ISTITUTO NAZIONALE DI FISICA NUCLEARE

Laboratori Nazionali di Frascati

G. Susinno: STATUS OF FREE QUARK SEARCHES.

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G. Susinno

Istituto Nazionale di Fisica Nucleare,
Laboratori Nazionali di Frascati, Rome, Italy
CERN, Geneva, Switzerland

1. INTRODUCTION

Since the introduction of the "quark" concept by Gell-Mann[1] and Zweig[2] in 1964, as an elementary constituent of hadrons, a wide range of phenomena can find an explanation based on the quark composition of particles.

Quarks were introduced as elementary, fractionally charged, spin $\frac{1}{2}$ particles, which grouped in triplets (qqq) and doublets (q$\bar{q}$) give a good description of baryon and meson spectroscopy.

Deep inelastic scattering measurements at SLAC were able to provide evidence for the presence of point-like charged objects inside the nucleon. These results were interpreted in terms of elementary constituents, named "partons"[3], soon identified as quarks.

At the time only three quarks (u, d, s) were necessary in order to describe all known particles and resonances. Subsequently a further quark ("charm") was introduced to explain the suppression of the $K^{o}_{L} \rightarrow \mu^{+}\mu^{-}$ decay and other processes involving a change in strangeness with no charge change[4].

The discovery of the J/ψ resonance by a group working at Brookhaven[5] and by a group working at SLAC[6], and the proliferation of a new spectroscopy confirmed the existence of this fourth quark. The discovery at FNAL[7] of a new narrow state gave evidence for the existence of a new hidden quark: "beauty". The first particle carrying a naked "beauty" flavor was recently observed by a group working at CERN[8].

Symmetry between quarks and leptons, and properties of weak interactions require that quarks and leptons should be grouped in doublets. So, at least, a further quark should exist: "truth".

Quarks should be spin $\frac{1}{2}$ particles. This follows from hadron spectroscopy, from the experimental check of the Callan-Gross[9] relation, and

from the angular distribution of jets produced in e^+e^- annihilation.
They have to obey Fermi statistics and so the Pauli exclusion principle
requires that quarks should exist in three different states of a new
quantum number: the colour[10]. The ratio R,

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)} ,$$

is in very good agreement with the hypothesis that quarks have fractional
charges and three-colour states[11].

The fractionally charged quark model is not unique. Gauge theory
models suggest that integral-charge quarks might exist[12].

Quarks were searched for in cosmic rays, stable matter, and accele-
rators. Measurements were carried out generally looking for fractionally
charged particles or (and) for high-mass stable particles.

On the hypothesis that a single hard hit on one of the constituents
is necessary in order to break a proton[13], low p_T hadron interactions
do not seem the right ones to search for free quarks. Hadron interactions
are "strong" but "soft". In this respect, electromagnetic interactions
are a better probe, being weaker but harder, and weak interactions should
be more likely, being the hardest. Another promising way to look for free
quarks should be e^+e^- annihilation, in which a $q\bar{q}$ pair could be directly
produced.

After the production, fractionally charged quarks should be stable
particles for charge conservation, but they have to go through a given
amount of material before their presence can be revealed, so an important
question is what the interaction cross-section of free quarks in ordinary
matter could be. The additive quark model, describing hadron cross-
sections, suggests that the absorption length for quarks should be about
three times the proton absorption length. A counter-argument is that a
free coloured particle could have a huge cross-section in matter[14].

In this review, after a quick look at the status of free quark
searches in cosmic rays, in stable matter, and in proton-proton interac-
tions, particular attention will be devoted to the latest results in e^+e^-
annihilation and ν interactions. A complete review can be found in papers
by Jones[15], Greenberg[16] and Barbiellini et al.[17].

2. SEARCHES IN COSMIC RAYS

The limits reported for this kind of search are taken from the review by Jones[15]. Limits are given in terms of quark flux. Searches in cosmic rays can be grouped into three different kinds of experiments.

2.1 Single particle searches

Here free quarks are looked for as single particles of anomalously low ionization. Combining the results of experiments of this kind, the following overall flux limits are reported in Ref. 15:

$$\phi \leq 1.1 \times 10^{-11} \ (cm^2 \ sr \ s)^{-1} \quad (90\% \ C.L.)$$

for quarks of charge $\frac{1}{3}$ and

$$\phi \leq 2.4 \times 10^{-11} \ (cm^2 \ sr \ s)^{-1} \quad (90\% \ C.L.)$$

for quarks of charge $\frac{2}{3}$.

2.2 Air-shower studies

Here free quarks are looked for inside a cosmic shower, on the hypothesis that they are liberated in high-energy interactions of primary particles in the upper atmosphere.

Limits achieved in these searches are[15]

$$\phi \leq 0.71 \times 10^{-11} \ (cm^2 \ sr \ s)^{-1} \quad (90\% \ C.L.)$$

for charge $\frac{1}{3}$, and

$$\phi \leq 1.4 \times 10^{-11} \ (cm^2 \ sr \ s)^{-1} \quad (90\% \ C.L.)$$

for charge $\frac{2}{3}$.

2.3 Time-delay technique

Here quarks are searched for as massive particles produced in interactions of cosmic-ray primaries in the upper atmosphere. If a particle of large rest mass is produced in the upper atmosphere it will arrive at the detector delayed with respect to the front of the shower. Some candidates were observed in such experiments, but no clear evidence for free quarks was obtained.

The limits achieved in these searches[15,18] are of the order of

$$\phi \leq \sim 10^{-10} \ (cm^2 \ sr \ s)^{-1} \ .$$

3. SEARCHES IN STABLE MATTER

Mass spectrometer measurements using samples taken from meteorites, (land) rocks, sea, and lunar rocks gave[15] no evidence for fractionally charged quarks in matter.

Another method used in searching for fractional residual charge in matter is analogous to the Millikan experiment. The most recent results of experiments of this kind come from two groups working respectively at Genova and Stanford Universities.

The Genova group[19] gives no evidence for fractional charges in matter and gives a limit on quark density:

$$\rho < 3 \times 10^{-21} \ quarks/nucleon \ .$$

Iron balls, suspended in a magnetic field between two capacitor plates, were used in this experiment. This group shows that the apparent charge of a ball takes the form

$$Q_R = q + \alpha \ \frac{\partial E_X}{\partial X} + \beta \ \frac{\partial H_X}{\partial X} \ ,$$

where the term $\alpha(\partial E_X/\partial X)$ comes from the "patch" effect due to the fact that the potential on the surfaces of the plates is not uniform; α is the polarizability of the sphere. Drifts, which cannot be attributed to variations in patch effects, were observed for several balls. These drifts were attributed to a new force of magneto-electric nature giving the term $\beta(\partial H_X/\partial X)$ where β is a coefficient depending on the sphere under study. To isolate this effect the Genova group changes $\partial H_X/\partial M$ from its normal value H_{XX}^0 to the values $H_{XX}^0 + \Delta H_{XX}$ and $H_{XX}^0 - \Delta H_{XX}$. Q_R can then be written:

