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by

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Abstract

We analyse recent measurements of the net charges of quark jets in neutrino and antineutrino interactions. The data indicates that (i) the two quarks in the nucleon fragmentation region prefer to behave as a diquark rather than as a pair of independent quarks, and (ii) the struck quark does not appear to suffer any "soft" charge-exchange of the kind that occurs when a valence quark inside a nucleon is slowed to $x \approx 0$.

There is a long standing theoretical belief [1] that when a quark hadronises into a jet of hadrons, the net charge of the jet will closely reflect the charge of the parent quark. Measurements of the net charges of quark jets in antineutrino [2] and neutrino [2,3] interactions have recently appeared, and it has been argued that they confirm this theoretical expectation. We have performed a more detailed analysis of the interpretation of these measurements [4], and find that we disagree with much of the previous analysis [2]. Nonetheless we find that the data do contain interesting information. In this letter we show how the measured energy dependences of the net charges of the quark jets have implications for the diquark structure of a nucleon, and the charge exchange properties of an "isolated" quark.

The measurements are made for values of Bjorken-x (x_B) such that the weak boson interacts predominantly with the nucleon valence quarks. Hence for antineutrino interactions the quark jet arises from a fast d quark, while in neutrino interactions the parent quark is a u quark. The advantage of (anti) neutrino interactions is that the parent quark is the same in every event, so we can take averages over many events. One goes into the centre-of-mass of the final hadronic system and measures the net charge of all the hadrons in the c.m. hemisphere containing the struck quark. This net charge will, when averaged over many events, be a function of the total hadronic c.m. energy W, and the parent quark q; so we write the net charge as Q(q;W). The theoretical predictions are

$$Q(d;\, W \to \infty) \approx -0.45 \qquad (1)$$

$$Q(u;\, W \to \infty) \approx +0.55 \qquad (2)$$

(see below for a derivation.)

The measurements are of course for finite values of W, and have finite errors, so there is the problem of extrapolating the measured $Q(q;W)$ to $W = \infty$. In general we expect (see below) that the leading W dependence of $Q(q;W)$ as $W \rightarrow \infty$ should consist of a simple power behaviour. For the experimental data to be of any use in constraining $Q(q;\infty)$ one must assume that this simple leading W dependence sets in at a value of W small enough to encompass most of the data. In practice this means $W \gtrsim 2.5$ GeV. This is not an unreasonable assumption: at such values of W we are well above the prominent direct channel resonances, and our experience with two-body charge exchange (which is what is involved here - see below) leads us to expect the leading asymptotic energy dependence to have set in. This is the assumption made in ref. (2), and it is an assumption we adhere to in the remainder of this paper.

Now in ref. (2) it is argued that one expects

$$Q(q;W) = Q(q;\infty) + \frac{\text{const.}}{W} \tag{3}$$

to be the W dependence. And indeed when plotted against 1/W, the data is readily fitted with straight lines of the form of eqn. (3), and moreover the best such fits satisfy the predictions (1) and (2) very well. See Fig. 1.

Unfortunately, contrary to what is implied in ref. 2, the errors are large enough that other simple functional dependences of $Q(q;W)$ are also possible: and they lead to different values of $Q(q;\infty)$. In Fig. 2 we replot the data

against $W^{-1/2}$ (there is a reason for choosing this form - see below) and fit it with straight lines, i.e. use fits

$$Q(q;W) = Q(q;\infty) + \frac{\text{const.}}{W^{1/2}} \tag{4}$$

We observe that the data is well-fitted by a parameterisation of the form (4). However, the values of $Q(q;\infty)$ are now

$$Q(u;\infty) \approx .2 \text{ to } .35 \tag{5}$$

$$Q(d;\infty) \approx -.65 \tag{6}$$

Although each individual set of data is just barely consistent within errors with the theoretical values (1), (2), if we take all the data together, then we can say that an extrapolation of the form (4) gives results <u>not</u> consistent with our theoretical expectations. This shows that without some strong arguments for a 1/W dependence, one cannot claim that the available data supports the predictions (1) and (2) (and of course, any such verification will be no stronger than the arguments one can muster on behalf of eqn. (3)).

