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SEARCH FOR FREE QUARKS AT PEP*

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ABSTRACT

The results of a search for fractionally charged particles produced in e^+e^- annihilation at 29 GeV/c^2 are discussed. Results from cosmic-ray searches for fractionally charged particles, tachyons, and massive particles using the same detector are also presented.

INTRODUCTION

With the commissioning of each new high energy accelerator a new chapter in the search for free quarks is begun. Inevitably the new possibilities opened up by increased energies or luminosities entices a few brave souls to

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search for the tantalizing particles with third integer charges proposed eighteen years ago as the ultimate constituents of matter. I will present some results of a search at PEP[1] during its first year of operation which followed this tradition. The experiment was sensitive to quarks produced in e^+e^- annihilation at 29 GeV center of mass energy, either exclusively in pairs ($e^+e^- \rightarrow q\bar{q}$) or inclusively along with hadrons ($e^+e^- \rightarrow q\bar{q}\ X$). The detector was also exploited to search for exotic particles, including quarks, in cosmic rays and I will present these results as well. The experimental work was completed in the summer of 1981 but the analysis is just now being completed and some of the results are still preliminary.

Modern searchers for free quarks must somehow remain enthusiastic in the face of the widely held theoretical conjecture that free quarks will never be discovered because they are permanently confined within hadrons.[2] From an experimental point of view the idea of quark confinement must be rigorously tested despite theoretical bias. This is especially true in light of the positive evidence for fractionally charged matter reported by Fairbank et al.[3] Free quarks with $Q = \pm 1/3$ or $Q = \pm 2/3$ are obvious candidates to explain Fairbank's result but free fractional charge does not necessarily mean free quarks. Indeed the existence of fractionally charged leptons or fractionally charged hadrons made up of integrally- and fractionally-charged quarks are not inconsistent with color confinement. Most free quark searches (including the ones I will describe) are also sensitive to other possible fractionally-charged particles.

Apart from the stable matter searches, most searchers for free quarks have concentrated on particles produced in cosmic rays or in hadronic collisions at accelerators. When the present experiment was proposed the possibility that quarks might be produced electromagnetically had been largely neglected. The effects of the existence of quarks in particularly dramatic in e^+e^- annihilation and this process is the best available method for concentrating energy in space. When compared to the "softer" and less well understood collisions of hadrons it may be a more likely place to look for liberated quarks.

EXPERIMENTAL METHOD

The FQS detector was designed to measure charge. The method was simple and there was no magnetic field. The charges of particles were determined from measurements of ionization energy loss (dE/dx) in plastic scintillators and velocity ($\beta = v/c$) by time-of-flight (TOF). To reduce the effect of the Landau tail and to improve resolution the most probable dE/dx was estimated with a truncated average of many individual dE/dx measurements. The charge (Q) was determined from the Bethe-Bloch formula

$$dE/dx = (Q^2/\beta^2)\ f(\beta).$$

where $f(\beta)$ is a slowly varying function of β. To a good approximation,

$$dE/dx \approx Q^2/\beta^2\ (dE/dx)_{MIP},$$

where $(dE/dx)_{MIP}$ is the ionization loss for a relativistic (minimum ionizing) $Q = 1$ particle.

A view of the FQS detector along the beam direction is shown in Fig. 1. The detector solid angle was 1/3 × 4π sr.

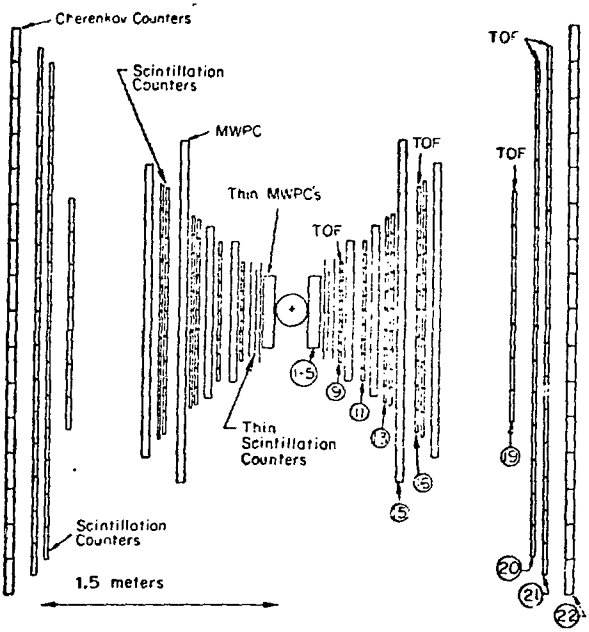

Fig. 1. Elevation view of the detector as viewed along the beam pipe. The elements are numbered sequentially from 1 to 22 moving outward from the IR (some of the layers are numbered in the figure). The "thin" MWPC's (layers 1 to 5) are not shown individually. Scintillation layers 9, 16, 19, 20, and 21 are equipped with TOF electronics.

