EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

"IS THE ABSENCE OF QUARKS AS WELL ESTABLISHED AS IS GENERALLY BELIEVED?"

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(Presented by A. Zichichi)

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The purpose of this paper is to show that the general belief that quarks do not exist is not based on such good experimental grounds. A world analysis of the experiments to search for quarks shows that those investigations performed in strong interactions are limited to small p_T values, that searches in electromagnetic interactions cover an even smaller p_T range, and that quark production in weak interactions is at present an unexplored field.

When we started the present analysis, I tested the opinions of theoretical and experimental physicists. For example, the question: "Is the quark mass limit 3 or 5 GeV?" produced the reply that it is certainly higher, not less than 10 GeV/c^2. Questions about the quark-to-pion flux, "Is it 10^{-2} or 10^{-4}?" received replies such as: "Oh no, certainly higher, at least 10^{-9}." At the end of last year I could not find a single physicist who would have been ready to insist on different figures than those quoted above. For 23 years people have searched for quarks without success.

As you know, this is the basic motivation for the "confinement" theories. However, if you study all published papers you find out that all the quark experiments performed so far have the common serious bias discussed above.

So far, quark searches have been carried out extensively in strong interactions 1); a few experiments 2) have been performed using electromagnetic probes, but an analysis of all these experiments shows that the transverse momentum of the searched quark has always been very limited 3). The results of this analysis are reported in Fig. 1. Here all published experiments with magnetic analysis, i.e. those where it was possible to

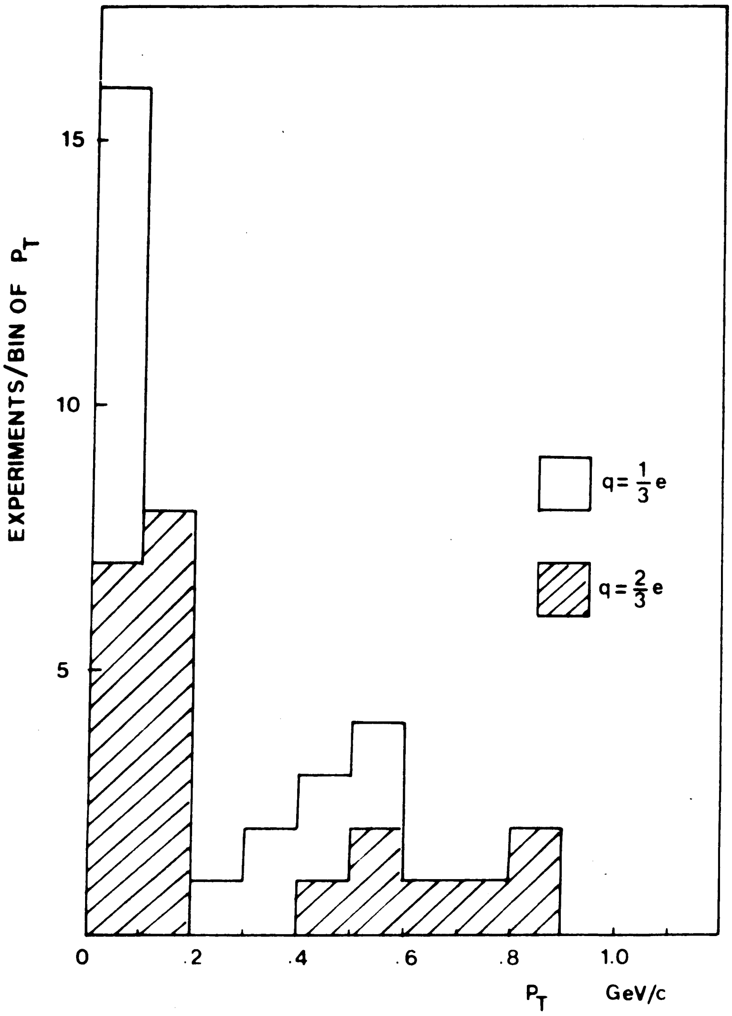

Fig. 1 Showing the values of p_T for published experiments carried out at well-defined p_T values. Note that 16 measurements have been made at p_T = 0.1 GeV/c and none above p_T = 1 GeV/c.

measure the transverse momentum (p_T) of the produced particles, are reported. Sixteen experiments have been performed with $p_T \leq 0.1$ GeV/c and 22 with $p_T \geq 0.1$ GeV/c, but out of the 38 experimental searches none was sensitive to transverse momenta above 1 GeV/c. In experiments with 0° beams without magnetic analysis, the geometric acceptance of the apparatus places a p_T limit of ≤ 1 GeV/c.