$$Q_R^{\pm} = q' + \beta(H_{XX}^0 \pm \Delta H_{XX}) \ .$$

In Fig. 1 the quantities $X = Q_R^- - Q_R^+$ versus $y = (Q_R^+ + Q_R^-)/2$ are reported for two different radii of the balls. Results fit very well the hypothesis of zero residual charge for all the balls measured.
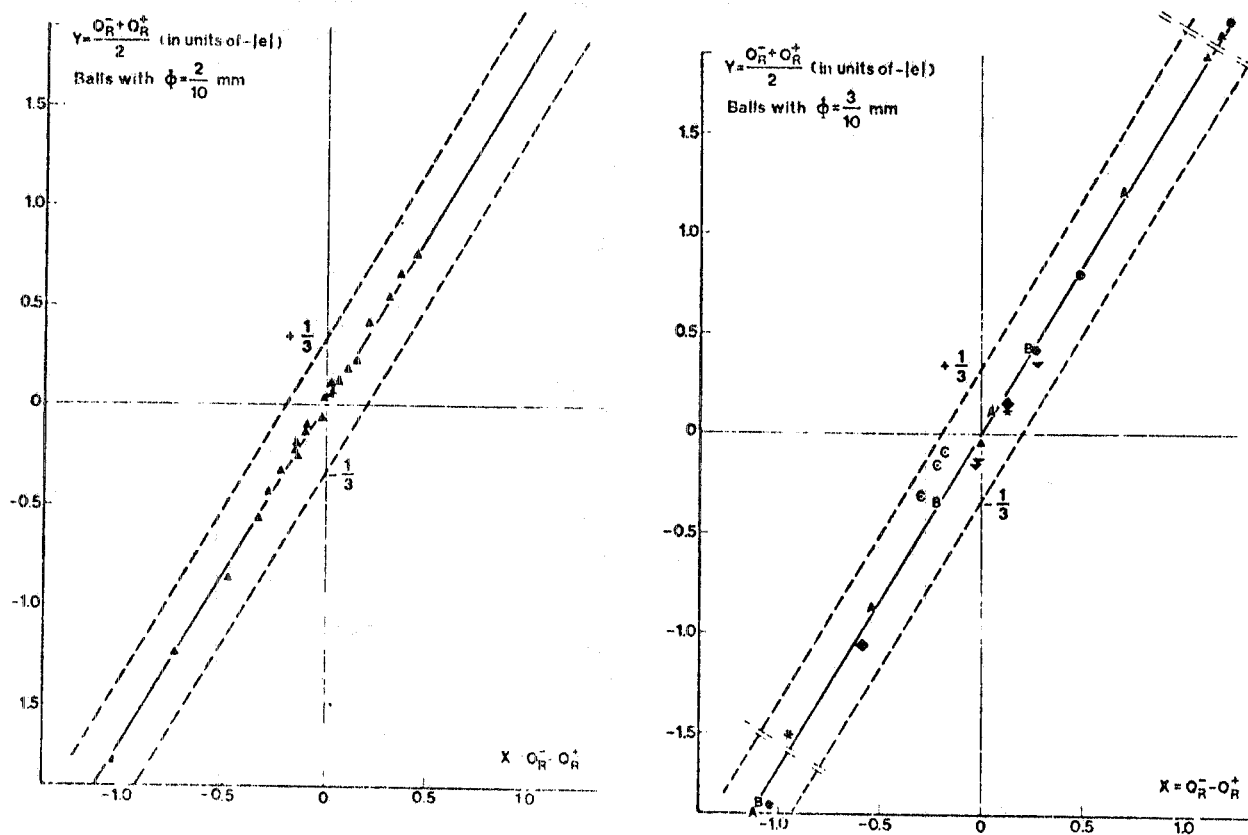
FIG. 1 - Results of the measurements for 23 balls with $\emptyset$ = 0.2 mm and for 24 balls with $\emptyset$ = 0.3 mm after the identification of the magneto-elec tric force in the experiment of Marinelli and Morpurgo[19].

The Stanford group[20] uses superconducting niobium balls instead of iron balls. They observe charges consistent with 0 or $\pm \frac{1}{3}$ and affirm that the new electromagnetic force reported by the Genova group cannot account for the fractional charges they have observed since they find no drifts with time and no random values of the residual charge but every measurement has been consistent with 0 and $\pm \frac{1}{3}$.

The results of the Stanford group are reported in Fig. 2. The number of fractional residual charges observed by this group gives a density of quarks in matter of

$$\rho = \text{ } 10^{-20} \text{ quarks/nucleon .}$$

No final conclusion concerning these experiments can be made at present.
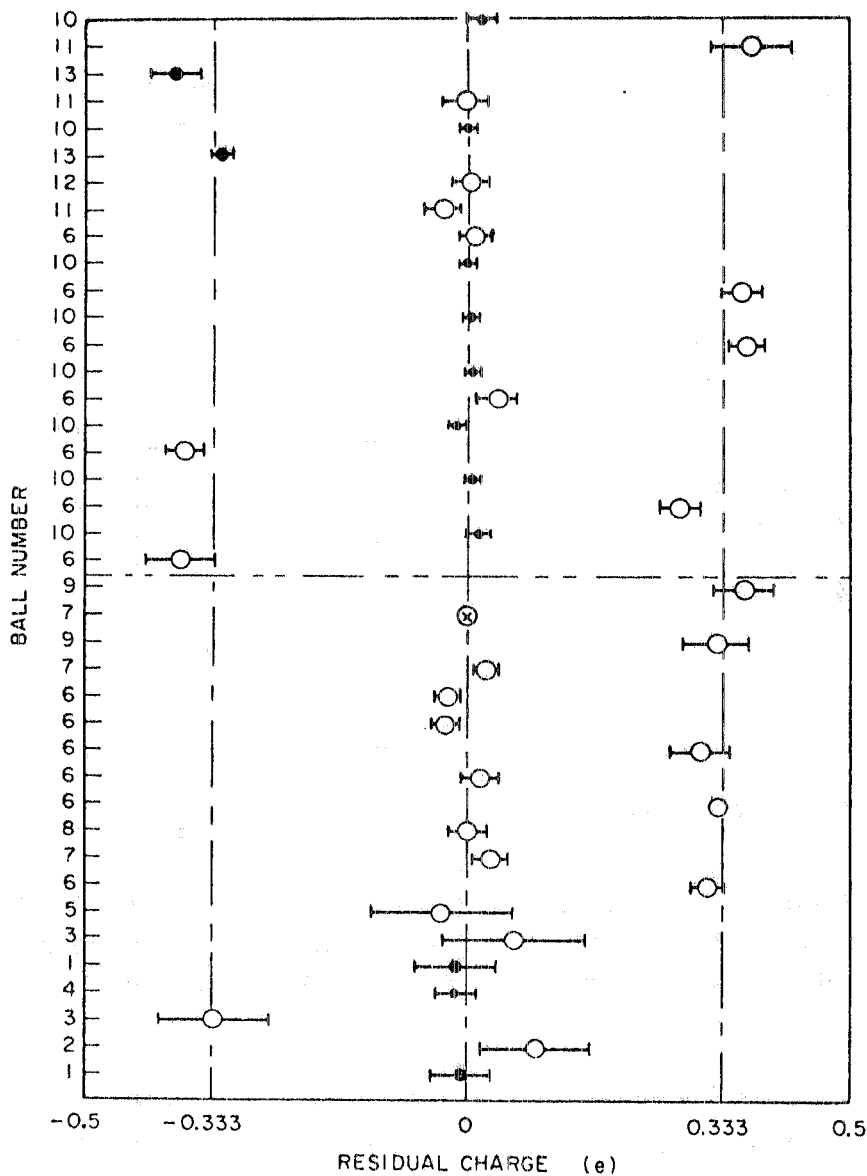
FIG. 2 - Residual charges measured in the experiment of La Rue, Phillips and Fairbank[20].

4. SEARCHES FOR QUARKS AT ACCELERATORS

4.1 Proton interactions

A complete review up to 1977 can be found in Ref.15. More recently new limits have been given by an experiment at FNAL[21] of a Chicago-Princeton Collaboration, and by two experiments at CERN-ISR of a CERN-Munich Collaboration[22] and of a CERN-Bologna Collaboration[23]. This one gives the most significant limits at the highest energy reached so far.