The detector consisted of two identical arms. Each arm was made up of 12 scintillation counter hodoscopes, 9 multiwire proportional chambers (MWPC), and a lucite Cherenkov counter hodoscope. Each counter had a photomultiplier (PM) at each end. A subset of 5 planes of scintillation counters (see Fig. 1) measured TOF over a 1.5 to 2.6 m flight path depending on the track angle.

The lucite Cherenkov counters gave a check on the velocity determination; they triggered on particles with $\beta \gtrsim 0.7$.

The chamber gas was 80% Ar - 20% CO_2. The inner 5 MWPC's were 1.6 cm thick and the outer MWPC's were 2.4 cm thick.

The inner 5 MWPC's measured dE/dx as well as position and in conjunction with the first 3 layers of dE/dx counters they were used to make a highly-interacting quark search to be discussed below. Table I lists the detector components, their orientation, and thickness in interaction lengths.

PERFORMANCE OF THE DETECTOR AND EXPERIMENTAL CHECKS

Cosmic rays were used to calibrate and align detector components. A serious consideration was to ensure sensitivity to lightly ionizing particles.

Scintillators: A cosmic ray pulse height spectrum from a typical scintillator is shown in Fig. 2. Scintillator attenuation length effects were accounted for by using the geometric mean of the two PM pulse heights. The low pulse heights in the figure were due to particles which "clip" scintilator edges. In our analysis this effect was accounted for by adding in the corrected pulse height from the adjacent counter for tracks near edges. The typical counter resolution was ≈28% FWHM for $(dE/dx)_{MIP}$ corresponding to

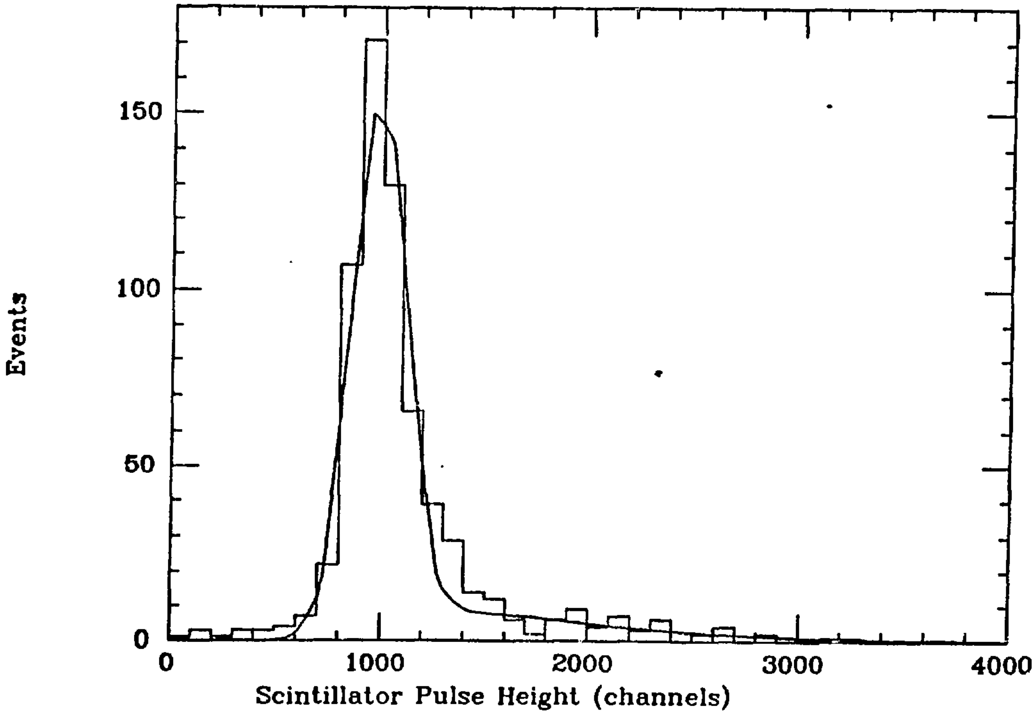

Fig. 2. A dE/dx spectrum from cosmic rays from a typical scintillator.

$\approx$150 photoelectrons. Discriminator thresholds for TOF were set at $\approx$1/30 of $(dE/dx)_{MIP}$. Counters used in the trigger were determined to be fully efficient for 1/10 × $(dE/dx)_{MIP}$ in tests which utilized the low pulse heights from edge hits.

After calibration and pulse height corrections the single counter time resolution for cosmic rays was $\sigma \approx 150$ psec. The resolution was slightly poorer for beam events, $\sigma \approx 180$ psec. The time resolution depends on pulse height and increases to $\sigma \approx 650$ psec for 1/9 × $(dE/dx)_{MIP}$.

