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Tests of the Quark-Parton Model In Soft Hadronic Processes

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Abstract

A simple quark-antiquark recombination model is used to predict some features of two-particle inclusive cross sections in the fragmentation region in soft hadronic processes. We compare π^+ cross sections observed at Feynman x_b in association with various "trigger" particles (at x_a) and discuss the dependence of the cross sections on an approximate scaling variable $\bar{x}_b = x_b/(1-x_a)$. Data from 360 GeV/c $\pi^- p$ interactions are consistent with our predictions.

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The quark-parton hypothesis has been used successfully to describe "hard" processes such as the production of high-mass meson and lepton pairs and of hadrons at large transverse momentum. These processes involve the hard scattering[1] of two elementary constituents (partons). For example, these two partons may undergo elastic scattering, followed by quark "decay" (fragmentation) $q \to h + X$ to produce a particular hadron h.

It is natural to ask whether quark-parton effects also appear in "soft" (small momentum transfer) processes -- as one would hope if perturbative Quantum Chromodynamics (QCD) is indeed appropriate for strong interactions. Recently, the relevance of the parton model to low P_T inclusive reactions has been demonstrated.[2-4] It has been shown [3] that in this region, the conventional quark fragmentation approach predicts a cross section which is too small in magnitude and which falls too fast with Feynman x, as a result of the convolution of the structure and fragmentation functions. However, a simple quark-antiquark recombination model describes the data very well.[3]

Here we show how two-particle inclusive reactions can be used to further probe the quark-parton structure of interacting hadrons. We consider the fragmentation process

$$A + B \to a + b + X, \qquad (1)$$

where a and b are low P_T fragments of A, each carrying a finite fraction (x_a, x_b) of the longitudinal momentum of A in the center of mass. Reaction (1) can be thought of experimentally as follows: we "trigger" on a fast hadron of a particular type at x_a, and study the cross sections, or ratios thereof, for hadrons of various types at x_b. Since little has been done on two-particle correlations in the fragmentation region, we discuss the qualitative aspects such as particle ratios and scaling, which arise from the simplest possible assumptions, rather than questions of detail.

In the quark recombination model for single meson production in the fragmentation region,[2-4] a valence quark from A combines with a sea antiquark to form the detected meson a, at Feynman x_a. Hence

$$F_{a/A}(x_a) = \frac{1}{\sigma}\frac{d\sigma}{dx_a} = \Sigma\int dx_1 dx_2 f_{q\bar{q}/A}(x_1,x_2)\phi_a(x_1,x_2)\ \delta(x_1+x_2-x_a), \qquad (2)$$

where the sum runs over the permutations of $q\bar{q}$ with the quantum numbers of a, $f_{q\bar{q}/A}(x_1,x_2)$ is the probability to find a quark at x_1 and an antiquark at x_2, and $\phi_a(x_1,x_2)$ is the probability for the $q\bar{q}$ system to form a. Multi-quark or quark-gluon components in the wave function are assumed to be negligible, or else to be included in an average way as two quasi-quarks. Since the sea quarks are concentrated near x=0, $F_{a/A}(x_a)$ will be approximately proportional to $f_{q/A}(x_a)$, the probability of finding q at x_a in A.[5] An equation similar to Eq. (2) can also be written for particles formed by the fusion of two sea partons. However this sea-sea contribution should be unimportant at large x_a unless the valence-sea recombination mechanism is not allowed by the quantum numbers.

The extension of the quark recombination approach to double fragmentation processes is straightforward.[6] Assuming that A is a baryon, and its detected fragments a and b are mesons, we write

$$F_{ab/A}(x_a,x_b) \equiv \frac{1}{\sigma}\frac{d^2\sigma}{dx_a dx_b} = \Sigma\int dx_1 dx_2 dx_3 dx_4\ f_{q\bar{q}q\bar{q}/A}(x_1,x_2,x_3,x_4)\phi_a(x_1,x_2)\ \phi_b(x_3,x_4)$$

$$\delta(x_1 + x_2 - x_a)\ \delta(x_3 + x_4 - x_b) \qquad (3)$$

Since the momentum fractions of the sea antiquarks are strongly concentrated near x = 0, the integrals over the sea antiquark momenta can be evaluated by setting $x_2 = x_4 = 0$. Hence we can approximate Eq. (3) by

$$F_{ab/A}(x_a,x_b) \sim f_{qq/A}(x_a,x_b). \qquad (4a)$$

In deriving Eq. (4a), we assumed a and b to be mesons while A was a baryon. A similar formula applies, if all three particles are mesons. If a and A are baryons while b is a meson, an equation similar to Eq. (4a) again applies; but a second mechanism is also possible in which two valence quarks from A combine with a sea quark to form a. Hence

$$F'_{ab/A}(x_a,x_b) \sim \int dx_1 dx_2\ f_{qqq/A}(x_1,x_2,x_b)\delta(x_1 + x_2 - x_a). \qquad (4b)$$