The Chicago-Princeton experiment searched for charge $\frac{1}{3}$ and charge $\frac{2}{3}$ particles produced with large p_T[13] in 400 GeV proton-Cu collisions. A spectrometer, set to accept unit charge particles of p_T = 6.15 GeV/c, was utilized. The respective p_T for charge $\frac{1}{3}$ and charge $\frac{2}{3}$ particles are 2.05 GeV/c and 4.10 GeV/c.

No fractionally charged particles were found at a level of approximately 10^{-9} of the pions produced of the same p_T for charge $\frac{1}{3}$ and at a level of approximately 10^{-6} for charge $\frac{2}{3}$. These limits hold true for quark masses up to 6.3 GeV/c^2 for charge $\frac{1}{3}$ and 8 GeV/c^2 for charge $\frac{2}{3}$.

The CERN-ISR experiments gave limits at higher c.m. energies with a $\langle p_T \rangle$ = 0.4 GeV/c. The mass range explored by these experiments is the largest reached in accelerator searches. The CERN-Bologna experiment reached $5 \cdot 10^{-11}$ in the flux limit for quark masses up to 21 GeV. In Table 1 the results from these three experiments are summarized.

Table 1

Accelerator	Ref.	$\sqrt{s}$ (GeV)	p_T (GeV/c)	Flux limit (ϕ_q/ϕ_c)	Quark mass limit (GeV/c^2)
FNAL	21	27.4	2.05 (q = $\frac{1}{3}$)	$\sim 10^{-9}$	6.3
			4.10 (q = $\frac{2}{3}$)	$\sim 10^{-6}$	8.0
CERN ISR	22	40.0	$\langle p_T \rangle$ = 0.4	4×10^{-8}	20
		54.0		7×10^{-10}	20
		62.0		10^{-6}	20
CERN ISR	23	52.5	$\langle p_T \rangle$ = 0.4	5×10^{-11}	21
		62.0		10^{-9}	26

4.2 e^+e^- annihilation

Results from three experiments at PETRA, SLAC, and PEP are reported in this section.

4.2.1 The JADE experiment

The JADE Collaboration[24] looked for new particles with charge $Q = \frac{2}{3}$, 1, $\frac{4}{3}$, $\frac{5}{3}$ in the energy range $\sqrt{s} = 27\text{-}35$ GeV, at PETRA. Particles were identified by simultaneous measurements of the mean energy loss dE/dx, and the "apparent momentum" p/Q.

Events were retained by demanding two tracks, originating from the interaction point, which are collinear to within $10°$ in space when looking for exclusive production $(e^+e^- \to q\bar{q})$. Mostly these were Bhabha and $\mu^+\mu^-$ events.

Candidates were searched for by plotting the mean energy loss of track 1 versus the mean energy loss of track 2, distinguishing "showering tracks" (mostly Bhabha events, Fig. 3a), from "non-showering tracks" (mostly $\mu^+\mu^-$ events, Fig. 3b). No events were found corresponding to
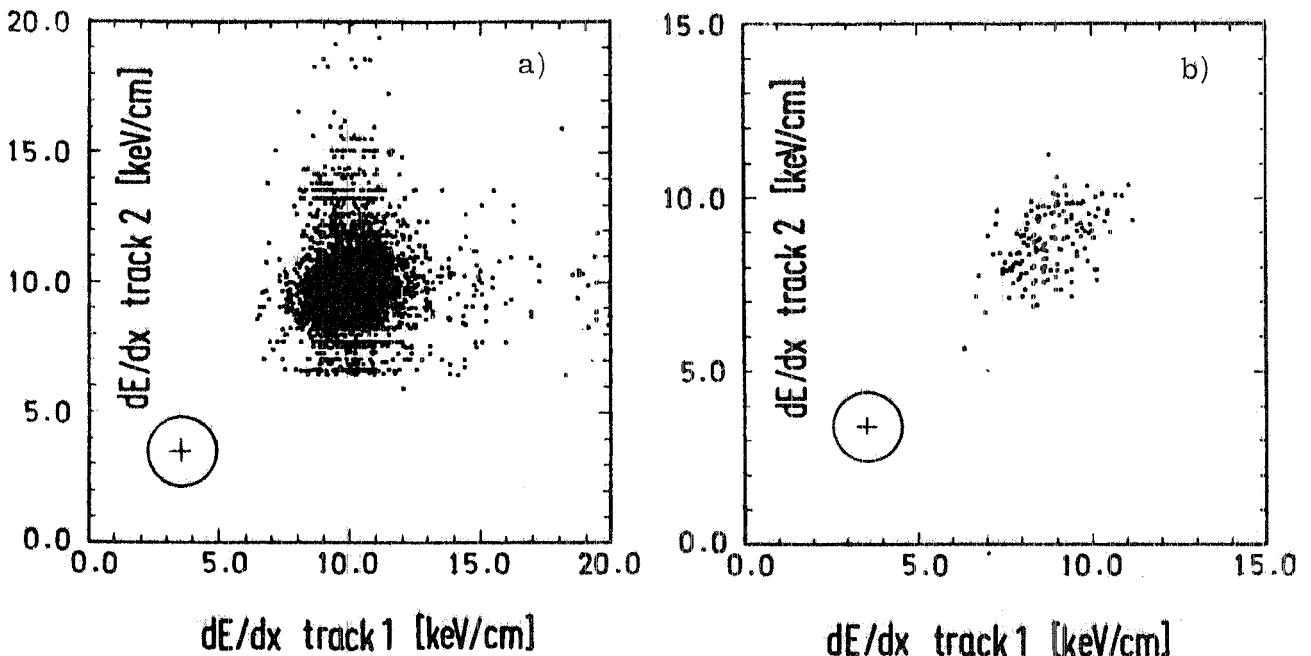
FIG. 3 - Energy loss of collinear two-prong events. dE/dx of track 1 versus that of track 2 for a) showering and b) non-showering tracks. The cross indicates the expectation for $Q = 2/3$ particles and the circle the 2.5 standard deviation contour. (Taken from the JADE experiment[24]).

$Q = \frac{2}{3}$ particles. Limits were given in terms of

$$R_Q = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

and were less than $\sim 10^{-2}$ (90% C.L.) for masses up to 12 GeV/c^2.