Table I. The components of the quark detector

Layer	Detector Type	Orientation Angle*	# of Elements	Pulse Height	TOF	Cumulative Collision Lengths (Normal Incidence)
1	thin MWPC	+45°		Yes		
2	thin MWPC	-45°		Yes		
3	thin MWPC	90°		Yes		
4	thin MWPC	0°		Yes		
5	thin MWPC	0°		Yes		.005
6	thin scint.	90°	8	Yes		.008
7	thin scint.	0°	8	Yes		.011
8	thin scint.	90°	10	Yes		.014
9	scint.	0°	10	Yes	Yes	.031
10	MWPC	80°				.045
11	scint.	0°	10	Yes		.072
12	MWPC	0°				.086
13	scint.	0°	10	Yes		.116
14	scint.	0°	10	Yes		.145
15	MWPC	100°				.160
16	scint.	0°	10	Yes	Yes	.202
17	scint.	0°	10	Yes		.243
18	MWPC	0°				.258
19	scint.	0°	7	Yes	Yes	.304
20	scint.	0°	15	Yes	Yes	.351
21	scint.	0°	16	Yes	Yes	.398
22	Cerenkov	0°	16	Yes		.492

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*For scintillation counters, 0° means the long axis is parallel to the beam line. For MWPC's, 0° means the anode wires are parallel to the beam line.

MWPC: Thresholds were set at 1/50 of $(dE/dx)_{MIP}$. Lightly ionizing particles were simulated by observing cosmic rays with reduced chamber voltage and thus reduced gain. A check was made with a thinner chamber and different chamber gas (80% He - 20% CH_4) to verify that the procedure was valid including the effects of primary ionization statistics.[4]

COSMIC-RAY SEARCH EXPERIMENTS

The FQS detector provided several valuable features for cosmic-ray searches including high segmentation, high redundancy, good tracking, and excellent TOF resolution. In general it was much more elaborate than detectors previously employed. Exploiting these characteristics we conducted single-particle searches for fractional charge, tachyons, and massive particles in cosmic rays. A more detailed discussion of these cosmic-ray searches are found in Refs. 5 and 6.

Search for fractional charge in cosmic rays: For cosmic rays the acceptance of the FOS detector was at large zenith angles (45° to 90°). The geometric admittance was 4.0×10^3 cm^2sr. It has been noted[7] that high zenith angle searches may be more sensitive than vertical searches to penetrating fractionally charged produced in high energy air showers because less penetrating particles (presumably of lower mass) would be effectively dispersed or absorbed by the intervening atmosphere. However, very few high zenith angle searches have been made.[7,8,9]

Three fractionally-charged candidates with low velocity were reported in a previous vertical search.[10] Although unconfirmed by a second experiment[11] such low velocity particles would have been missed in previous experiments without TOF.

Cosmic-ray data for the fractional charge search were collected for $\approx 2.3 \times 10^6$ sec. About 2/3 of the data were obtained while the detector was enclosed in the $\approx$ 250 g/cm^2-thick PEP shielding tunnel and the rest after it was removed. The trigger requirement was at least one hit in layer 9 on either arm and at least one hit in 16 on each arm. Using MWPC and scintillator information a loose tracking requirement identified $\approx$ 85% of the $\approx 10^7$ triggers as single particle events. After a series of cuts to eliminate several systematic effects (primarily due to showering particles, interactions in the detector, and errors due to mistracking) no candidates for particles with $Q \lesssim 0.8$ were found. The analysis efficiency was 98% for $Q = 1/3$ and 95% for $Q = 2/3$ as determined by Monte Carlo. The final flux limits (90% C.L.) are shown in Fig. 3. Table II compares our limits with those of previous high zenith angle searches and previous searches with TOF.

Table 2. Searches for Fractional Charge at Large Zenith Angles

Expt.	Range of	Flux		Flux	
	Zenith Angles	Q=1/3	β	Q=2/3	β
Ref. 8	45°$\lesssim\theta\lesssim$90°	$\lesssim 2.3\times10^{-10}$	≈1	---	---
Ref. 7	75°$\lesssim\theta\lesssim$90°	$\lesssim 1.7\times10^{-8}$	≈1	$\lesssim 1.7\times10^{-8}$	≈1
Ref. 9	θ ≈84°	---	---	$\lesssim 5.1\times10^{-8}$	0.5-0.9
This expt.	45°$\lesssim\theta\lesssim$90°	$\lesssim 2.9\times10^{-10}$	0.6-1.0	$\lesssim 2.6\times10^{-10}$	0.1-1.0
		$\lesssim 2.5\times10^{-10}$	0.1-0.6		