It is therefore interesting that (contrary to statements in ref. (2)) naive parton model arguments lead to (4) not (3)! The argument [4] can be briefly indicated as follows. There are two sources for the W dependence; the struck quark will occasionally be slowed down so much that it passes into the nucleon fragmentation hemisphere, and, conversely, one or both of the nucleon valence quarks may leak into the c.m. hemisphere that normally contains the struck quark. These are essentially just quantum number exchange processes, like charge exchange. Their probability will of course decrease with W. Since what is involved is the slowing down of valence quarks, this W dependence can be obtained immediately from what (one believes) one knows about nucleon valence distributions near $x = 0$. There the valence quark distribution is suppressed by a factor $\sim x^{1/2}$ relative to the sea. So the probability for a valence quark to be found at say 1 GeV in the c.m. is (if the total c.m. energy is W)

$$x^{1/2} = \left(\frac{2}{W}\right)^{1/2} \tag{7}$$

and so we see that the probability for this kind of leakage is proportional to $W^{-1/2}$ and not to W^{-1}, and so (4) is to be preferred to (3).

We have a dilemma. If we follow our theoretical prejudices as to the probability for slowing down quarks we must use (4), and then we contradict our theoretical prejudices concerning the net charges of quark jets. It seems we must either give up (4) or (1,2). Clearly we will retain (provisionally) the theoretical expectation that is the most solidly based. We have sketched an argument for (4), which is based on conventional ideas about charge exchange [(4)]. The argument for (1,2) is usually given within the context of a simple cascade picture of quark fragmentation. However, it can be given much more generally, as we shall now briefly do.

Consider a u quark, for example, that fragments somehow into hadrons, as in Fig. 3. At some fixed c.m. rapidity y_o we make a cut and we measure the average net charge of hadrons faster than y_o. Now, this net charge will just

equal the u quark charge plus whatever charge enters the hadronic system with $y > y_o$ from the rest of the event at $y < y_o$. Since the hadrons with $y > y_o$ have net mesonic quantum numbers (baryons are an inessential complication) it is clear that the charge entering from $y < y_o$ must have the net quantum numbers of an antiquark plus some integer. This antiquark can either be $\bar{u}$ or $\bar{d}$ (we shall include the relatively rare strange quark later). If y_o is sufficiently far in phase space from the u quark ($W \to \infty$) then, if the dynamics does not have long range charge correlations, we expect $\bar{u}$ and $\bar{d}$ to be equally probable. This leaves the integer valued charge leakage. This will follow some distribution with width σ, and, assuming no long range charge correlations, an average of zero. So if we average over many events the net hadronic charge is just that of the u and the average antiquark charge, i.e.

$$\begin{aligned} Q(u;\, W \to \infty) &= u + \frac{\bar{u} + \bar{d}}{2} = .5 \\ Q(d;\, W \to \infty) &= d + \frac{\bar{u} + \bar{d}}{2} = -.5 \end{aligned} \tag{8}$$

Strangeness at the observed level will alter (8) slightly and will give us the predictions (1) and (2).

The above argument for (1) and (2) rests only on the hypothesised absence of long range correlation in charge. It would be very surprising if this were not to be the case, and in any case we observe that the usual charge exchange argument for the $W^{-1/2}$ dependence of (4), is also based on short range correlations; amongst other assumptions. So the way to resolve our dilemma is to retain (1-3) and to reject (4-6). We now point out some interesting consequences of this choice.