So, if in order to break a proton it was necessary to give to one of its constituents a transverse momentum greater than 1 GeV/c, the above-quoted experiments would lose their significance. One experiment not included in this list is that of Fabjan et al.4), because, in spite of the fact that no magnetic analysis was available in this search, the authors$^{4)}$ state that their experiment was sensitive to the highest possible value of p_T of the produced quark (for example as high as 20 GeV/c); in fact the set-up was placed at 90° in the (pp) c.m.s. and the total energy ranged from $\sqrt{s} = \sqrt{2080}$ GeV to $\sqrt{s} = \sqrt{3844}$ GeV. On the other hand, these results are also presented in terms of the ratio ϕ, flux of quarks over flux of π's, which is reported to be of the order of 10^{-9}. In order to clarify the relevance of this experiment in the general belief that quarks do not exist, it should be pointed out that the value of 10^{-9} for ϕ, applies to p_T values below 1 GeV/c, while the sensitivity of this experiment to $p_T \simeq 20$ GeV/c would correspond to the above ratio ϕ, worsened by at least ten orders of magnitude.

As is well known, since many years indirect experimental evidence [deep inelastic scattering effects and SU(3) multiplets] support the idea that the proton is made of super-elementary point-like objects. Fractional$^{5,6)}$ or integral$^{7)}$ values have been proposed for their charge states. Their mass should be as low as a few hundred MeV $^{8)}$, but they have never been observed; as mentioned above, impressive mass limits above the 10 GeV level have been published$^{1)}$. The conventional way out of this puzzle is either to say that the "quarks" are mathematical entities$^{9,10)}$ deprived of physical meaning, or that quarks indeed exist and make-up hadrons; but they are, for example, bound by forces which increase with distance, i.e. they are confined$^{11)}$ inside the particles of which they are the basic constituents.

We wish to propose a completely different point of view, based on the known basic features of strong, electromagnetic, and weak interactions, and on an intuitive model of the proton "breaking" mechanism, which we believe is very plausible on physical grounds. If this model is accepted, the conclusion is that searches for quarks so far have not been made in the right experiments.

It is well known that strong interactions are "strong" but very "soft". Electromagnetic interactions are weaker but harder. Weak interactions are the hardest we know. Nevertheless, all previous attempts to break the proton have been mainly concentrated in the field of strong interactions. Figure 2 shows the present limits on quark production in strong interactions at CERN ISR$^{4,12)}$.