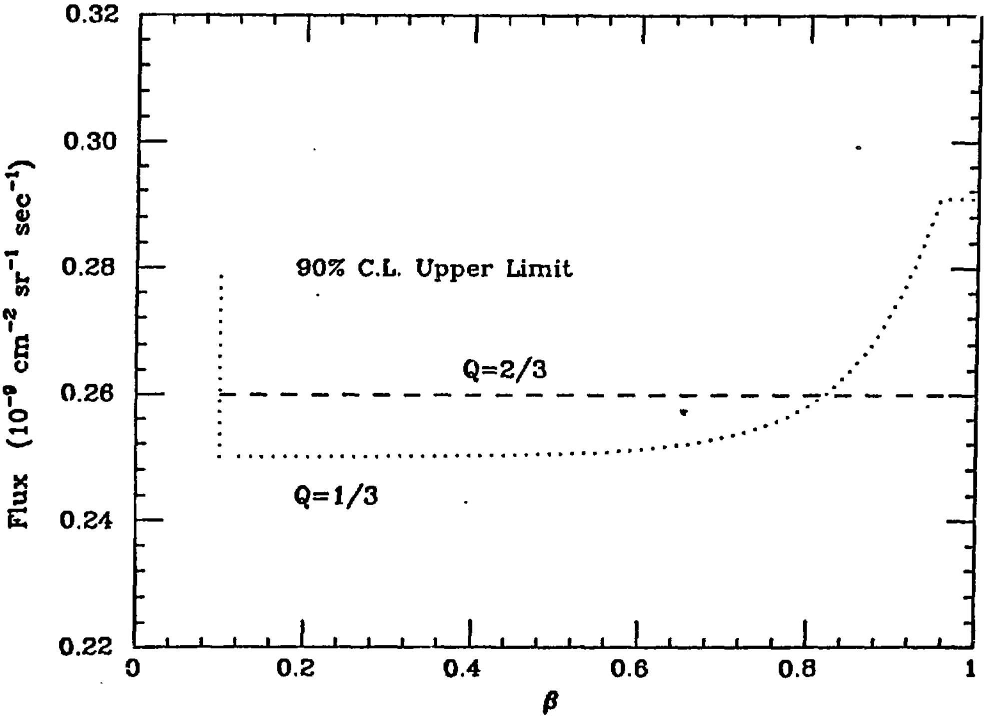

Fig. 3. Flux limits from the present cosmic ray single particle fractional charge search as a function of β.

Tachyon Search: Most cosmic ray searches for faster-than-light particle looked for particles preceding the relativisitc front of air showers. From time to time positive evidence has been claimed but none have survived subsequent scrutiny.[12]

Only two previous experiments[13,14] measured particle velocity directly. Both used the TOF method and large plastic scintillators. Ashton[14] obtained a limit of

$\Phi_t < 2.2 \times 10^{-5}$ cm^{-2} sr^{-1}sec^{-1} for particles with $\beta > 1.6$ producing a signal corresponding to a dE/dx of > 4 MeV/cm in plastic scintillator.

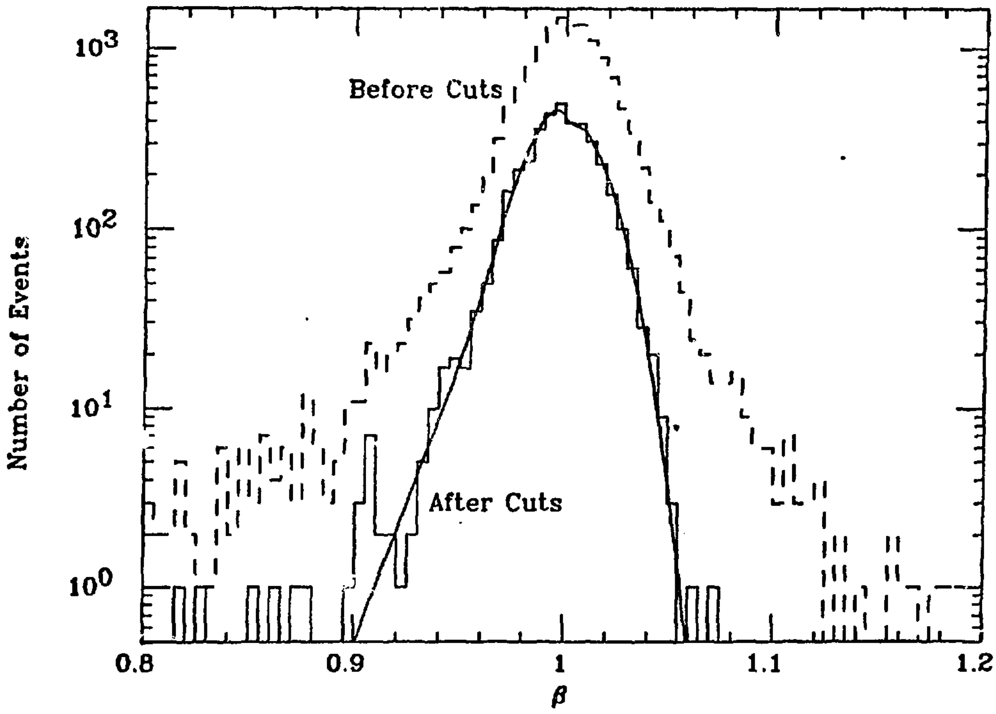

Fig. 4. Experimental velocity distribution before and after cuts to reduce the effects of showering particles. (See text).

In the present experiment the most serious systematic effect was from showering particles producing multiple hits in the long TOF counters, thus causing errors in the determined velocity. To reduce this background we required eight TOF measurements along the track and no more than two hit TOF counters not associated with the track. Figure 4 shows the velocity distribution for a one-hour run before and after this cut was applied.

For a run of 8×10^5 sec we observed six events above $\beta = 1.1$ and none above $\beta = 1.2$. The 6 events are above the 0.04 expected if the velocity resolution were Gaussian but they were not inconsistent with our estimate of undetected showers. Nevertheless, we state a limit only for $\beta \gtrsim 1.2$, we obtain

$\Phi_t < 2.4 \times 10^{-9}\ \mathrm{cm}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{sec}^{-1} \beta > 1.2(90\%\ \mathrm{CL})$ for tachyons able to deposit at least 0.24 MeV/cm in plastic scintillator.