The plot of observed energy loss versus the apparent momentum of the tracks (Fig. 4) was analysed in order to search for candidates in inclusive production ($e^+e^- \to q\bar{q}X$). All the candidates (tracks deviating by more than 2.5 standard deviations in dE/dx and momentum values from the π, K, p, e) were explained by ordinary particles (positive-charge deuterons and tritons, overlapping tracks, and tails of dE/dx distribution of π, K, p, e).
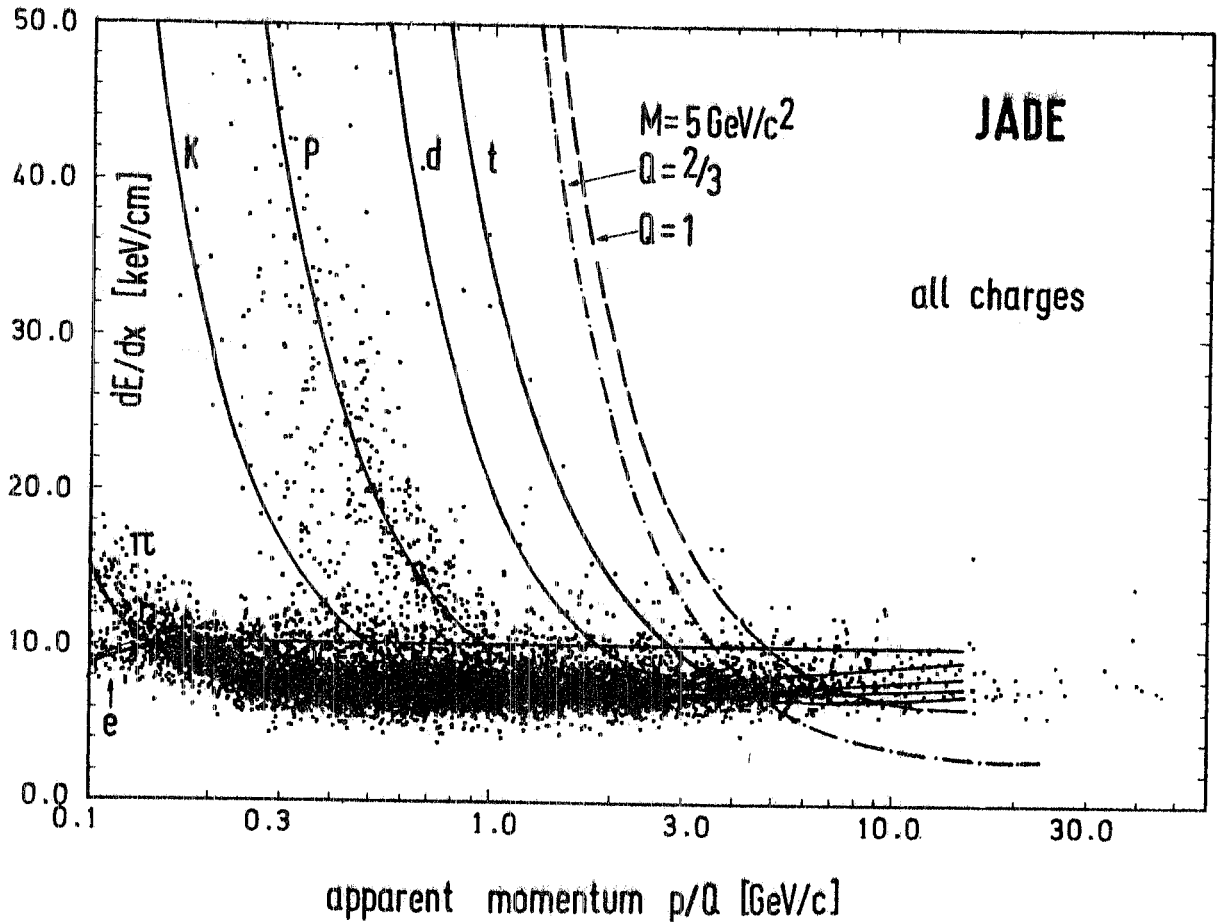

FIG. 4 - Energy loss of positive and negative tracks in multi-hadron events as a function of apparent momentum p/Q. Also shown are the lines expected for the known stable particles e, π, K, p, d, t (solid lines) and a hypothetical particle with mass M = 5 GeV/c^2 and charge 2/3 and 1 (dotted lines). (Taken from the JADE experiment[24]).

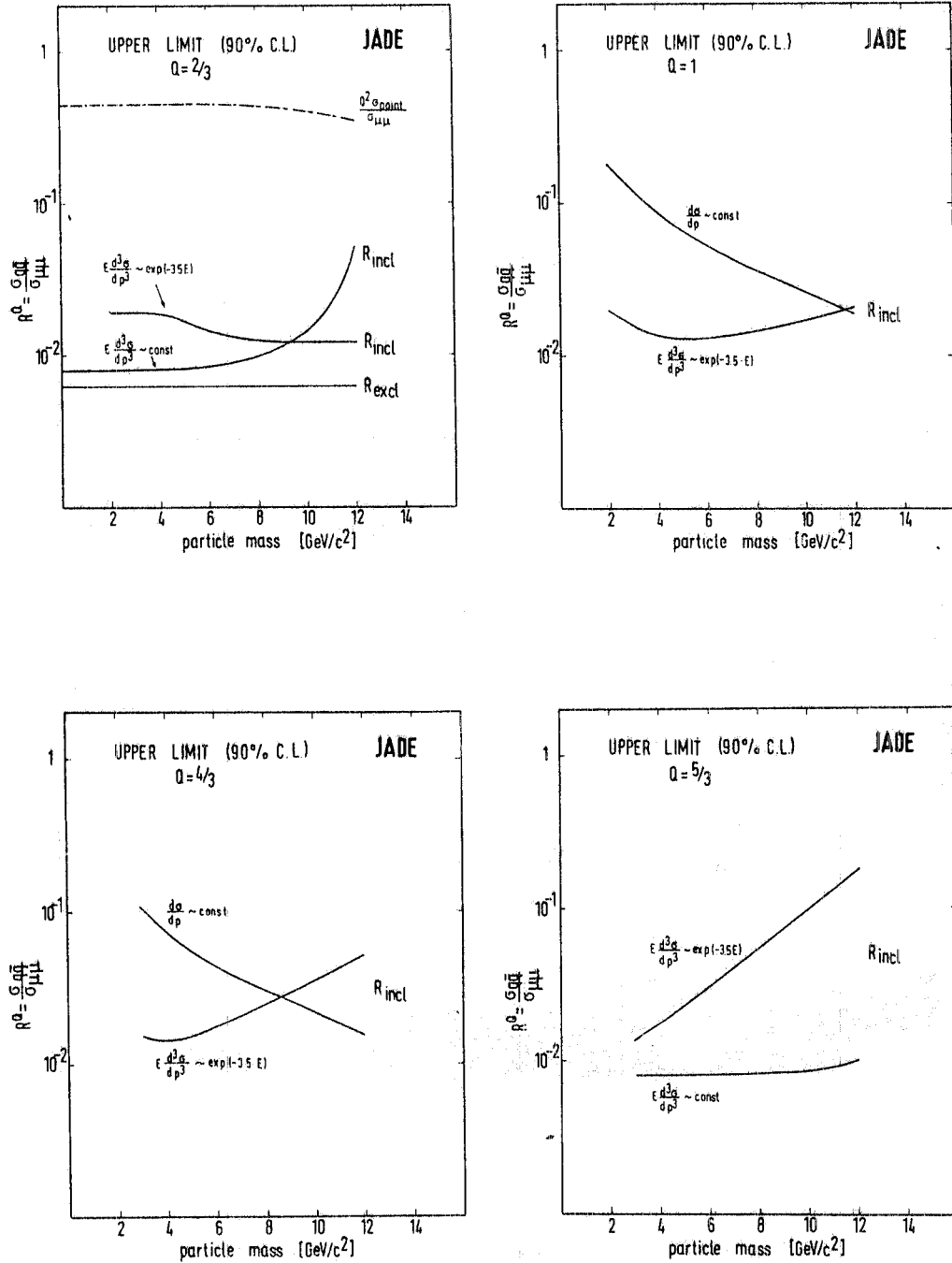Limits obtained by this experiment are given in Fig. 5.

FIG. 5 - 90% confidence level upper limits on $R_Q = \sigma_{q\bar{q}}/\sigma_{\mu\mu}$ for the exclusive and inclusive production of quarks as a function of particle mass for different values of the charge. (Taken from the JADE experiment[24]).

4.2.2 The Mark II experiment at SPEAR

A search was undertaken for $Q = -2/3$ and $Q = -1$ particles with a mass greater than a proton mass in e^+e^- annihilation using the Mark II detector at SPEAR in the energy range $\sqrt{s} = 3.9$-7.4 GeV [25].