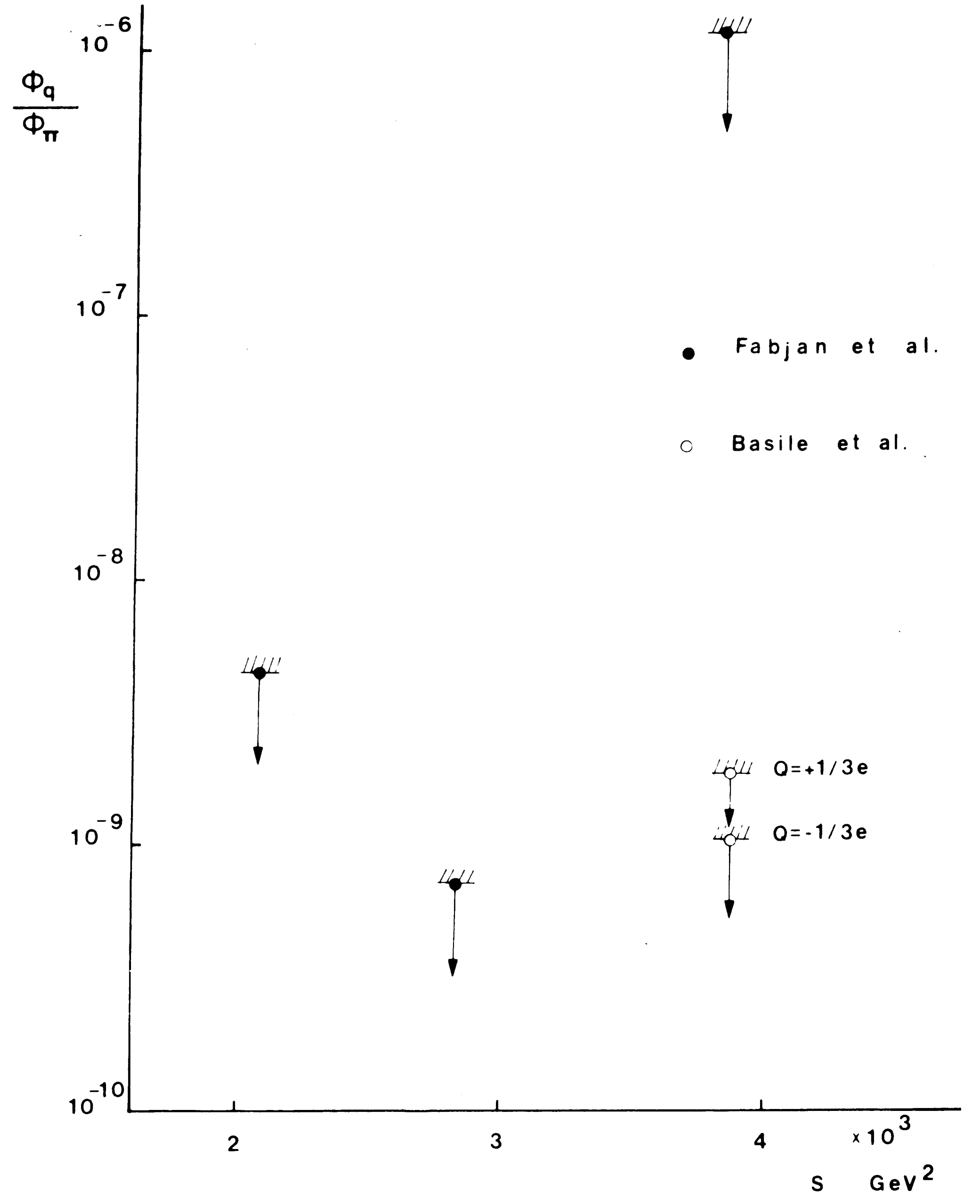

Fig. 2 Summary of the limits for the ratio flux of quarks over flux of pions, relative to ISR experiments: full points refer to Ref. 4, open circles refer to Ref. 12.

The highest value of c.m. energy so far investigated is $\sqrt{s}$ = 62.2 GeV. At this energy the observation of one event[12)] with Q = +(1/3)e, provides with 90% confidence level the following upper limit on the flux of quarks compared with the flux of pions:

$$\frac{\phi_{Q\,=\,+(1/3)e}}{\phi_{\pi^\pm}} \leq 1.78 \times 10^{-9} \ .$$

Here again the value of p_T is limited, to less than 1 GeV/c.

Notice that the enormous amount of total energy, 62.2 GeV, available in the (pp) c.m. system, is associated with the complex of hadronic cloud and point-like constituents which make up the proton. In the (pp) collision the total energy available to each single component of the proton complex is obviously very much smaller than 62.2 GeV.

The same difficulty exists for high transverse momentum phenomena induced by hadronic probes.

From an intuitive point of view it is perfectly plausible that, in order to break the proton, a high p_T should be given to one of its constituents at once in a single action as illustrated in Fig. 3.

If the interaction between the two quarks is of a hadronic nature, the large p_T value could be the result of many small p_T^i, with $p_T = \sum_i p_T^i$, and $p_T^i \ll p_T$, as illustrated in Fig. 4. In a proton-proton collision, with a high transverse momentum proton observed in the final state, it is not clear so far on what firm basis it would be possible to conclude that the single exchange process of Fig. 3 is responsible for the observed high p_T proton and not the multiple one illustrated in Fig. 4, or even the more complicated one of Fig. 5, where the many p_T^i's are exchanged between different quark lines. Each p_T^i may never be sufficient to break a proton;

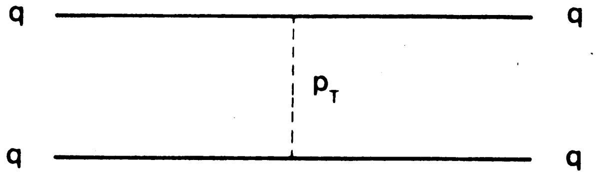

Fig. 3 Feynman diagram illustrating the exchange of a large p_T between two quarks

