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Study of the Approach to Scaling and Factorization in Proton Fragmentation into $\pi^{\pm}$

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Abstract

From an analysis of previously published data as well as some new results from the Fermilab 30-inch bubble chamber, we study the energy dependence of inclusive $\pi^{\pm}$ production in the target proton fragmentation region. The dependence at high energy is shown to be consistent with an $s^{-\frac{1}{2}}$ behavior. Furthermore, both π^{+} and π^{-} data show evidence for Pomeranchuk factorization in the limit of infinite energy.

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The concepts of scaling (differential cross sections which are independent of center of mass energy, $\sqrt{s}$) and Pomeranchuk factorization (cross sections which are independent of the incident projectile) are of great importance, both experimentally and theoretically, in high energy elementary particle interactions. Such regularities, if observed experimentally, would simplify the problem of describing secondary particle spectra produced in the collision of a projectile and target particle and could yield information on the nature of the Pomeranchuk singularity and on the validity of the secondary trajectory exchange process for the single particle inclusive reactions:

$$a + b \rightarrow c + \text{anything}. \qquad (1)$$

In this letter we present an analysis of published data as well as some new results on inclusive $\pi^{\pm}$ production at high energy. These data, produced in the fragmentation region of the target proton, suggest that both scaling and factorization are being approached with an $s^{-\frac{1}{2}}$ energy dependence as suggested by the Mueller[1] Multi-Regge expansion for the single particle spectrum.

Consider reaction (1) in the kinematic region where the produced article c has a small momentum in the rest frame of the target particle b. e denote this process by

$$b \overset{a}{\to} c \ . \tag{2}$$

ollowing Chan et al.[2] and Miettinen[3] we expect that the invariant single article distribution $f(s,P_L,P_T^2) = E^{d^3\sigma}/dp^3$ for reaction (2) should have he form

$$f(s,P_L,P_T^2) = A(P_L,P_T^2) + \sum_M B_M(P_L,P_T^2)\ s^{-\frac{1}{2}} \ , \tag{3}$$

here $P_L(P_T)$ is the longitudinal (transverse) momentum of particle c in the est frame of b. The first term in (3) comes from the Pomeranchuk singulaity and the second term arises from the approximately exchange-degenerate eson trajectories ($M = \rho,f,\omega,A_2 \ldots$) with t=0 intercept $\alpha_M(0)\simeq 0.5$.

The above Mueller-Regge phenomenology leads to several definite redictions[2] when combined with various principles: (a) applying charge onjugation at the projectile vertex implies that $\Delta f \equiv f(b\overset{a}{\to}c) - f(b\overset{\bar{a}}{\to}c) = \sum_{,odd\ C} 2B_M(P_L,P_T^2)s^{-\frac{1}{2}}$; (b) duality and exchange degeneracy (EXD) for reacions with exotic $ab\bar{c}$ predict that $f(b\overset{a}{\to}c)$ should be energy independent. vidence already exists[4] that this is not strictly true for $pp \to \pi^{\pm}$ and new ata from Fermilab also show (see below) an energy dependence for the proess $\pi^+p \to \pi^-$; (c) if the Pomeranchuk singularity and the meson Regge rajectories behave as simple poles, then factorization of the residues A nd B [e.g. $B_\rho(P_L,P_T^2) = \beta^\rho_{b\bar{c}}(P_L,P_T^2)\beta^\rho_a$] implies that the asymptotic distribuion for process (2) should be independent of the projectile a when normalzed to σ^∞_{ab}, the asymptotic ab total cross section. A few isolated hecks[3,5-7] of these predictions have been made but, with one exception,[7]

they use data below 20 GeV/c and make the assumption that the exotic reactions have no energy dependence.