Massive Particle Search

Particles with masses of about 4.2 GeV/c^2 and unit charge have been suggested by several cosmic-ray experiments and a few accelerator searches.[15] We looked for heavy particles with the FOS detector after it was removed from PEP shielding tunnel. A steel absorber about 30 gm/cm^2 was placed between the two arms. We then searched for slowly-moving particles which slowed too little in the detector to be tritons. No particle inconsistent with being either a proton or a deuteron was found and our resulting flux limit for particles with 4.2 GeV/c^2 are shown in Fig. 5. The positive result of a previous vertical search[15] is shown in the figure but since the range of zenith angles are different the two experiments are hard to compare directly.

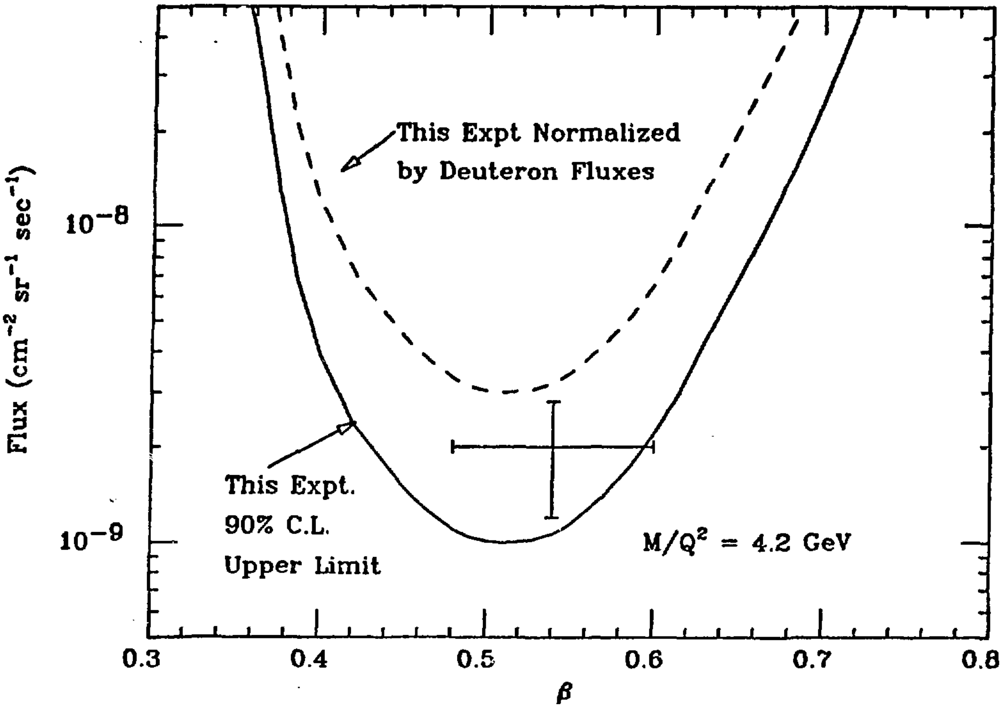

Fig. 5. Experimental flux limits on particles with 4.2 GeV/c^2. The data point is the observed flux from Ref. 15. The dotted line in the limit normalized to the observed deuteron flux.

Search for Fractional Charge at PEP

Colliding beam data were obtained at 29-GeV center-of-mass energy; the total luminosity was 16.0 pb^{-1} obtained from small-angle Bhabha scattering. The counters in the inner layers of the detector (scintillators between lay 9 and 17, see Fig. 1) were aligned in radial "roads" in each arm with 5 of the 6 counters hit. A separate fast trigger requirement was a hit in layer 9 and 16 in each arm. These conditions introduce a slight loss of efficiency for $Q = 1/3$ particles at relativistic velocities that is reflected in the final results.

QED check: To gain confidence in the detector operation we measured the angular distribution of the reaction $e^+e^- \rightarrow e^+e^-, \mu^+\mu^-$. Events were selected by requiring: (1) one and only one track in each arm, (2) tracks must come from the interaction region and correspond to particles produced in time with the beam crossing, and (3) collinearity of the tracks must be better than 4.0°.

After correcting for background the cross section agreed with the QED prediction and our measured luminosity to better than 5%. The angular distribution is shown in Fig. 6.

Exclusive Fractional Charge Production: To search for $e^+e^- \rightarrow q\bar{q}$ we made the following selection: (1) and (2) above, (3) tracks back to back within 8° in the polar and azmuthal angles, and (4) at least three times must be measured along a track and the assumption of a constant velocity and production at the beam crossing time must yield a fit to the TOF data with $\chi^2 < 9$ per degree of freedom. These cuts reduced 1.5×10^6 triggers to 1.3×10^4 events.