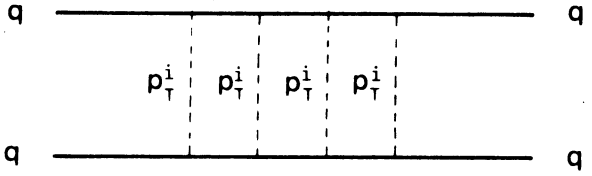

Fig. 4 Feynman diagram illustrating a series of small p_T^i exchanges between two quarks. The p_T^i is never sufficient to break the proton. Thus, after the series of p_T^i, the final state is again a bound system of quarks and hadronic cloud, and the emerging proton shows a large $p_T = \sum p_T^i$.

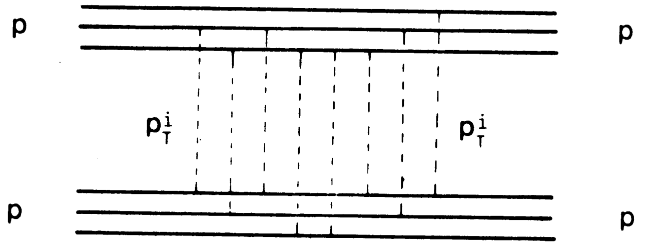

Fig. 5 Feynman diagram illustrating a large p_T hadronic process as result of the exchange of many p_T^i between different quark lines.

thus after the series of p_T^i exchanges, the final state is again a bound system of quarks and hadronic cloud, and the emerging proton shows a large $p_T = \sum_i p_T^i$. This is obviously not restricted to the proton case. Quite generally, if in a hadron-hadron collision we observe a high p_T particle, either a pion or a proton or a hadron of any sort, the transverse momentum carried out by the observed particle is by no means sure to be the result of a single high p_T transfer process; rather it is likely to be the result of many small p_T^i exchanges, building up a high p_T process.

A good evidence that a high p_T can be transferred in a single action (Fig. 3) between two quarks of two protons would be a jet-structure in purely hadronic collisions. This jet-structure has so far not been clearly established in terms of a single transfer process being responsible for the observed "jet-like event"13). On the other hand, quarks have neither been searched for so far in jet-like events, nor in high p_T events3). But even if this were the case, there would still be the problem of being sure that these events correspond to a high p_T single transfer process between the super-elementary constituents of the two interacting hadrons (Fig. 3). In fact, once again we should emphasize that strong interactions are strong but very "soft". Therefore the observation of a high p_T event produced in hadronic interactions does not imply that the high value of p_T observed is associated with a single exchange process.

For this to be true, a "hard" probe is essential. Electromagnetic and weak interactions provide hard probes. A high p_T process produced by a weak probe is sure to be associated with a single momentum transfer, multiple exchanges being excluded by the values of the coupling constants. Figures 6 and 7 illustrate the case of a weak-boson exchange; the same

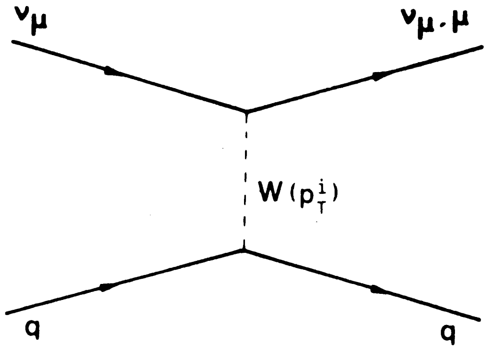

Fig. 6 Feynman diagram illustrating the interaction between a lepton and a quark via an intermediate weak boson. All p_T is transferred in this process in a single action.

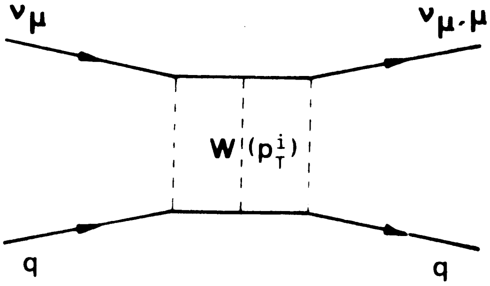

Fig. 7 Feynman diagram illustrating multiple exchanges between a lepton and a quark, via an intermediate weak-boson. Each W-line causes a depression factor. Thus the splitting of p_T is very unlikely when a weak coupling is involved.

qualitative features are expected if instead of a weak boson, a photon is exchanged between two quarks. In the field of electromagnetic interactions, evidence for jet-like structure has been reported at SPEAR in (e^+e^-) annihilations[14), but no quark search has so far been performed in these jet-like events.