Next we discuss a possible scaling variable to describe the momentum distribution of particle b in the presence of a trigger particle a at x_a. Following the Kuti-Weisskopf model[7] where the parton momentum distributions are determined by Regge behavior and phase space, one can derive a scaling relation of the form

$$f_{qq/A}(x_a,x_b) = g(x_a)\ \ h(\tilde{x}_b), \qquad (5)$$

with $\tilde{x}_b = x_b/(1-x_a)$, the ratio of the longitudinal momentum of b to its maximum value. Since the u and d distributions in the proton are known to be different, the Kuti-Weisskopf model must be modified. This makes Eq. (5), therefore, only approximate.

We now use these results to make some specific predictions of this model. Consider the inclusive two-particle fragmentation of a proton. In particular, let the trigger particle be a K° ($=d\bar{s}$), $\pi^+(=u\bar{d})$ or π^- ($=d\bar{u}$) and let the second particle be a π^+. Since in the proton fragmentation region the trigger hadrons are produced from the valence d or u quarks, according to Eq. (4a), the probability that the π^+ is produced at x_b in association with a K°, π^+ or π^- at x_a is $\sim f_{uq/p}(x_a,x_b)$ in all cases. The normalization is however different for the various cases and depends on the relative abundance of $\bar{s}$, $\bar{d}$ and $\bar{u}$ quarks in the sea. Since in all cases the second (π^+) meson contains a valence

u quark which was part of a diquark pair, we predict that the average number of π^+'s at $\tilde{x}_b$ per trigger π^- ($\bar{n}_{\pi^-}$) at x_a is equal to the average number of π^+'s per K° trigger ($\bar{n}_{K^\circ}$) and is twice the average number of π^+'s per π^+ trigger ($\bar{n}_{\pi^+}$). The last equality occurs because the valence diquark left over with a π^+ trigger is ud rather than uu.

These predictions assume that the average number (m) of each species ($\bar{u}$,$\bar{d}$,u,d) of sea quarks available for recombination is large (m>>1) so that the probability of a second valence quark picking up either a $\bar{u}$ or $\bar{d}$ sea quark is independent of the quantum numbers of the trigger. In general however we find from simple combinatorics

$$\bar{n}_{\pi^-} \simeq \frac{2m}{2m-1}(\bar{n}_{K^\circ}) \simeq \frac{m}{m-1}(2\bar{n}_{\pi^+}), \qquad (6)$$

where we have ignored the (small) probability of recombination of a valence quark with an $\bar{s}$ sea antiquark and any dispersion in the sea quark multiplicities. In fact we expect m to be ∿2-3 on the basis of the average pion multiplicity in the central region or by considering the fractional contribution of each species to the nucleon's momentum in the center of mass.

To test these predictions we have used data obtained by exposing the Fermilab 30-inch hydrogen bubble chamber-wide gap spark chamber hybrid system to a 360 GeV/c π^- beam.[8] Secondary protons with laboratory momentum less than 1.4 GeV/c are identified visually by ionization. This approximately corresponds to $x_p \leq -0.3$. Outside this region secondary fragments are only distinguished by their charge and have been assigned the pion mass. In addition, $K^\circ_s \to \pi^+\pi^-$ decays have also been identified. In the above model we can assume that the K°_s in the proton fragmentation region are predominantly K° rather than $\bar{K}^\circ$.

In Fig. 1 we show $\bar{n}_{\pi^-}$, $2\bar{n}_{\pi^+}$ and $\bar{n}_{K^\circ}$ as a function of $\tilde{x}_{\pi^+}$ for various ranges of trigger x_a. We see that each of these quantities is approximately independent of x_a so that our prediction of $\tilde{x}_b$ scaling holds remarkably well. In addition we note that the shape of these distributions is independent of the choice of trigger particle as indicated by the common lines drawn through the data. (This provides evidence that we are justified in using the no-resonance approximation,[6] as the resonance spectra in the $\pi^+\pi^-$ or π^+K° systems are quite different from that in the (exotic) $\pi^+\pi^+$ system.)

The data shown in Fig. 1 agree with the prediction of Eq. (6) that $\bar{n}_{\pi^-} > \bar{n}_{K^\circ} > 2\bar{n}_{\pi^+}$. The statistical quality of the data is such that we cannot quote a precise value for the ratios; however, the average ratios for $|x_a| > 0.2$ are consistent with $\bar{n}_{\pi^-}/\bar{n}_{K^\circ} \sim 1.3$ and $\bar{n}_{\pi^-}/2\bar{n}_{\pi^+} \sim 1.7$. These ratios yield values of m (2.2 and 2.4) which are consistent with each other and with our above expectations.