The search for exclusive production ($e^+e^- \rightarrow q\bar{q}$) was done by selecting two-prong data requiring a collinearity of less than $10°$, an apparent momentum p/Q greater than a half that of the beam energy, and a cut on dE/dx between 20% and 65% of the value expected for $Q = 1$ particles. An upper limit of $R_Q \sim 10^{-4}$ for $Q = 2/3$ and $1.0 < m_Q < 2.8$ GeV/c^2 was obtained.

Time of flight and "apparent momentum" p/Q were used in this experiment to determine an "apparent mass" of each track

$$m_T^2 = \frac{p_Q^2}{Q^2} \left(\frac{1}{\beta^2} - 1 \right) = \frac{m_Q^2}{Q^2} .$$

The observed spectra of m_T^2, with $m_T^2 > 1.6$ (GeV/c^2)^2, for $Q > 0$ (Fig. 6a) and $Q < 0$ (Fig. 6b) were analysed to search for $Q = -1$ heavy-mass, inclusively-produced candidates.

Fits to the $Q = +1$ data gave masses and widths for the observed deuteron and triton signals coming from beam-gas interactions. Fixing these masses and widths, the $Q = -1$ data were fitted to obtain upper limits on the number of events from $\bar{d}$ and $\bar{t}$ production. These limits were assumed to hold, approximately, for any other massive stable particle with charge $Q = -1$ and ordinary nuclear interactions. When expressed in terms of R_Q they became $R_Q \leq 3.1 \times 10^{-4}$ for the mass region $m_Q = 1.7$-2.3 GeV/c^2 and $R_Q \leq 1.9 \times 10^{-3}$ for $m_Q = 2.3$-3.0 GeV/c^2.

$Q = -2/3$ massive candidates were looked for, in this experiment, requiring, for tracks with $m_T^2 > 1.6$ (GeV/c^2)^2, a dE/dx between 20% and 65% of the value expected for $Q = 1$ particles. The scatter plot of "apparent momentum" versus m_T^2 for tracks surviving the cuts is shown in Fig. 7. The authors, analyzing these results in terms of the number of candidates in each of several quark mass intervals, obtained the 90% confidence level upper limits reported in Table 2.
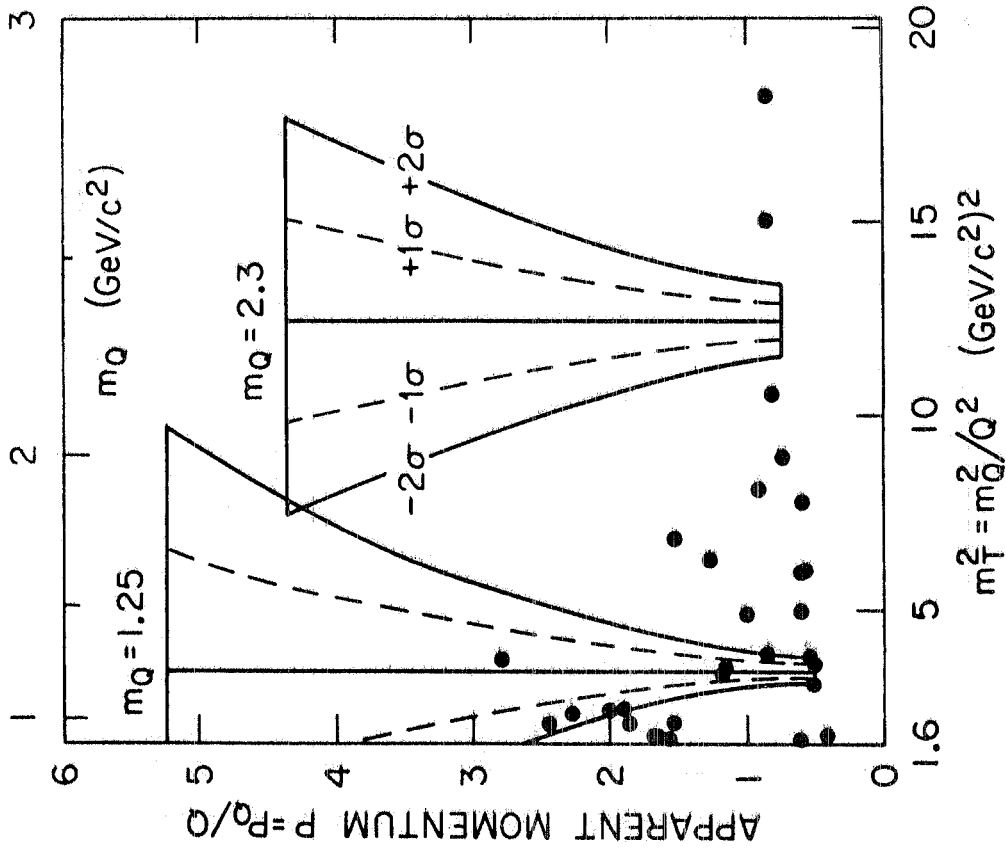
FIG. 7 - Scatter plot of m_T^2 versus apparent momentum for Q<0 data satisfying the vertex requirement and the dE/dx cuts for Q = -2/3. Also indicated are expected regions for typical quark masses M_Q = 1.25 and 2.3 GeV/c². (Taken from the MARK II experiment[25]).

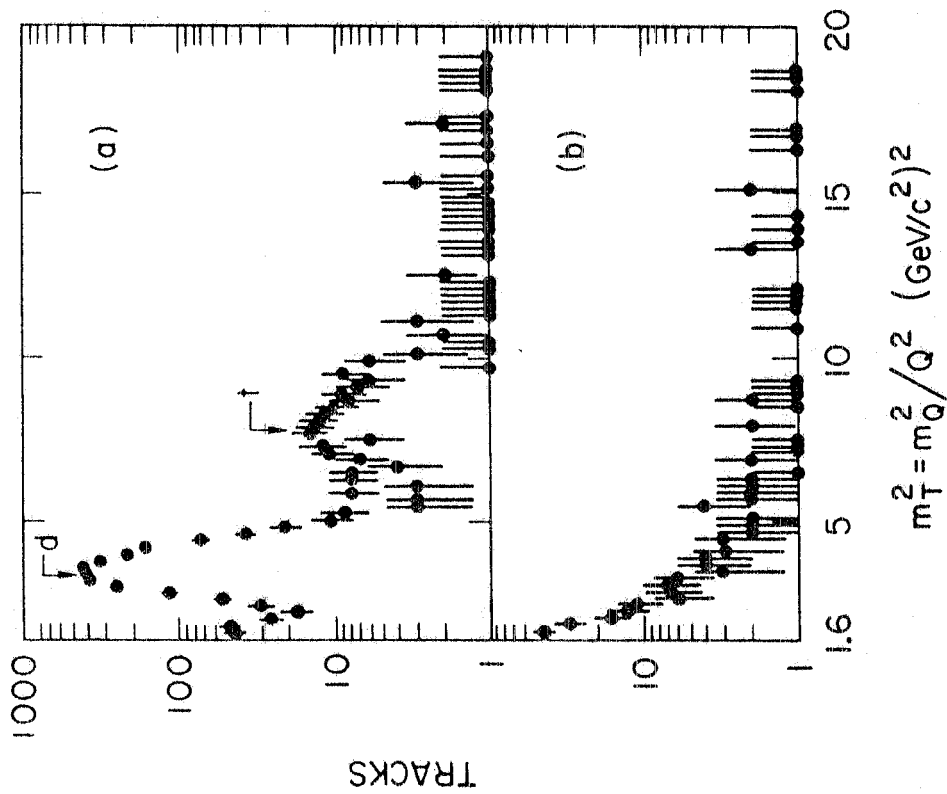FIG. 6 - Mass spectrum m_T^2 of tracks with m_T^2 > 1.6 (GeV/c²)² for a) Q>0 and b) Q<0. (Taken from the MARK II experiment[25]).