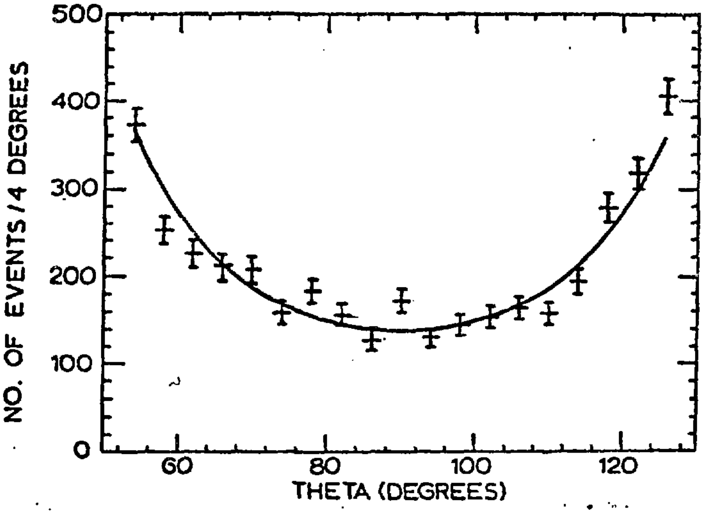

Fig. 6. The angular distribution for the events from the combined reactions $e^+e^- \rightarrow e^+e^-$, $\mu^+\mu^-$, plotted in terms of the production angle θ, relative to the beam direction. The curve shows the QED prediction, normalized to the total number of events.

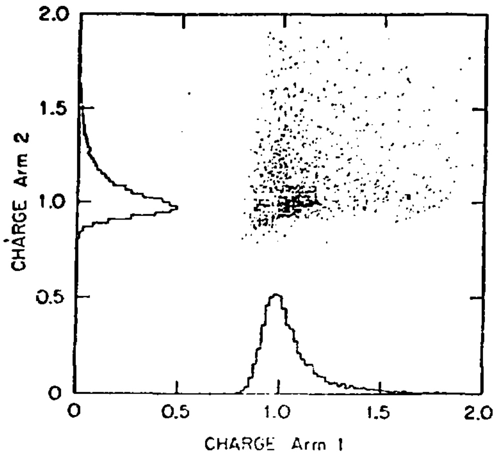

Fig. 7. A scatter plot of the measured charge in each arm of the detector for two-prong events. The charge measured in each arm of the detector is projected into a histogram illustrating the overall charge resolution. There are about 13,000 events in the figure.

Figure 7 shows a scatter plot of the charge for each arm for the selected events. We required $Q \lesssim 0.8$ for both tracks and thus no candidates were found as seen in Fig. 7. We converted our limits on the differential cross section to total cross section limits by making radiative corrections and using the expected angular distribution for pointlike fermions. Figure 8 shows the limits from this experiment as well as the recent limits for $Q = 2/3$ exclusive production from the MARK II[16] and JADE[17].

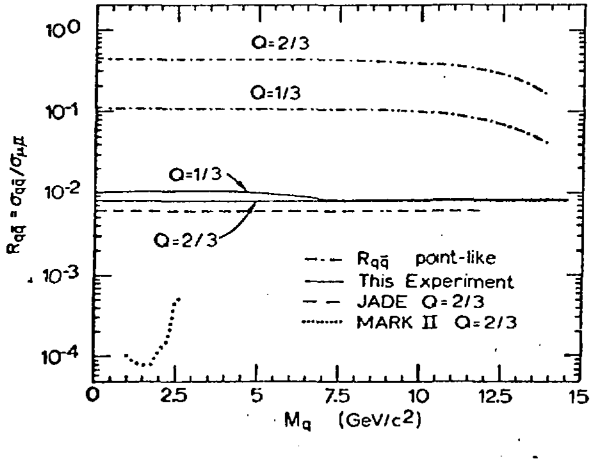

Fig. 8. Limits (90% confidence level) on exclusive quark production in e^+e^- annihilation. The limits for JADE are from Ref. 5 and the limits from MARK II are from Ref. 4.

Present limits are now sufficient to rule out fractionally charged lepton production with either $Q = 1/3$ or $Q = 2/3$ up to masses of ≈ 14 GeV/c^2. A more detailed discussion of this exclusive quark search is found in Ref. 18.

Inclusive Fractional Charge Production

The process $e^+e^- \rightarrow q\bar{q} + X$ is probably more likely to produce free quarks. In multiparticle final states we lost efficiency for measuring charge when more than a single particle hit a counter.

The following cuts reduce the 1.5×10^6 triggers to 6.1×10^3 events. (1) Events must be in time with the beam crossing and the particles must move out from the interaction point. (2) Three or more tracks are required. (3) To reduce backgrounds from accidental tracks at least two tracks are required to have dE/dx greater than 25% of normal. This last cut reduced the efficiency for those events in which there were 2 relativistic $Q = 1/3$ quarks and only one other particle within the acceptance.

