predictions of the QCD model and to two quark-antiquark models with $\langle P_t \rangle = 300$ MeV and $\langle P_t \rangle = 500$ MeV respectively.

FIGURE 45.
The broad jet oblateness distribution $\frac{1}{N} \frac{dN}{dO_b}$
under the same condition as Figure 44.

The T_n and T_b thrust distributions of the flat events in the region $O_b > 0.3$ are shown in Figures 46 and 47 along with the QCD and high P_t $q\bar{q}$ models. The observed distribution is also compared to a "flattened" $q\bar{q}$ model in which the quarks have $\langle P_t \rangle = 500$ MeV in the thrust-major plane and $\langle P_t \rangle = 300$ MeV in the thrust-minor plane. The T_n distribution in Figure 46 is in good agreement with the QCD model predictions and has the same general shape as the thrust distribution for high energy $e^+e^- \rightarrow q\bar{q}$ reactions shown in Figures 32 and 33. As expected the T_b distribution, however, is much broader than that of T_n and agrees only with the QCD predictions.

The distributions in Figures 46 and 47 demonstrate that the relative yield of flat events, and the shape of these events as measured by T_n and T_b , can only be explained by the QCD model. The distributions T_n and T_b further exclude phase space (which peaks at lower thrust values) as well as $q\bar{q}$ models as possible explanations of the energy flow plots.

The development of the 3-jet structure with decreasing thrust and increasing oblateness, as predicted by QCD [48], is shown in a series of energy flow diagrams in Figures 48-50.

As seen in Figure 48 the events at high thrust values are dominated by a 2-jet structure characteristic of $e^+ + e^- \rightarrow q + \bar{q}$. In Figure 49, where the thrust is lower, we begin to see the appearance of the gluon jet; and in Figure 50 the 3-jet events are predominant. It is important to note that in all three cases the data agree with the QCD model prediction,

FIGURE 46.

The thrust distribution of the narrow jet for events with $O_p \geq 0.3$. Also shown are the various model predictions including a flattened q $\bar{q}$ (500, 300) discussed in the text. Note the narrow jet thrust distribution is consistent with thrust distribution of all the hadron events labelled "ALL DATA". This curve is normalized to the data of Figure 33.

FIGURE 47.
The thrust distribution of the broad jets for events
with $O_b > 0.3$. The curves are discussed in the text.

FIGURE 48.

Energy flow diagram in the thrust-major plane for high energy data (27-31.6 GeV) with $T > 0.9$.
The solid line is the prediction of QCD.

FIGURE 49.

Same as Figure 48 for events with $0.8 \leq T \leq 0.9$ and broad jet oblateness $Q_j > 0.1$.

FIGURE 50

Same as Figure 48 for events with $T < 0.8$ and $O_b > 0.1$.

showing the increased incidence of hard non-collinear gluon emission with decreasing thrust and increasing oblateness. The energy flow in the minor-thrust plane contains only two nearly identical lobes similar to the narrow jet in Figure 43b, in good agreement with QCD predictions. In Figure 51 we unfold the energy flow diagram of Figure 50 to see more clearly the comparison of the data with the predictions of QCD, $q\bar{q}$ ($\langle P_t \rangle = 500$ MeV), and a "mixed model" consisting of a combination of $q\bar{q}$ and phase-space contributions. All models in Figure 51 are normalized to have the same areas (as the data) before the individual cuts are imposed. The normalization for the mixed model was determined by adjusting the $q\bar{q}$ ($\langle P_t \rangle = 300$ MeV) and phase-space contributions to agree with the measured thrust distribution as illustrated in Figure 52. As seen in Figure 51, only QCD can describe the observed 3-jet structure. The conclusions obtained by the JADE, PLUTO and TASSO collaborations on their tests of Q.C.D. and studies of multi-jet events are in good agreement with us. (See section 4.4).

A very powerful method to eliminate phase-space as a source of the 3-jet events and in fact eventually to study the nature of the individual jets is shown in Figure 53. Here the thrust distributions

FIGURE 51.

The unfolded energy flow diagram of Figure 50 as compared to QCD, the quark model ($\langle P_t \rangle = 500 \text{ MeV}$) and a mixed $q\bar{q}$ and phase space model (see text).

FIGURE 52.

Illustration of the method used in determining the maximum permissible admixture of phase-space to $q\bar{q}$ in the mixed model shown in Figure 51.

FIGURE 53.

Thrust distribution $\frac{1}{N} \frac{dN}{dT}$ for each individual jet in the 3-jet sample of Figure 50 which were selected by using $O_b > 0.1$ and thrust < 0.8 . The corresponding distribution normalized to the same total number of 3-jet events are also shown for QCD (solid curve) and phase-space model (dashed curve).

of each of the jets, separated according to their position in the energy flow figure are compared to the expectations of QCD and phase-space. The thrust distributions agree well with the QCD prediction but are in strong disagreement with phase space predictions.

e) Determination of the Strong Coupling Constant α_s

Recent experiments on scaling violations in lepton inelastic scattering [49], on high P_t events in dilepton production by hadrons [50], and multi-jet events in e^+e^- annihilations [37, 40, 51] all indicate that the results are explained naturally in the quantum chromodynamics (QCD) theory of the strong interaction of quarks and gluons [7]. The strong coupling constant $\alpha_s(q^2)$ between quarks and gluons has been measured indirectly in quarkonium bound states [52], and in deep inelastic experiments [49]. At PETRA, where the q^2 is much larger, computations are expected to be more reliable. In addition, high energy e^+e^- annihilations offer a more direct way of measuring α_s and testing perturbative QCD because it is expected to give rise to multi-jets which can be systematically identified.