Table 2

90% confidence level upper limits for $e^+e^- \to q\bar{q}X$ and $Q = -\frac{2}{3}$

| m_Q (GeV/c²) | Events | | Eff. | $\int \mathcal{L}\, dt$ above thresh. (nb⁻¹) | $\sigma(q\bar{q}X)$ (pb) | Aver. E_{cm} (GeV) | $R_Q(q\bar{q}X)$ |
	Maximum observed	Limit					
1.0-1.25	11	10.8	0.47	14154	2.3	4.5	5.6×10^{-4}
1.25-1.9	5	6.5	0.49	19891	1.0	5.2	3.0×10^{-4}
1.9-2.1	3	6.8	0.49	18920	0.76	5.3	2.3×10^{-4}
2.1-2.6	1	3.9	0.50	13778	0.56	6.0	2.3×10^{-4}
2.6-3.0	1	3.9	0.50	5178	1.5	6.7	8.0×10^{-4}

4.2.3 The PEP-14 experiment

Preliminary results on a search for fractionally charged particles at PEP at $\sqrt{s} = 29$ GeV were reported at the 1981 Spring Meeting of the APS by the Northwestern University-Frascati-LBL-Stanford University-University of Hawaii Collaboration. The charge of detected particles was determined from measurements of dE/dx and velocity. Results on dE/dx measurements are shown in Fig. 8.
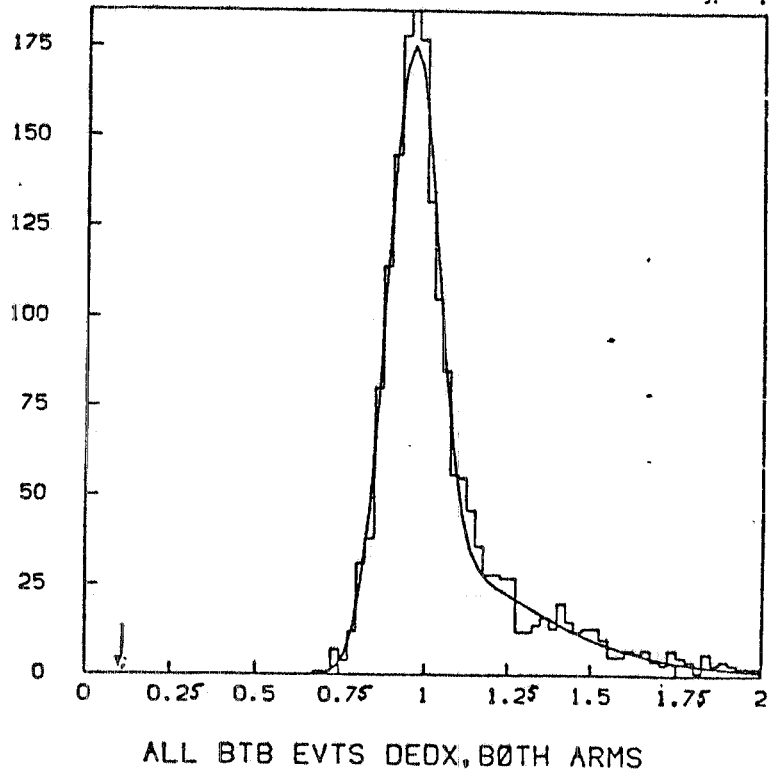

FIG. 8 - Ratio of the measured energy loss to the energy loss for charge Q = 1 particles. (Data presented at the 1981 Spring Meeting of the APS by the PEP-14 group).

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An upper limit on $R_Q \leq 0.04$ was obtained, for exclusively produced charge $Q = \frac{1}{3}$ quarks up to masses of 12.5 GeV. The upper limit in the case of inclusively produced charge $Q = \frac{1}{3}$ quarks ranges between 0.1 and 1.0 for quark masses between 1 and 10 GeV/c^2.

Results from the three reviewed e^+e^- experiments are summarized in Tables 3 and 4.

Table 3

Exclusive production ($e^+e^- \rightarrow q\bar{q}$)

Detector	Ref.	Q	$\sqrt{s}$ (GeV)	$R_Q = \dfrac{\sigma(e^+e^- \rightarrow q\bar{q})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$	Quark mass limit (GeV/c^2)
JADE	24	$\frac{2}{3}$	27-35	$\sim 10^{-2}$	0-12
Mark II	25	$\frac{2}{3}$	3.9-7.4	$\sim 10^{-4}$	1.0-2.8
PEP-14	See text	$\frac{1}{3}$	29	4×10^{-2}	0-12

Table 4

Inclusive production ($e^+e^- \rightarrow q\bar{q}X$)

Detector	Ref.	Q	$\sqrt{s}$ (GeV)	$R_Q = \dfrac{\sigma(e^+e^- \rightarrow q\bar{q}X)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$	Quark mass limit (GeV/c^2)
JADE	24	$\frac{2}{3}$	27-35	$\sim 10^{-2}$	0-12
		$1, \frac{4}{3}, \frac{5}{3}$		$10^{-1}-10^{-2}$	0-12
Mark II	25	-1	3.9-7.4	3.1×10^{-4}	1.7-2.3
				1.9×10^{-3}	2.3-3.0
		$-\frac{2}{3}$		$(2-8) \times 10^{-4}$	1-3
PEP-14	See text	$\frac{1}{3}$	29	$\sim 10^{-1}$	1

4.3 Neutrino and antineutrino nucleon interactions

Results of the CERN-Bologna-Frascati-Roma Collaboration[26] searching for fractionally charged quarks in the wide-band neutrino and antineutrino beam of the CERN SPS are reported here. Interactions take place in a 23 t lead target, optimized assuming an absorption length for quarks three times that of a proton.

Outgoing tracks are seen by scintillation counter hodoscopes for dE/dx measurements, and by an avalanche chamber for the measurement of the specific ionization of all charged particles produced with high accuracy even in jet-like events. Muons of known momentum selected by a μ-range telescope are used for calibration purposes.

In this experiment quarks are recognized as particles with ionization less than the minimum ionization of a charge $Q = 1$ particle. Charge $Q = \frac{1}{3}$ quarks are revealable in the β range, $\beta \geq 0.4$, while for charge $Q = \frac{2}{3}$ quarks, the possible values for β are ≥ 0.8. The acceptance of the apparatus for quark detection was evaluated via Monte Carlo calculation, assuming for the produced quark an angular distribution similar to the μ ("leptonic") or to the hadrons ("hadronic") produced in neutrino interactions. The acceptance so determined is 0.44 for the "leptonic" and 0.28 for the "hadronic" cases.

A fast electronic analysis was done for fractionally charged quarks not accompanied by a jet of particles ("isolated"). Candidates selected according to their dE/dx in the scintillation hodoscopes were visually scanned, searching for low ionizing tracks in the avalanche chamber. No good candidate was found obtaining the 90% confidence level upper limits for the flux of fractionally charged quarks per neutrino interaction reported in Table 5. Figure 9 shows how the experimental limits vary with the ratio $\lambda_{quark}/\lambda_{hadron}$, where λ is the hadronic-like absorption length.