In this letter we re-evaluate these predictions in light of the new data now available from Fermilab for the processes (2) in which the target particle b is a proton and the produced particle c is a $\pi^{\pm}$. We present an analysis of data[8-10] for which a = $\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, and γ ranging from an incident momentum of 3.7 GeV/c to 400 GeV/c. Since transverse momentum is well-known to be limited and in order to achieve increased statistics[11] we integrate over P_T^2 and study the distribution[12] $G(P_L) = \frac{1}{\sigma_T^{\infty}} \int f(s,P_L,P_T^2)dP_T^2$, evaluated in the laboratory system and integrated over the region $-0.4 \leq P_L \leq 0.2$ GeV/c. (The qualitative conclusions we draw later are insensitive to small variations in the upper limit used.) Figure 1 shows $I(s;b\overset{a}{\to}c) \equiv \int_{-0.4}^{0.2} G(P_L)dP_L$ as a function of $s^{-\frac{1}{2}}$ for $\pi^{\pm}$ production from all available reactions.

The dominant features of these two plots are the following:

a) As noted elsewhere,[4] the cross section for the process $p \overset{p}{\to} \pi^-$ appears to rise from threshold before falling at the higher energies; it is quite possible that future high energy data from Fermilab will show a similar effect for $p \overset{K^+}{\to} \pi^{\pm}$;

b) Many of the processes (e.g. $p \overset{\pi^-}{\to} \pi^-$, $p \overset{\gamma}{\to} \pi^-$, $p \overset{K^-}{\to} \pi^-$, and $p \overset{\pi^+}{\to} \pi^+$) show no apparent rise at low energy (threshold effect) and only a rapid decrease with increasing energy;

c) Other reactions (e.g. $p \overset{\pi^+}{\to} \pi^-$ and $p \overset{\pi^-}{\to} \pi^+$) also show no threshold effect over the energy range studied but are somewhat less dependent on energy;

d) The data show no evidence for any scaling behavior up to the highest energies presently attained at Fermilab. In particular, most reactions

exhibit falling cross sections in disagreement with the hypothesis of limiting fragmentation.

e) The approach to a possible scaling behavior in the limit of infinite energy does appear consistent with the expected $s^{-\frac{1}{2}}$ dependence of Eq. (3). Furthermore, almost all the data suggest that if such a scaling limit does exist, then it is being approached from above;

f) Because of the detailed structure of Eq. (3) for the different processes studied, Figure 1 does not immediately confirm or refute the hypothesis of factorization at any energy below and perhaps including Fermilab energies. However, the trend of the data for most of the processes shown does suggest that factorization may hold in the limit of infinite energy, i.e., the data appear to converge at a common point[13] as $\sqrt{s} \to \infty$. Certainly the Fermilab data are in better agreement[7] than data at lower energies.[8]

It is of interest to relate the above observations to the various efinitions[2,9] of exoticity (see Table I) of the different particle combinaions in process (2). From Table I we see that the rise from threshold ppears related to ab being the exotic combination, since $p \xrightarrow{\pi^+} \pi^-$ does not how a rise. We would then predict that $p \xrightarrow{K^+} \pi^\pm$ and $p \xrightarrow{p} \pi^+$ are the only ther reactions in Table I to show a similar rise.

Those reactions (discussed in (b) above) which show no apparent rise t low energy but whose cross sections exhibit a strong energy dependence re characterized by having no exotic combination of particles. From Table I, e would expect that the processes $p \xrightarrow{\bar{p}} \pi^\pm$ and $p \xrightarrow{\gamma} \pi^+$ would also show similar rends. While no data have been published on $p \xrightarrow{\bar{p}} \pi^+$ or $p \xrightarrow{\gamma} \pi^+$, the invariant ross section at $P_L = 0$ for the reaction $p \xrightarrow{\bar{p}} \pi^-$ does show[6] a rapid decrease ith energy .

The two reactions for which there are high energy data and which nibit less rapidly falling cross sections ($p \xrightarrow{\pi^+} \pi^-$ and $p \xrightarrow{\pi^-} \pi^+$) are aracterized by having $a\bar{c}$ exotic. From Table I we predict that Fermilab ta will show that the reactions $p \xrightarrow{K^+} \pi^-$ and $p \xrightarrow{K^-} \pi^+$ also have slowly rying inclusive cross sections in the proton fragmentation region. Premably, the energy dependence of the cross sections for the reactions which ve $ab\bar{c}$ exotic implies that the meson EXD is, in fact, only approximate, or at Eq. (3) is not strictly true, or both. Whether or not these exoticity assifications are relevant will be clarified when more data on $K^{\pm}p$ intertions become available for a wider range of energies.