Finally it is interesting to note that $2\bar{n}_{\pi^+}$ rises above the common line for small $|x_a|$ and $|\tilde{x}_b|$. This is expected because as the trigger π^+ particle moves into the sea region, two (rather than one) valence u quarks become available to form a π^+. For the π^- and K° triggers two u valence quarks are always available, independent of x_a.

We have also obtained the two particle inclusive cross sections for pion and proton production in the target fragmentation region. These enable us to measure the relative importance of Eq. 4(a) and (b), i.e. the relative probability for a secondary nucleon to contain one or two valence quarks. In Table I(a) we give the two-particle cross sections for a π^- at x_a and a proton at x_b. We note that these data extend out to the kinematic limit $|x_a| + |x_b| \simeq 1$ and that the probability of finding a proton and a trigger π^- is about 18%,

independent of $x_a(\pi^-)$ for $0.5 > |x_a| > 0.1$. (The value for a proton and π^+ trigger is 12%.) For comparison, for untriggered events we find that 34% of the inelastic events have an identified fragmentation region proton. In Table I(b), the two-particle cross sections for $\pi^-(x_a)$ and $\pi^+(x_b)$ are given. Here we note that the π^+ are produced almost entirely at $|x_a| + |x_b| < 2/3$. The data of Table I are also consistent with scaling in $(x_a + x_b)$ for $|x_a|$, $|x_b| > 0.1$, which follows from the simple Kuti-Weisskopf model (Eq. 3).

The interpretation of the above seems straightforward: the dipions are produced from two valence quarks according to Eq. (4a) and so, for most of the data $|x_a| + |x_b|$ of the two pions is <2/3. For $\pi^-(x_a)\ p(x_b)$, it appears that Eq. (4b) describes the data. The π^- is created from one valence d-quark and one sea $\bar{u}$-antiquark. Whenever a proton is created, it is formed by the recombination of the other two valence quarks and a sea quark. There does not appear to be a large probability that a single valence quark picks up two sea quarks to become a proton. On the other hand, the low percentage of events with both a fast proton and a fast $\pi^\pm$ trigger suggests that when one valence quark is removed in the trigger, the remaining two quarks tend to separate and dissociate into two mesons rather than pick up another quark to form a nucleon. (Of course, to conserve baryon number a baryon has to appear near x=0.) Since one of the original motivations for postulating colored vector gluons was to bind the $q\bar{q}$ but not the qq system, we have a result consistent with QCD.[9]

In summary, we have shown that the $q\bar{q}$ recombination model, when applied to two-particle inclusive cross sections in soft hadronic processes, provides some simple predictions which appear to be satisfied by the data.

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5. By (longitudinal) Lorentz invariance ϕ cannot depend on $x_a = x_1 + x_2$. Since we expect $\phi(x_1,x_2)$ to depend on the longitudinal momentum fractions $x_1/(x_1 + x_2)$ and $x_2/(x_1 + x_2)$, with $x_2 = 0$ the arguments of ϕ become fixed near one and zero respectively. Hence $\phi(x_1,x_2)$ can be taken to be constant.
6. Refs. 2-4 have made the no-resonance approximation that each meson at large x contains one valence quark and that no valence quark gives rise to more than one fast secondary. Our neglect of resonances is consistent with the observation that ρ° decays account for only a small fraction of pions at $x \gtrsim 0.1$, see "ρ°(770) Production in π^-p Interactions at 100, 200 and 360 GeV/c", P. D. Higgins et al., paper in preparation (1978).
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Table I

Cross Sections (mb), $d^2\sigma/dx_a dx_b$, for $\pi^- p \to \pi^- pX$, $\pi^-\pi^+X$ at 360 GeV/c

$|x_a(\pi^-)|$

(a)

$\lvert x_b(p)\rvert$	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
1.0								
0.9					0.3	0.9	35	
0.8					--	5.8	63	
0.7					1.4	16	99	
0.6				0.9	5.1	21	112	
0.5			0.3	2.2	8.4	23	147	
0.4		0.3	2.9	4.0	6.2	21	113	
0.3	--	0.3	1.2	2.1	3.3	9.2	42	

(b)

$\lvert x_b(\pi^+)\rvert$	0.7	0.6	0.5	0.4	0.3	0.2	0.1	0.0
1.0								
0.9								
0.8								
0.7								2.1
0.6					0.3	0.8	3.8	
0.5					--	3.5	24	
0.4					3.9	7.4	56	
0.3			0.3	1.9	9.5	20	139	
0.2		0.7	3.3	5.1	26	79	453	
0.1		1.3	7.0	26	70	255	1417	
0.0	4.9	7.6	53	96	288	1771	8106	

The solid lines are drawn for $(x_a + x_b) = 1$ and $= 2/3$. The statistical errors may be estimated from the normalization of 3 μb/event.