As we pointed out earlier, the W dependence arises from the leakage of the 3 valence quarks between the two c.m. hemispheres. The specific interactions of interest here are νp, νn, $\bar{\nu} p$ and $\bar{\nu} n$, and these have hadronic final states that may be represented at the quark level as in Fig. 4. Observe that leakage of the struck quark out of its own hemisphere reduces $|Q(q;W)|$ below its asymptotic value. Thus it is clear that the W dependence of the νp data [3] is dominated by leakage of the remnant proton valence quarks into the struck quark hemisphere. On the other hand we expect that the W dependence of the $\bar{\nu} N$ data of ref. (2) (N represents 36 % H_2 and 64 % Ne) is dominated by the leakage of the struck quark because the average charge of the remnant nucleon valence quarks is close to zero. Because both pieces of data favour [5] a 1/W dependence for consistency with (1) and (2), we feel confident in asserting that both the struck quark and nucleon valence quark leakages contribute <u>individually</u> as 1/W.

So, let us first consider the remnant nucleon valence quarks. As we remarked earlier the conventional expectation is that an individual valence quark has a small x momentum distribution proportional to $x^{1/2}$; and this then gives a leakage $\propto W^{-1/2}$. This is an expectation based [4] on our understanding of soft hadronic physics, and should be valid within a nucleon, or within its remnants. However, we have seen that experiment indicates a W^{-1} dependence. So we conclude that the <u>individual</u> leakage of the remnant valence quarks is not dominant. We now observe that similar arguments to those above suggest that diquark leakage falls more rapidly than $W^{-1/2}$, probably more like W^{-1}. It is thus plausible to conclude that the two remnant valence quarks behave largely as diquarks rather than as independent quarks.

In the simplest such picture there will be two constants to be determined,

a and b, where a/W is the probability for a diquark of unit charge to leak into the opposite hemisphere, and b/W is the probability for a struck quark of unit charge to leak into the nucleon hemisphere. In each case we have to weight these probabilities by the appropriate charges. Since we have data for three different interactions, we can use the data to test the picture quantitatively -- and also (if successful) to determine a and b.

At first glance the experimental errors appear quite large and one might imagine that they would not constrain the theory very tightly. This is in general true; however, if, as here, we constrain the intercepts at $W = \infty$ to be as in (1) and (2), then the effective uncertainties are much reduced. Sample fits to the data, as shown in Fig. 1, give

$$Q^{\nu p}(u;W) = .55 + \frac{1.9 \pm .14}{W} \qquad (9)$$

$$Q^{\nu N}(u;W) = .55 + \frac{.9 \pm .15}{W} \qquad (10)$$

$$Q^{\bar{\nu} N}(d;W) = -.45 + \frac{.94 \pm .06}{W} \qquad (11)$$

(The errors are conservative and correspond to the dashed lines in Fig. 1). If we now express the leakages in terms of a/W, b/W multiplied by the relevant charges we obtain

$$1.45\,a + .55\,b = 1.9 \pm .14 \qquad (12)$$

$$.83\,a - .55\,b = .9 \pm .15 \qquad (13)$$

$$.16\,a + .45\,b = .94 \pm .06 \qquad (14)$$

In obtaining (12-14) there are two points to note.

(i) The charges used in weighting (a) and (b) are as follows. The u quark is weighted by 0.55 and the uu diquark by (2-0.55) = 1.45. The d quark is weighted by -0.45, and so on.

(ii) In $\bar{\nu}N$ we have both $\bar{\nu}p$ and $\bar{\nu}n$; these are in a ratio 2.45 : 1 taking the 36 % H_2, 64 % Ne composition of N into account, and also noting that the W^- boson interacts with the u quark and hence twice as often with each proton as with each neutron. For νN the ratio changes by a factor of 4 because the W^+ boson interacts with the d quark.