The charge was calculated for tracks satisfying the following two conditions: (1) at least 5 of the innermost "road" dE/dx counters had signals above 3% of $(dE/dx)_{MIP}$ and (2) the track must have intersected at least two TOF counters with valid TOF hits. Figure 9 is a plot of $1/\beta$ vs dE/dx for the selected tracks. The region below the $Q = 0.5$ curve would contain >95% of any charge $Q = 1/3$ particles. There is one point in this region with $dE/dx = 0.9$ and $\beta = 0.4$. This event was traced to a single incorrect TOF value along the track. Eliminating this value gave $\beta \approx 1$. This hypothesis was verified by a hit Cherenkov counter along the track and the candidate was discounted.

Similarly >95% of the $Q = 2/3$ particles would fall below the line marked $Q = 0.75$ in Fig. 9. There are 16 candidates. These candidates were examined

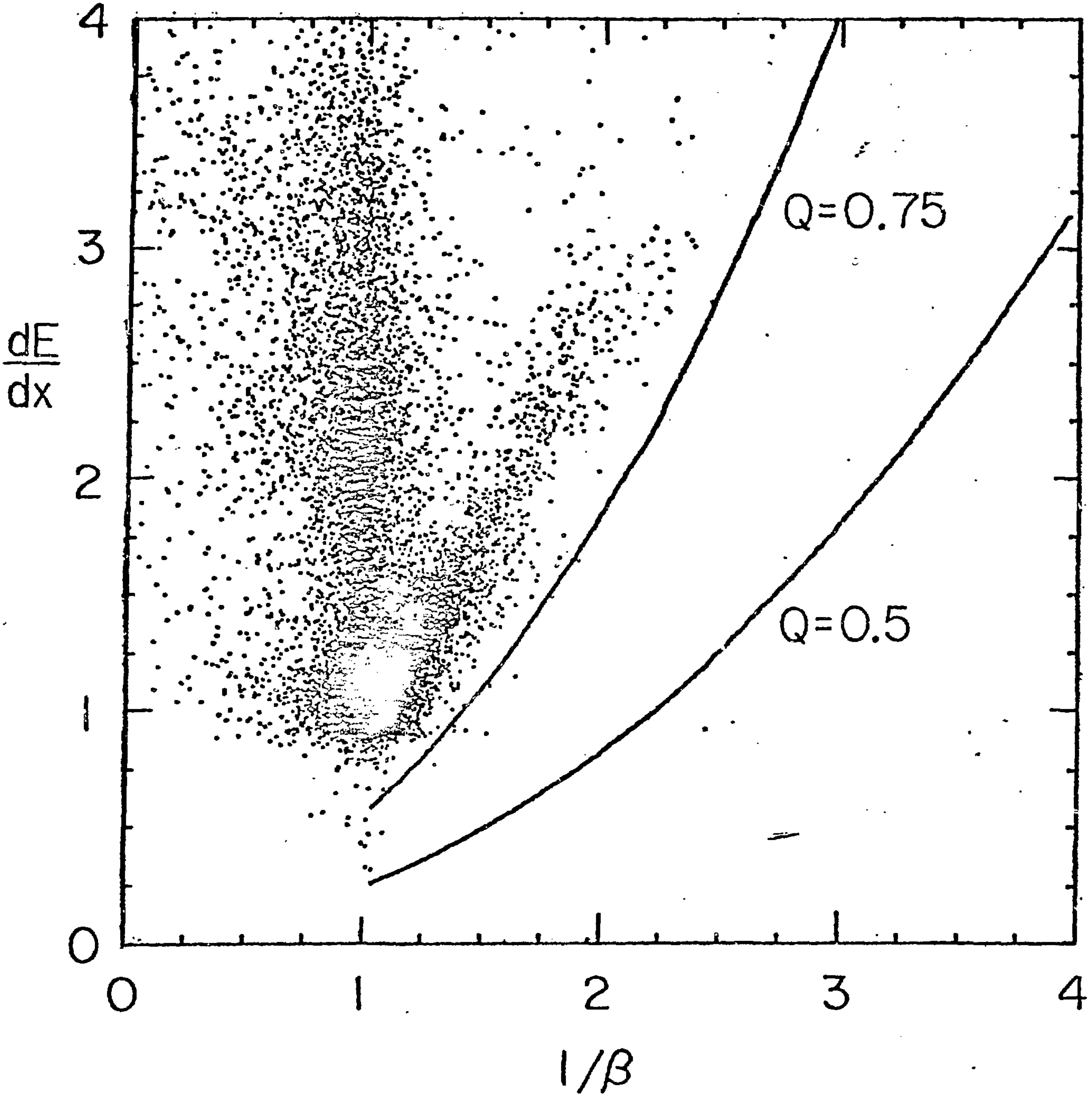

Fig. 9. dE/dx vs. 1/β for tracks (13840) in events which pass the selection criteria of the search for charge 1/3e particles. Q = 0.5 and Q = 0.75 contours are also shown. Tracks with low 1/β are accidental tracks which use very early time values in the outer counters. The tracks with high dE/dx and β ≈ 1 are due to more than one particle in the road counters. Candidates are discussed in the text.