If we assume that factorization does in fact hold in the infinite ergy limit, we can inquire which reactions would exhibit an approximate ctorization at finite energies. From Figure 1, one expects that those ocesses whose cross sections are closest to the infinite energy cross ctions will be the ones which might obey an approximate form of factorizaon. As discussed above these are the processes characterized by having exotic. This conclusion differs from that of Erwin et al.[7] who suggested at $ab\bar{c}$ is the relevant combination. From Table I we see that a test of ese two hypotheses would be a detailed comparison at Fermilab energies tween $p \xrightarrow{K^-} \pi^+$ and $p \xrightarrow{\pi^-} \pi^+$ which should show an approximate factorization $a\bar{c}$ is the relevant pair but which will not show factorization if $ab\bar{c}$ is e relevant combination.

Finally, we explicitly test the prediction[2] from charge conjugation at $\Delta f = ks^{-1/2}$. This is shown in Figure 2 for available data where we fine

$$\Delta f(\pi p \to \pi^-) \equiv H(s;p \xrightarrow{\pi^-} \pi^-) - H(s;p \xrightarrow{\pi^+} \pi^-) \ . \qquad (4)$$

We see that the $\pi p \to \pi$ data are quite consistent with the predictions of the Regge phenomenology. The $Kp \to \pi^-$ data do not cover a wide enough energy range to be significant but do suggest that the slope, k, of the line is the same as that for the πp data. Assuming[14] that the meson trajectory coupling to the π, β_π^M, is twice that to the K, β_K^M, one would only expect equal slopes if EXD were to hold exactly. Thus, an indication that the slopes for Kp and πp are similar would suggest that f-A_2 EXD is valid for the $ab\bar{c}$ three-body scattering process.

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- Since errors were not always available we have had to estimate the uncertainties on several of the data points. In no case have we assigned an error of less than 5%.
- For consistency we have used for σ_T^∞ the values given at 200 GeV/c by A. S. Carroll et al., Phys. Rev. Letters 33, 928 (1974) and 33, 932 (1974).
- It is interesting to note that the π^+ asymptotic cross section is approximately twice that for π^- production. This ratio appears insensitive to varying the upper limit of integration from $P_L = 0$ to $P_L = 0.2$ GeV/c.
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FIGURE CAPTIONS

1. The invariant cross section for inclusive π production, evaluated in the laboratory system and integrated over all P_T^2 and over $-0.4 < P_L < 0.2$ GeV/c, versus $s^{-\frac{1}{2}}$. The lines are hand-drawn to guide the eye through the data. (a) π^- and (b) π^+ production.

2. The difference between the target fragmentation cross sections for (a) $\pi^- p \to \pi^\pm$ and $\pi^+ p \to \pi^\pm$ and (b) $K^- p \to \pi^-$ and $K^+ p \to \pi^-$ as a function of $s^{-\frac{1}{2}}$. The straight lines are drawn to guide the eye.

Table I

Exoticity of Various Particle Combinations

action	$ab\bar{c}$	$b\bar{c}$	$a\bar{c}$	ab
$p \to \pi^-$	E	N	E	N
$p \to \pi^-$	N	N	N	N
$p \to \pi^-$	E	N	E	E
$p \to \pi^-$	N	N	N	N
$\to \pi^-$	E	N	N	E
$\to \pi^-$	N	N	N	N
$\to \pi^-$	N	N	N	N
$p \to \pi^+$	N	N	N	N
$p \to \pi^+$	N	N	E	N
$p \to \pi^+$	E	N	N	E
$p \to \pi^+$	N	N	E	N
$\to \pi^+$	E	N	N	E
$\to \pi^+$	N	N	N	N
$\to \pi^+$	N	N	N	N