A careful analysis is in progress on the avalanche chamber photographs, looking for candidates also inside a jet of particles. The tracks are seen on film as a succession of blobs. The distribution of the distance x between successive primary ionizing collisions for a track of length L is given by

$$g(x;\mu) = \mu^2 L \, e^{-\mu x} \, ,$$

Table 5

Summary of the results on quarks
with $Q = \frac{2}{3}$ and $\beta \geq 0.8$, and with $Q = \frac{1}{3}$ and $\beta \geq 0.4$

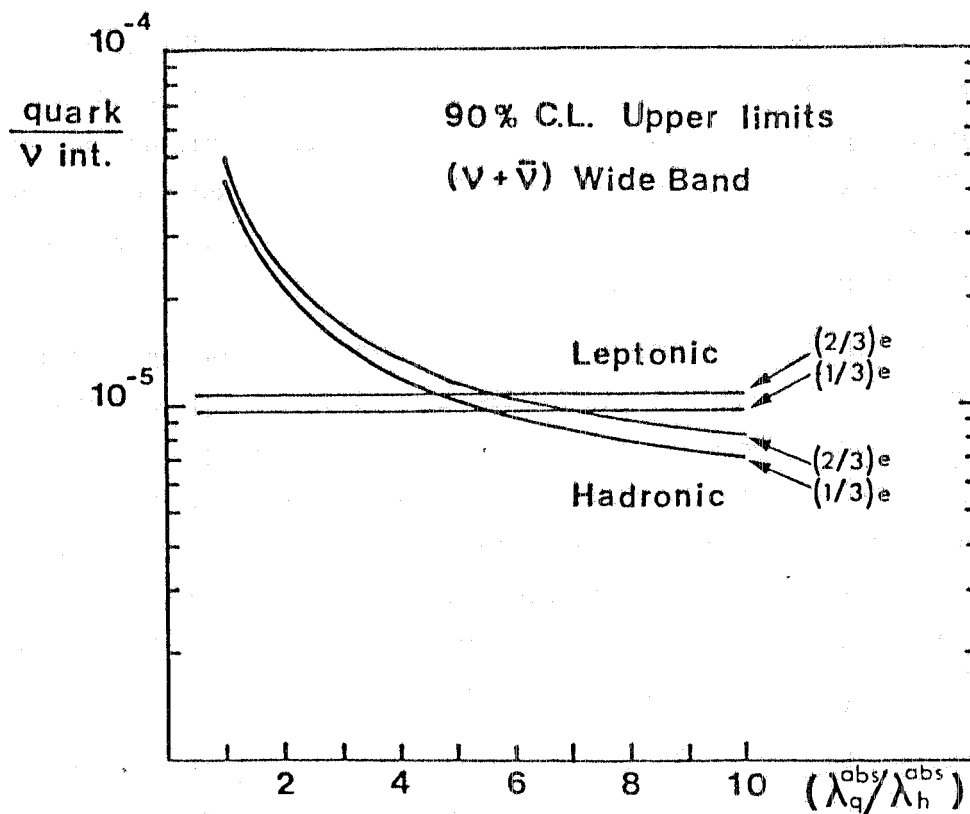| Beam		ν wide-band	$\bar{\nu}$ wide-band
Total No. of protons on target (400 GeV)		$(0.8 \pm 0.08) \times 10^{18}$	$(1.76 \pm 0.18) \times 10^{18}$
No. of ν ($\bar{\nu}$) interactions		$(5.7 \pm 0.80) \times 10^5$	$(2.5 \pm 0.35) \times 10^5$
90% C.L. quark flux upper limit	Leptonic case $Q = \frac{1}{3}$	$(1.38 \pm 0.25) \times 10^{-5}$	$(3.14 \pm 0.57) \times 10^{-5}$
	Leptonic case $Q = \frac{2}{3}$	$(1.57 \pm 0.28) \times 10^{-5}$	$(3.58 \pm 0.65) \times 10^{-5}$
	Hadronic case $Q = \frac{1}{3}$	$(2.16 \pm 0.43) \times 10^{-5}$	$(4.93 \pm 0.99) \times 10^{-5}$
	Hadronic case $Q = \frac{2}{3}$	$(2.47 \pm 0.49) \times 10^{-5}$	$(5.63 \pm 1.13) \times 10^{-5}$

FIG. 9 - 90% confidence level upper limits on the flux of quarks per neutrino interaction for the "leptonic" and "hadronic" cases as a function of the ratio of the absorption length of quarks to the "normal" hadron absorption length. (Taken from the CERN-Bologna-Frascati-Roma Collaboration experiment[26]).

where μ is the primary ionization per unit length. In order to fit the experimental distribution, this formula must be modified to take into account that blobs close together cannot be individually resolved. Assuming an exponential variation of the blob sizes the following formula was derived

$$g(x';\mu,r) = \mu^2 L \ e^{-\mu x'} \left[1 - e^{-x'/2} \left(1 + \frac{x'}{2} \right) \right]$$

with

$$x' = x - \frac{\mu r^2 (\mu r + 3)}{(\mu r + 1)} \ ,$$

where r is a parameter related to the average radius of the blobs.

Data for three muon momenta were fitted using this two-parameter formula. Figure 10 shows the experimental results and the theoretical[27] primary ionization as a function of γ for the gas mixture used.
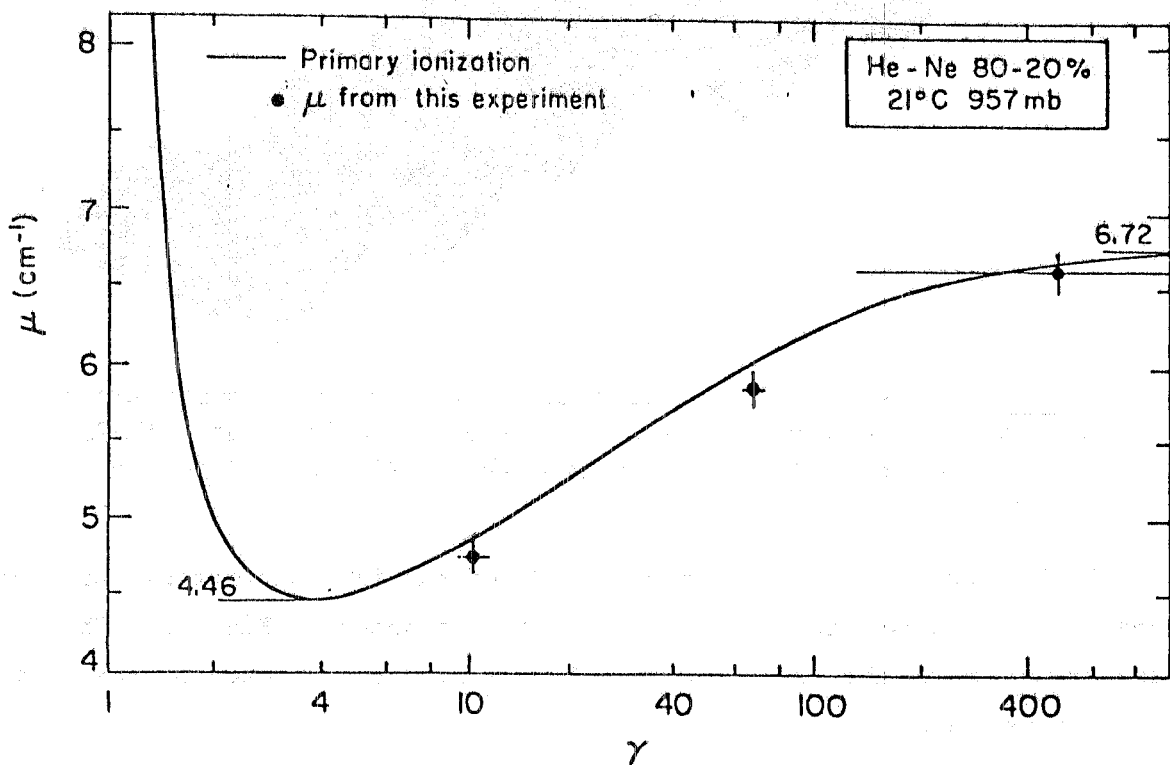

FIG. 10 - Measured primary ionization for three muon momenta compared with theoretical calculations by Ermilova et al.[27]. (Taken from CERN-Bologna-Frascati-Roma Collaboration experiment[26]).