If we now look for solutions of (12-14) we find that such solutions exist - so that the diquark picture is indeed compatible with the data. Values for a and b are

$$a \approx 1.88 \quad ; \quad b \approx 1.36 \tag{15}$$

with (correlated) errors of about 10 %. It may appear counterituitive that the diquark slows down more readily than the quark (i.e. $a > b$ in (15)). However, we must remember that while the quark is rather close to $x = +1$ initially (it loses some momentum through perturbative gluon bremsstrahlung), the diquark will typically have $x \lesssim -0.4$ because of the momentum carried by glue in the nucleon; simple estimates then show that (15) implies that a quark slows down through a given rapidity interval about twice as readily as the diquark. This may seem more reasonable (although that is not really clear because the dynamics in the two cases is surely qualitatively different).

How to interpret the 1/W dependence of the quark leakage? In the case of the two remnant valence quarks we were able to interpret their 1/W behaviour as

a signal that the two quarks prefer to interact as a diquark system rather than independently; this is interesting but not totally unexpected - and certainly did not require any revision of our ideas about soft, quantum number exchange. For the isolated struck quark we have no such convenient interpretation handy; the usual charge exchange picture predicts a $W^{-1/2}$ dependence quite uncompromisingly. So if we take the analysis of this paper seriously, we must conclude that the usual soft charge exchange is not operative, or at least not dominant, here. In this respect we may indulge in some speculation. Consider ordinary charge exchange as viewed in the target rest frame. This is conventionally [6] seen as a long time interaction, with the quantum that is to be exchanged slowing down by "bremsstrahlung" for a time of order E_{lab} before the actual collision. At the moment when the projectile passes close to the target, the charged quantum is very slow in the target rest frame and is absorbed, thus completing the charge exchange. The crucial point is to note how the softness of the interaction requires a certain extended space-time structure. Now in a hard collision any charge exchange that occurs before the actual hard interaction is irrelevant because the weak current picks out a particular quark with a particular momentum fraction that depends on Q^2 and W^2 only. After the hard interaction all the quanta are moving away from each other, so the kind of charge exchange described above would have difficulty in occurring. So we may speculate that in this respect at least the hadronisation that transforms the partons resulting from a hard interaction into the observed hadrons, differs qualitatively from the soft interactions that occur in normal hadron collisions. If the 1/W slowing down of the struck quark is not due to conventional soft charge exchange what is it due to? Noticing that due to the perturbative bremsstrahlung of gluons (in the leading log approximation) the quark spectrum acquires a $1/W$ (up to logs) tail to its spectrum, might incline us to speculate that this is indeed the leakage being measured experimentally.

We conclude with a warning and a practical comment [4]. The warning is that we have, as emphasized earlier, followed the experimental groups in assuming the leading W dependence to set in at around $W \approx 2.5$ GeV. Without such an assumption, the presently available data does not usefully constrain $Q(q;\infty)$. However, as we remarked earlier this is not an unreasonable assumption. The practical comment is that it would be interesting if the experimental groups would analyse their data by keeping the invariant mass of the struck quark jet fixed while varying the total hadronic c.m. energy W. This means one sits in a frame other than the overall c.m. frame. In such a situation one fixes the contribution of the quark charge leakage, while varying the "diquark" leakage, and this can test further the picture presented in this letter.

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3. N. Schmitz: Lectures at the XX Krakow School, Zakopane, June 1980, MPI-PAE/Exp. El. 88.

4. M. Teper: In preparation.

5. It is difficult to do a proper error analysis without detailed information on the nature of the experimental errors. We note that in ref. (2) the statement is made that the exponent of W is -1 ± 0.2: this is indeed a stronger statement than we would have been inclined to make.

6. See for example:
   J. Koplik, A.H. Mueller: Phys. Rev. D12 (1975) 3638.

Figure Captions

Fig. 1 The net charge of hadrons in the c.m. hemisphere containing the struck quark, is plotted versus 1/W for $\nu p^{(3)}$, $\nu N^{(2)}$ and $\bar{\nu} N^{(2)}$ interactions as in refs. (2,3). Straight line fits with the theoretically expected intercepts (see text) are shown. The dashed lines correspond to the errors in eqns. (9-11).