Figure Caption

Fig. 1 The average π^+ multiplicity per trigger particle as a function of $\tilde{x}_b = \tilde{x}_{\pi^+}$ for various values of x_a of the π^-, K° and π^+ trigger. Note that the π^+ trigger data have been multiplied by 2 (see text). A common line with the same absolute normalization has been drawn for purposes of comparison.

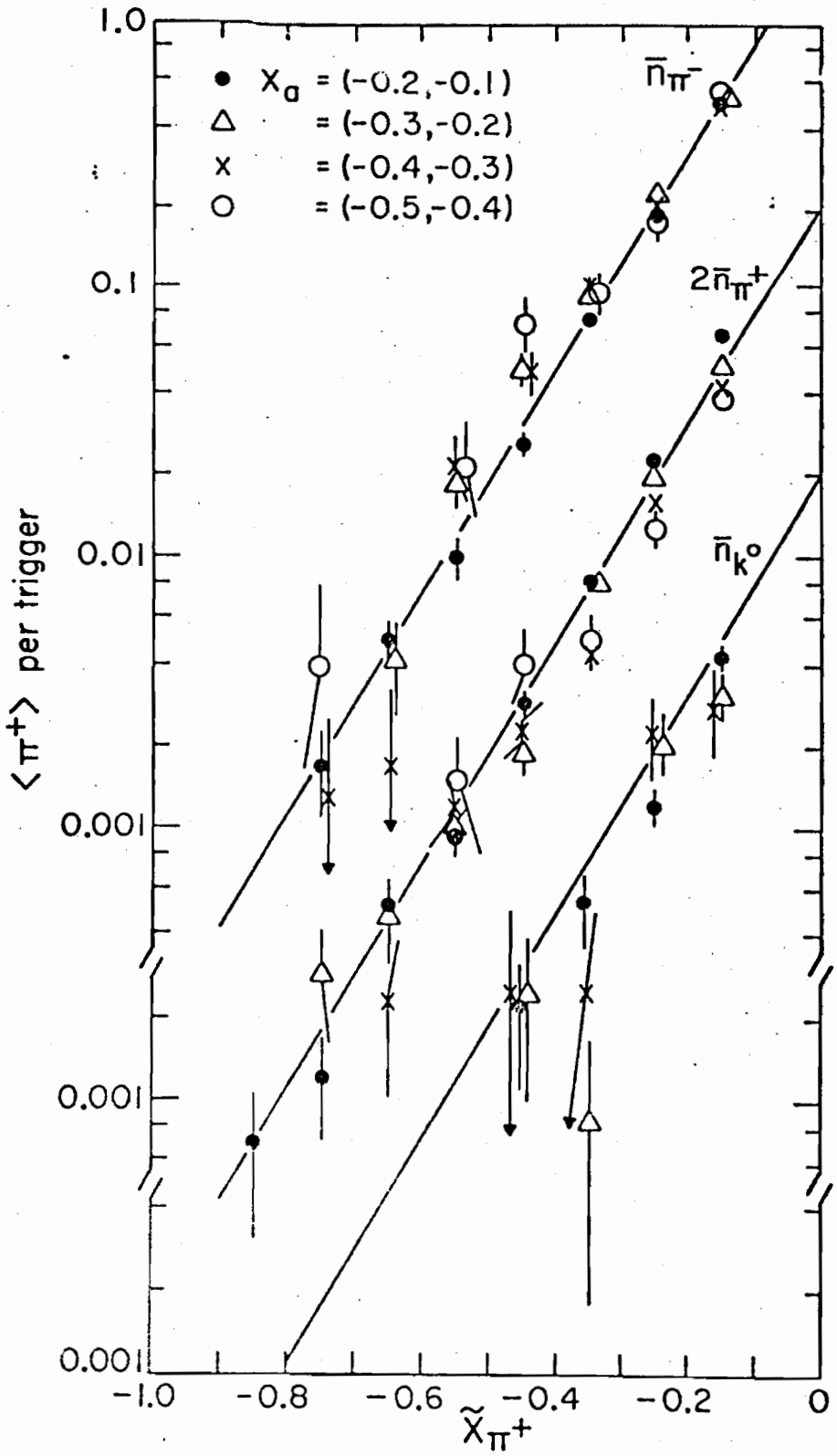
1.0
0.1
0.01
0.001
0.001
0.001
$\langle \pi^+ \rangle$ per trigger
X_a = (-0.2,-0.1)
= (-0.3,-0.2)
= (-0.4,-0.3)
= (-0.5,-0.4)
$\bar{n}_{\pi^-}$
$2\bar{n}_{\pi^+}$
$\bar{n}_{K^0}$
-1.0
-0.8
-0.6
-0.4
-0.2
0
$\tilde{X}_{\pi^+}$

Fig. 1