Efficient probes for penetrating the hadronic cloud, without being q^2-degraded, are the non-strong ones. The weak boson is certainly the best we know today. Thus a basic process of proton-breaking could be via a W-exchange mechanism, as illustrated in Fig. 6. Another way to provide a point-like constituent of a hadron with a large p_T, is via a direct neutrino-quark contact point-like interaction, as shown in Fig. 8. The neutrino is certainly a very efficient probe for penetrating the

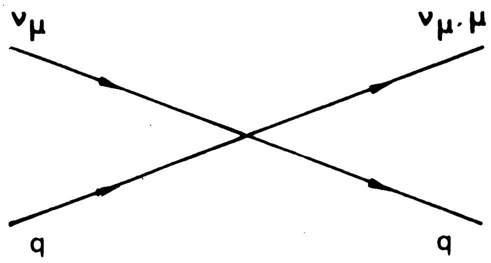

Fig. 8 Feynman diagram illustrating a direct neutrino-quark contact point-like coupling.

hadronic cloud of a proton without being q^2-degraded. A very good way of breaking the proton would thus be via high-energy neutrino interactions. These arguments can obviously be extended to the domain of electromagnetic interactions, with a point-like lepton-quark coupling, or with a single hard photon exchange. Evidence for single hard photon exchange between the electron and a quark are the well-known deep inelastic phenomena. But no quark search has been made in association with deep inelastic effects at SLAC.

As mentioned above, so far quark searches have been carried out extensively only in strong interactions; but the search for quarks in the "hard" component of these interactions (high p_T and jet-like events) is many orders of magnitude less sensitive than the soft part, which is the only one investigated. The search in electromagnetic interactions provides much lower values of the quark mass limit and refers to an even lower value of the transverse momentum; here again no quark searches have been made in association with the observed jet and deep inelastic events.

Quark production in neutrino interactions is an as yet unexplored field.

If the reason for quark absence so far is not "absolute confinement" but the nature of the proton breaking mechanism, which would require a big bang to be given to one of the super elementary constituents, then the quark limits in all previous experiments lose their significance.

We would like to see these ideas put to experimental test, with an intensive search for quarks in high-energy neutrino interactions$^{15)}$, in electromagnetic interactions, and also in the "hard" tails of the strong interactions.

I would like to include in this talk the first results obtained by the Bologna-CERN Group in a preliminary test experiment performed at CERN with the SPS high-energy neutrino beam. It is important to emphasize that these results apply only if we think we know the production mechanism for quarks; this remark is valid for any experiment, even if it is often not clearly emphasized by the authors.

From the point of view of the experimental observations, there are three main classes of event:

1) $$\nu + N \left[\begin{array}{l} \to \nu + q + q + q \\ \to \mu + q + q + q \end{array} \right.$$

i.e. quark production via a proton breaking mechanism induced by either the neutral or charged weak current. Reaction (1) is a very clear case.

2) $\nu + N \to$ quark + "all the rest", where one "quark" recoils against "all the rest".

3) $$\nu + N \left[\begin{array}{l} \to \nu + \text{(jet-like + quark) + "the rest"} \\ \to \mu + \text{(jet-like + quark) + "the rest".} \end{array} \right.$$

Here the quark is contained in the hadronic jet.

The first two classes are suitable to experimental investigation with our apparatus.

However, if the only way in which quarks are produced is in association with very large hadronic showers, then our present apparatus would have been unable to detect them.

Let me just mention the basic points. Figure 9 shows the experimental set-up which consists mainly in a set of dE/dx counters to measure fractional charges. The time-of-flight (TOF) system is essential for eliminating many spurious effects, including edge effects and cosmic-ray showers passing through the light-guides.

The basic results are shown in Table 1. Out of some 8000 effective ν interactions, we observed no events. Thus for quark production mechanisms which follow the pattern of classes 1 and 2 above or in which quarks are produced in association with the normal multiplicity of hadrons as seen in neutrino events, the rate of quark-producing interactions is, with 90% confidence, less than 5.0×10^{-3} of the normal neutrino interactions.