Fig. 2 Data as in Fig. 1 but now plotted versus $1/W^{1/2}$. Good straight line fits are possible, as shown, but the intercepts are now far from their theoretically expected values.

Fig. 3 A fast u quark fragments into a jet of hadrons. The total charge of hadrons with $y > y_o$ is given by that of the u quark, and whatever charge flows across $y = y_o$ from the rest of the event with $y < y_o$. This consists of an antiquark charge ($\bar{u}$ or $\bar{d}$) plus an integer as shown (see text).

Fig. 4 The usual fast quark content of the final state in (a) νp (b) νn (c) $\bar{\nu} p$ (d) $\bar{\nu} n$ interactions.

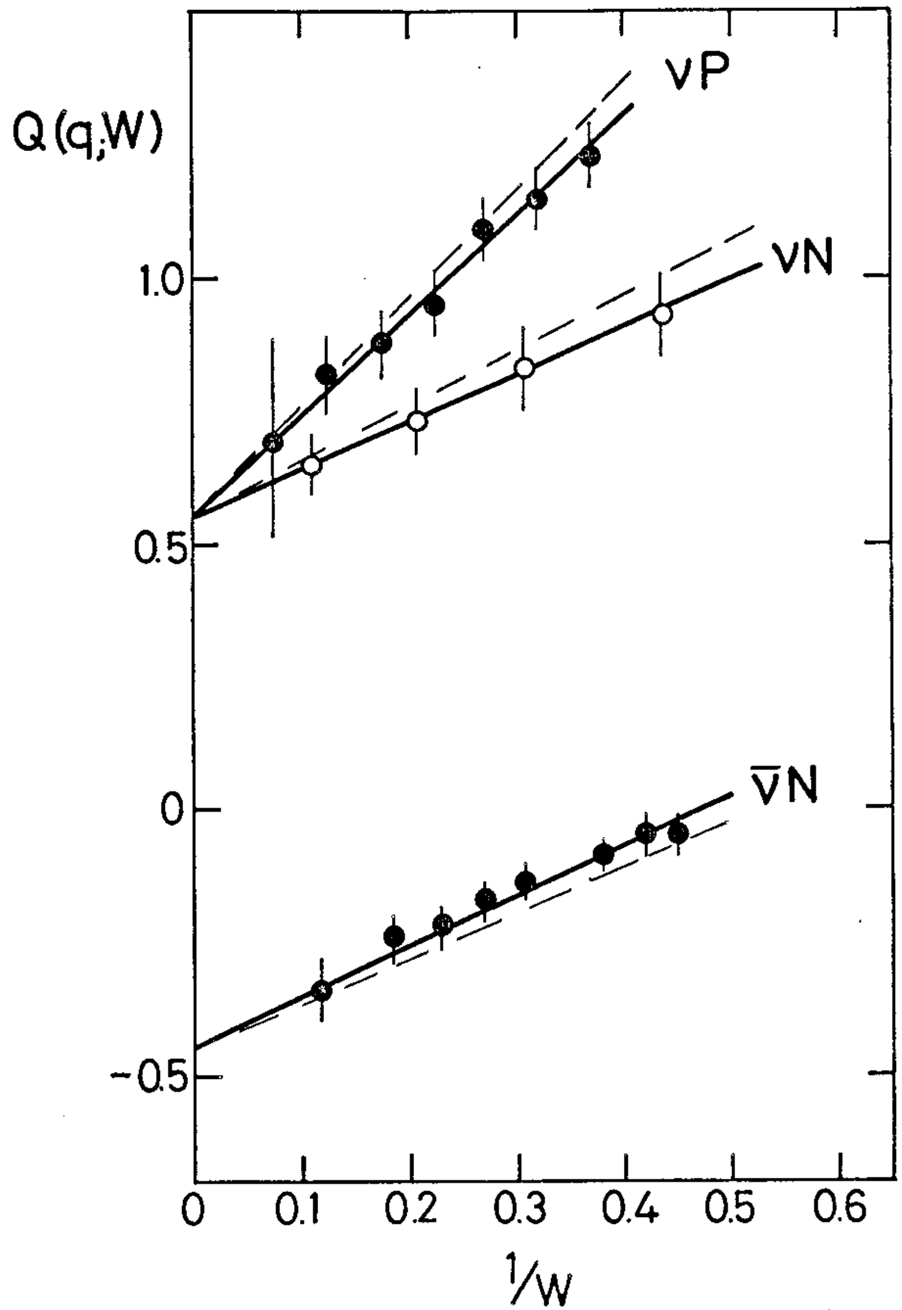
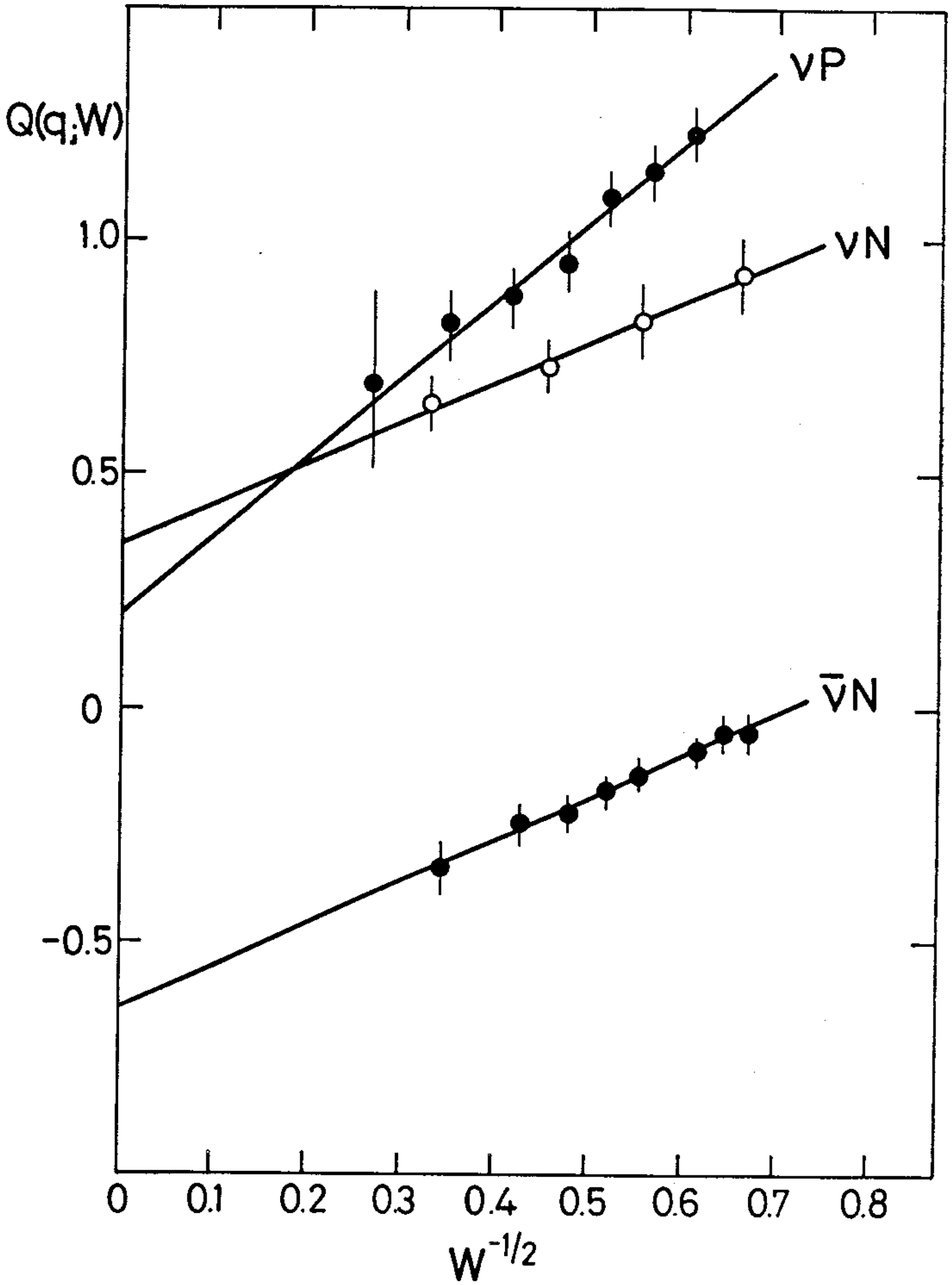