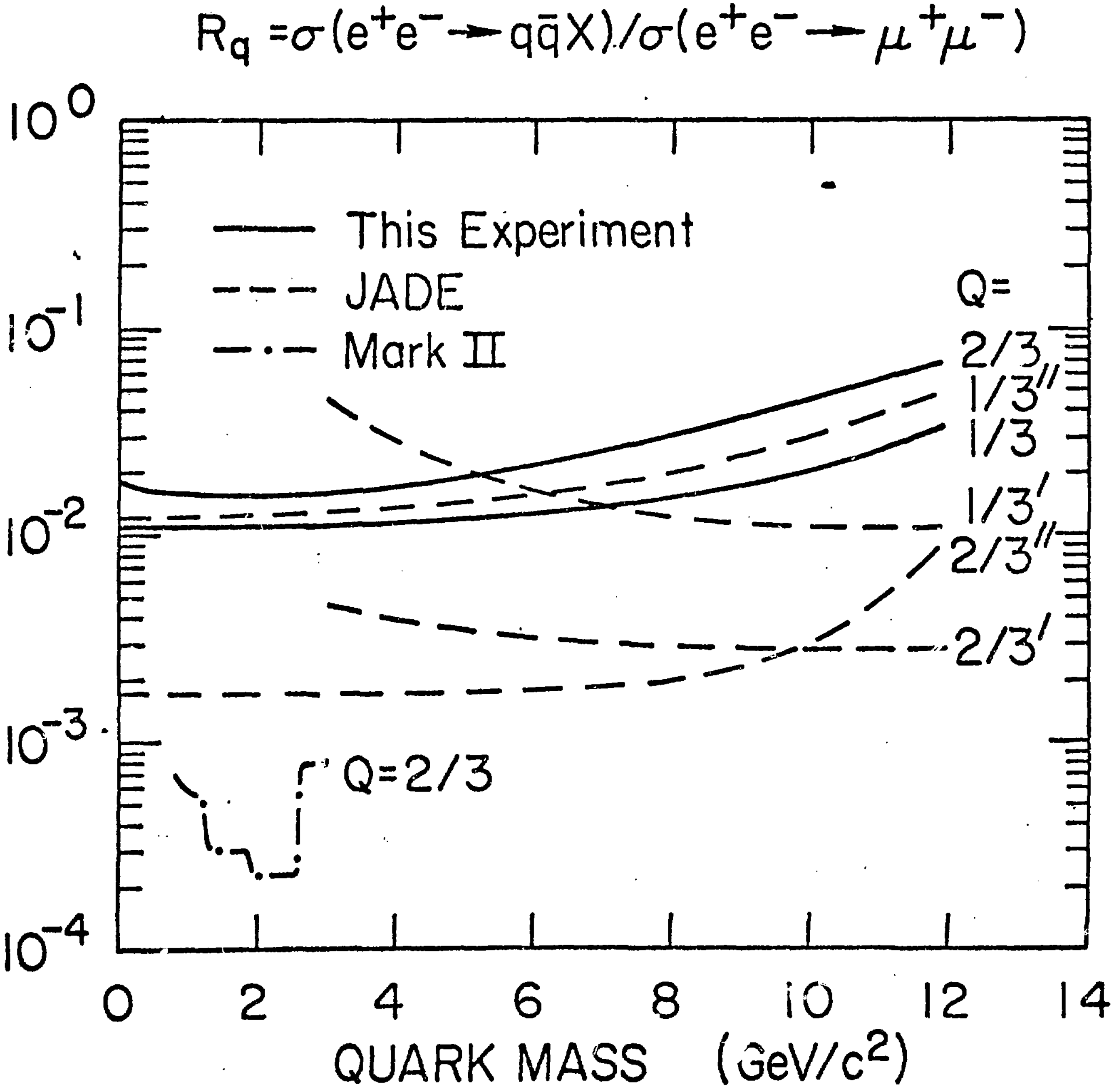

Fig. 10. Upper limits on quark production ($R_q=\sigma_{q\bar{q}X}/\sigma_{\mu\mu}$). Results from MARK II and JADE are included. In the JADE data analysis[17] two hypothetical quark momentum spectra were used. The results from both of them are shown here. We used a Monte Carlo most similar to the JADE model identified by the double primes in the figure.

individually and could be attributed to two causes: accidental tracks due to low-energy photons (7 events) and tracks which passed along the edges of "road" counters depositing some of their energy in the counter wrappings. Additional cuts eliminated all of these tracks but only 35% of the "normal" tracks. The final limits are shown in Fig. 10 along with the limits from the MARK II[16] and JADE[17].

These results are preliminary but a paper is being prepared for Physics Letters.[19]

Highly Interacting Quark Search

One interesting possibility for why quarks have not yet been discovered at accelerators is that they have anomously large interaction cross sections and thus they interact before they reach the detector.[20,21] To explore this possibility the inner 5 MWPC's of the FOS detector were equipped with read-out for dE/dx. This system was capable of detecting quarks with 100 times normal hadronic cross sections. This data is still being analyzed but preliminary indications are that no quarks have been seen. The final results will be presented soon.

Conclusion

The most likely result of looking for something that is not expected to be there is a null result but if you don't look you will certainly never find anything.

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