The blob count I (blobs/cm) and the blackness b, defined as the sum of the blob lengths divided by the total length of a track, are related to μ and r by

$$I = \frac{\mu}{(\mu r + 1)^2}, \qquad b = \frac{\mu r(\mu r + 2)}{(\mu r + 1)^2}.$$

The photographs are measured by automatic machines (an FSD of the CNAF in Bologna and the PEPR at Frascati). Figure 11 shows the density profile of successive blobs as seen with the PEPR.
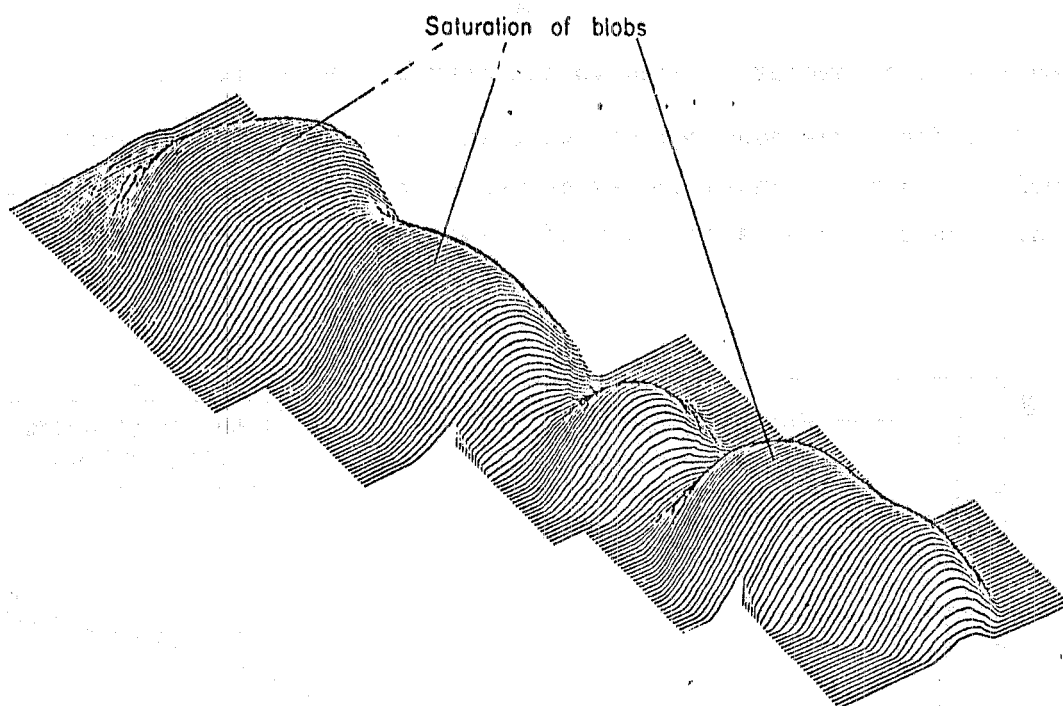

FIG. 11 - Density profile of successive blobs along a short portion of an avalanche-chamber track as seen with the Frascati PEPR. (Taken from CERN-Bologna-Frascati-Roma Collaboration experiment[26]).

Preliminary results, relative to 23% of the full statistics, give no candidates. The scatter plot of I versus b is shown in Fig. 12. The bands relative to the charges Q = 1, $^2/_3$, $^1/_3$ are superimposed on the data in the same figure.

In Table 6 the 90% confidence level upper limits for the flux of quarks per neutrino interaction, obtained until now, are reported. These limits hold also for quarks accompanied by a jet of particles.
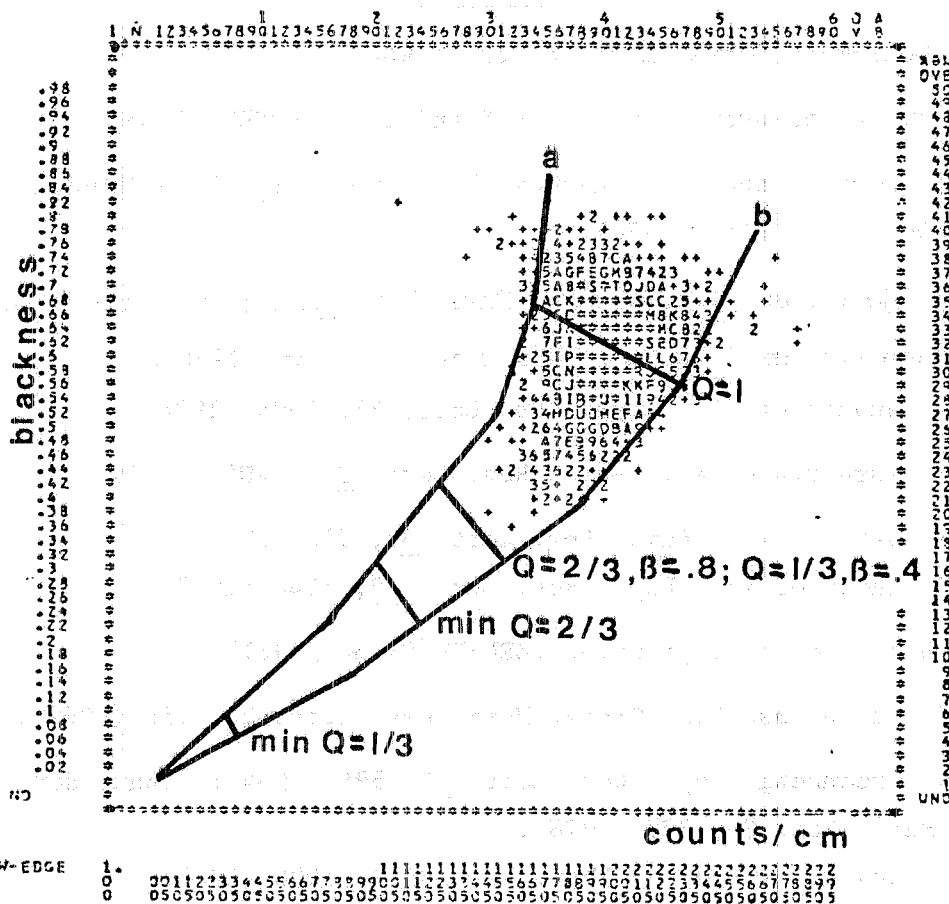
FIG. 12 - Scatter plot of I (counts/cm) versus b (sum of the blob lengths divided by the total length of a track) for tracks measured in the CERN-Bologna-Frascati-Roma experiment. Lines are calculated for two different values of the average radius of the blobs (a : $\langle r \rangle$ = 1.4 mm, and b : $\langle r \rangle$ = 1 mm). The area in which candidates are expected is indicated.

Table 6

Limits on free quark production with $|Q|$ = $^2/_3$ and $\beta \geq 0.8$ and $|Q|$ = $^1/_3$ and $\beta \geq 0.4$ for quarks accompanied also by a jet of particles (23% of the full statistics)

Beam		ν wide-band	$\bar{\nu}$ wide-band
Total No. of protons on target (400 GeV)		0.8×10^{17}	5.3×10^{17}
No. of ν ($\bar{\nu}$) interactions		5.7×10^4	7.5×10^4
90% C.L. quark flux upper limit	Leptonic case $\quad |Q| = ^1/_3, \, ^2/_3$	0.9×10^{-4}	0.7×10^{-4}
	Hadronic case $\quad |Q| = ^1/_3, \, ^2/_3$	1.5×10^{-4}	10^{-4}

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