FIG. 1


Q(q;W)
νP
νN
ν̄N
1.0
0.5
0
-0.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
W^{-1/2}

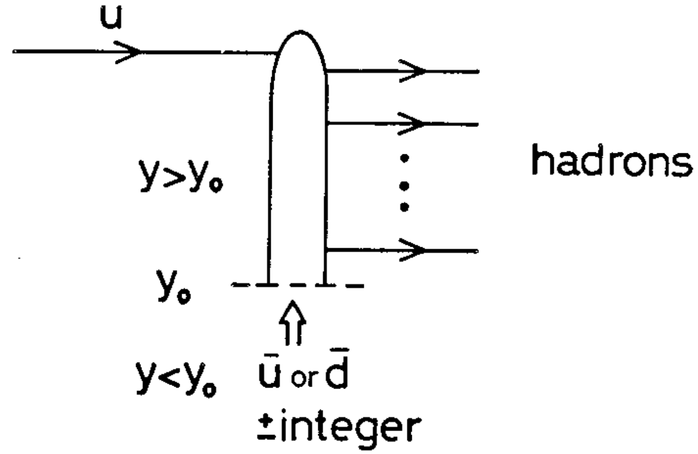

u
hadrons
y>y₀
y₀
y<y₀
ū or d̄
±integer

FIG.3

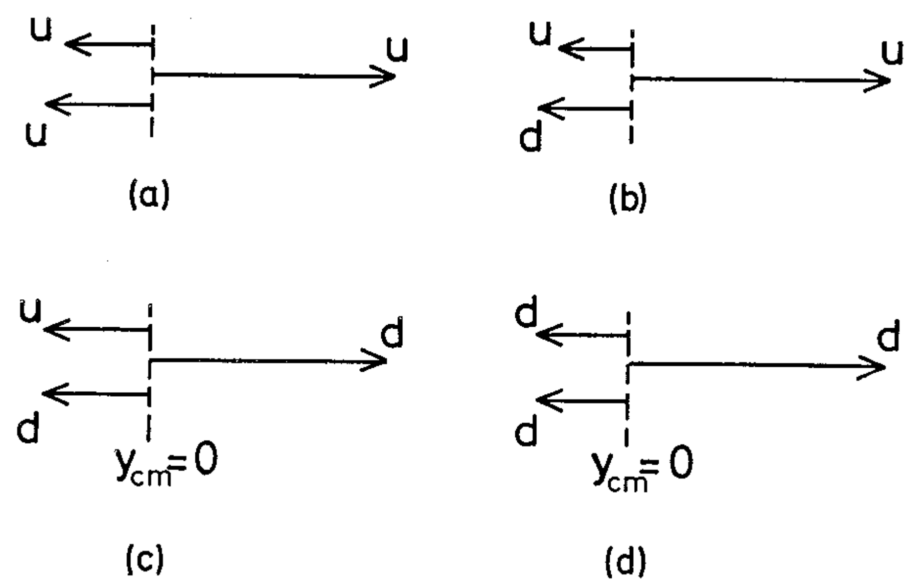

u
u
u
(a)
u
d
u
(b)
u
d
d
y_cm=0
(c)
d
d
d
y_cm=0
(d)

FIG.4