The 3-jet events discussed in the previous section, which consist of $q\bar{q}g$ fragmentation products with relatively small backgrounds from fluctuations of phase-space-like processes or quark-antiquark intermediate states, allow us to make further comparisons of the event properties with the predictions of QCD. In particular the relative yield of 3-jet events and the shape distribution gives a way to measure directly α_s , the strong coupling constant.

We used several methods in determining the strong coupling constant α_s , including:

- 1) the average oblateness $\langle O_b \rangle$,
- 2) the fraction of events with $O_b > 0.3$,
- 3) the relative yield of events with $O_b - O_n > 0.3$ where O_n is constrained to be greater than zero.

For each quantity we allowed α_s to vary in the QCD model, and we then determined the range of α_s values for which the QCD model predictions agree with the data within errors. In particular, the samples obtained using criteria 2) and 3) consist predominantly of 3-jet events from $e^+e^- \rightarrow q\bar{q}g$, in which the gluon emitted is both very energetic and at a large angle with respect to both the quark and antiquark. This leads to an event sample where the number of events in the sample is a quasi-linear function of α_s , and in which the influence of non-perturbative effects which are not calculable in QCD is minimal. For criterion 2), for example, we observed 161 events, which matches the QCD model with $\alpha_s = 0.23$. The $e^+e^- \rightarrow q\bar{q}$ contribution is calculated to be 21 events. The predominance of $q\bar{q}g$ in a sample with $O_b > 0.3$ is maintained even if $\langle P_t \rangle$ is allowed to vary from 225 MeV to 500 MeV in the model. With $\langle P_t \rangle = 500$ MeV the $e^+e^- \rightarrow q\bar{q}$ contribution is calculated to be 58 events.

The methods described above yield a self-consistent set of α_s values, as illustrated in Figure 54. On the basis of the results of the three methods we obtain

$$\alpha_s = 0.23 \pm 0.02 \text{ (statistical error)} \\ \pm 0.04 \text{ (systematic error)}$$

The large systematic error was mostly due to uncertainties in QCD calculations [12]. For method 2) the range of α_s due to variation in $\langle P_t \rangle$ from 225 to 400 MeV is ± 0.01 and the change in α_s due to different cuts in O_b from $O_b > 0.3$ to $O_b > 0.15$ or cuts in O_n from no cuts to $|O_n| < 0.1$, is -0.01 . For method 2), changing the fragmentation function $zD(z)$ to $1-z$ for u, d and s quarks and $zD(z)$ to z for c and

FIGURE 54.

The left graph: The average value of oblateness $\langle O_b \rangle$ for all events with $E_{\text{vis}} \geq 0.7 \sqrt{s}$ as a function of α_s , computed by varying α_s in the QCD model.

The right graph: The fraction of hadronic events with $O_b > 0.3$ (σ_{3j}) as a function of α_s in the QCD model.

b quarks does not change the α_s value noticeably. Tables V and VI show in detail the change of α_s with respect to the O_b cuts and O_n cuts.

Our value of α_s is consistent with the value of the JADE group obtained with a different Monte Carlo program. (See section 4.4). The value of α_s [45, 53] is in qualitative agreement with the values obtained in deep inelastic lepton nucleon scattering experiments [49], and in the analysis of the quarkonium states [52]. However, detailed comparison among these results cannot yet be made without accurate higher order QCD calculations.

TABLE V

Value of α_s with different O_b cuts, without cuts in O_n and $P_t = 247$ MeV.

$O_b >$	α_s
0.15	0.22 ± 0.02
0.20	0.22 ± 0.02
0.25	0.22 ± 0.02
0.30	0.23 ± 0.02

TABLE VI

Value of α_s with different $|O_n|$ cuts, with $O_b > 0.3$ and $\langle P_t \rangle = 247$ MeV.

$ O_n <$	α_s
No Cuts	0.23 ± 0.02
0.24	0.23 ± 0.02
0.20	0.23 ± 0.02
0.16	0.23 ± 0.02
0.12	0.22 ± 0.03
0.08	0.22 ± 0.03

4.4 Comparison with other experiments at PETRA

Our detector uses calorimetric techniques which are very different from other PETRA groups (JADE, PLUTO and TASSO) which use solinoidal magnetic field followed by particle identification devices. These differences in technique imply that the event selection criteria, Monte Carlo analysis programs, and the assignment of systematic errors are quite different. However, despite the different techniques used the results of all the PETRA groups are complementary and supportive of each other in their physics conclusions on the test of QED [54], on the measurement of R, the search for new flavors [51, 55] and on the effects of hard gluon jets [51, 56].

5) Conclusions

In the first year of experimentation with a simple detector, we have obtained the following results

- 1) We have established the validity of quantum electrodynamics to a distance $< 2 \times 10^{-16}$ cm. Electrons, muons and tau leptons are point-like with sizes smaller than 2×10^{-16} cm.
- 2) The relative cross sections and event distributions show that there is no new charge $2/3$ quark pair production up to $\sqrt{s} = 31.6$ GeV.
- 3) The energy flow of events at high energies is in good agreement with quantum chromodynamics. The quantity of flat events and their distributions disagree with the simple quark antiquark model prediction.
- 4) We have discovered 3-jet events; the rate of their production and their distribution agree with the prediction of QCD.
- 5) We have measured the strong interaction coupling constant α_s .

There are two reasons which made it possible to obtain these results:

- 1) In e^+e^- collisions, the signal is clear and unique. Every event has a definite physical interpretation and can be analyzed in terms of QED or QCD. This is quite different from our previous experience with proton proton collisions where the signal of the virtual photon events is less than one part in 10^6 of the background.

- 2) PETRA was reliably constructed and available for use by experimentalists from the beginning.

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