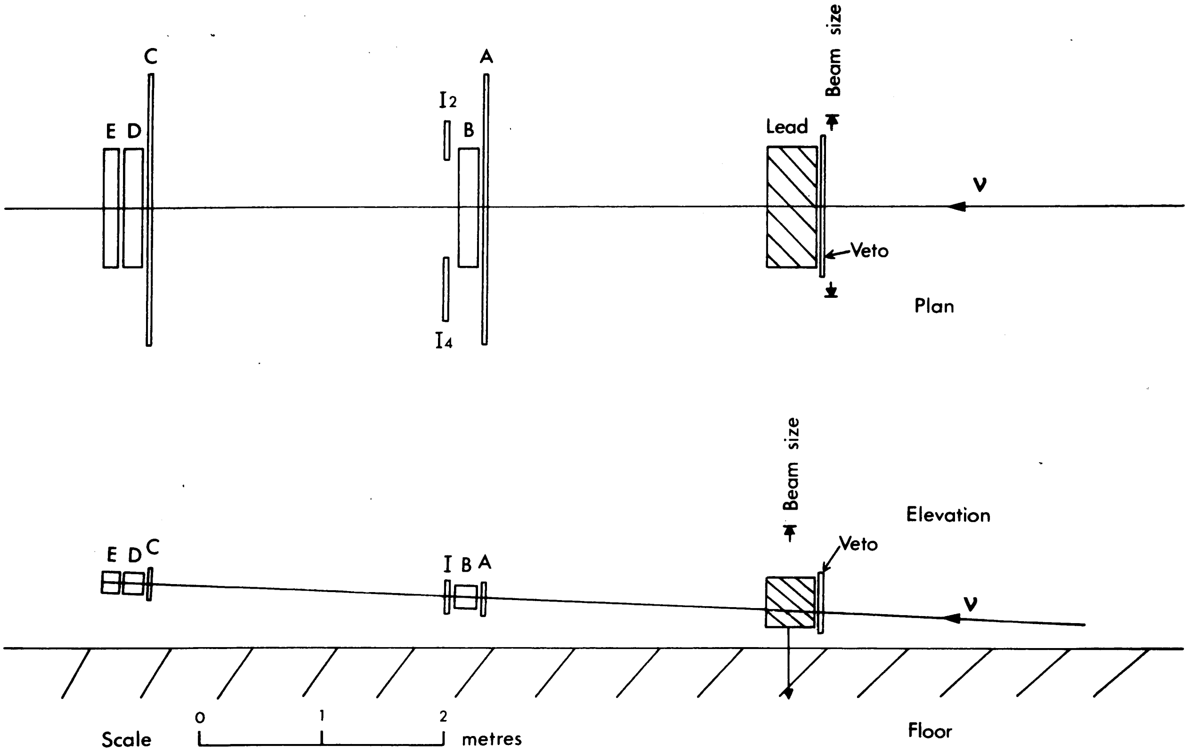

Fig. 9 Experimental arrangement for the test run. A, B, and C were coincidence counters which also measured pulse height and time of flight. D and E were auxiliary counters which were not needed for the present analysis. I2, I4, and "Veto" were counters which set a flag if they were struck in a particular event. The target was the concrete floor for much of the running time, the lead being available only later in the test.

Table 1

Basic results of the quark search

Neutrino interactions in one interaction length of target	7900
Quark interaction length	270 g/cm^2
Solid angle × single particle detection efficiency (assuming quarks are produced with angular distribution similar to muons)	2.0 ± 0.7%
Quark multiplicity/interaction	3
Number of interactions × single quark acceptance × × quark multiplicity	474
$\frac{\text{Interactions producing quarks}}{\text{Total number of interactions}}$ (90% confidence)	$(5.0 \pm 1.6) \times 10^{-3}$

It is our intention to extend this search using a more selective, high-acceptance counter array which will be triggered not only by reactions 1 and 2 but also by events with very high multiplicity. For the latter, a streamer chamber will be an essential part of the apparatus.

CONCLUSION

Numbers like 10^{-9} for quark fluxes compared to pions apply only for p_T values below 1 GeV/c; No quark searches in high p_T, jet like events or in deep inelastic phenomena have been made. There is only one result at the level of 5×10^{-3} for very clean production mechanism in weak interaction: this is all we know after 23 years of quark searches.

I think you will agree with me that by no means has the quark search been sufficiently extensive to justify the common belief that they do not exist as free particles.

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