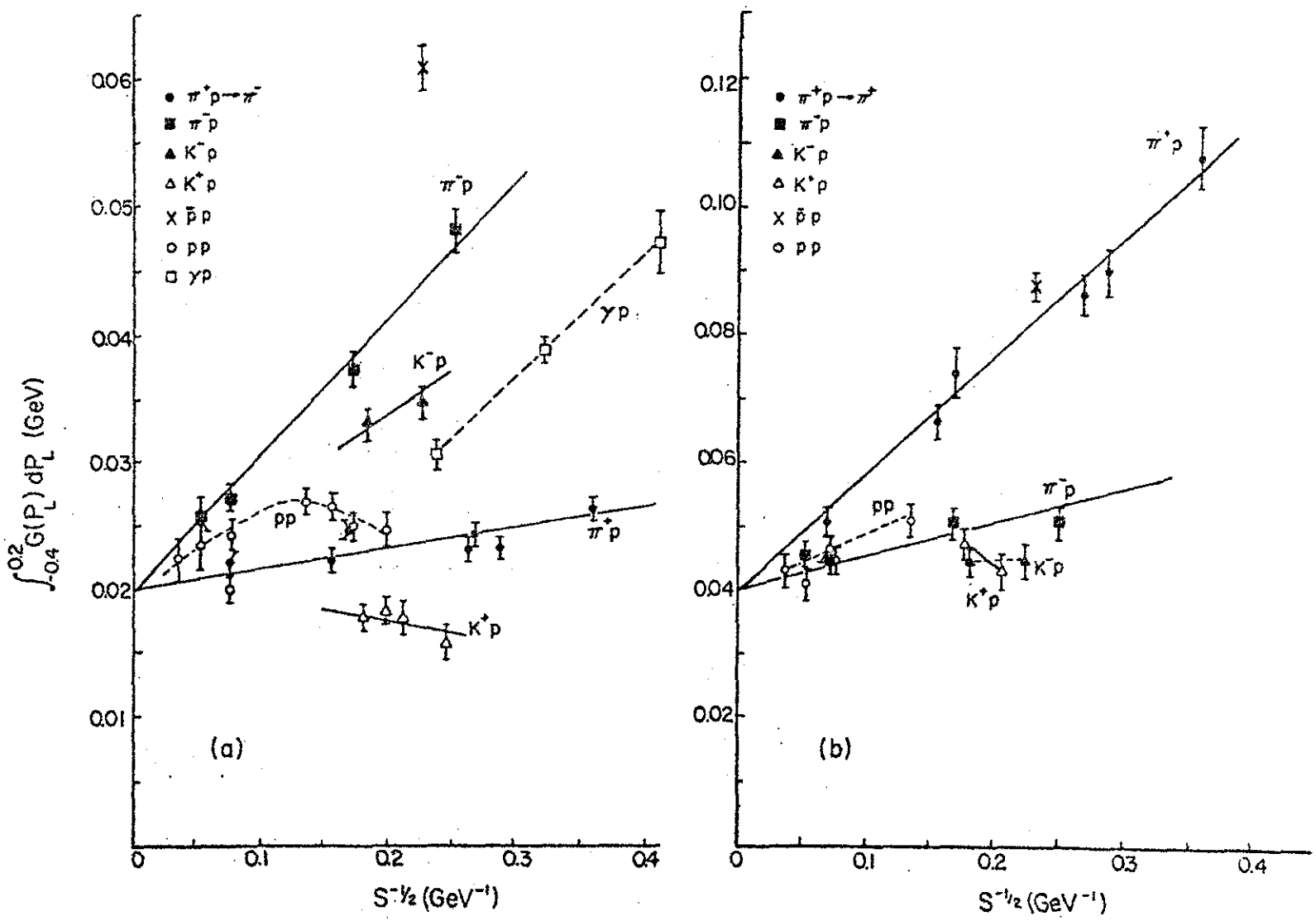
$\int_{-0.4}^{0.2} G(P_L)\, dP_L$ (GeV)
$\pi^+p \to \pi^-$
π^-p
K^-p
K^+p
$\bar{p}p$
pp
γp
π^-p
K^-p
γp
pp
π^+p
K^+p
(a)
$S^{-1/2}$ (GeV^{-1})
$\pi^+p \to \pi^+$
π^-p
K^-p
K^+p
$\bar{p}p$
pp
π^+p
pp
π^-p
K^-p
K^+p
(b)
$S^{-1/2}$ (GeV^{-1})

Figure 1

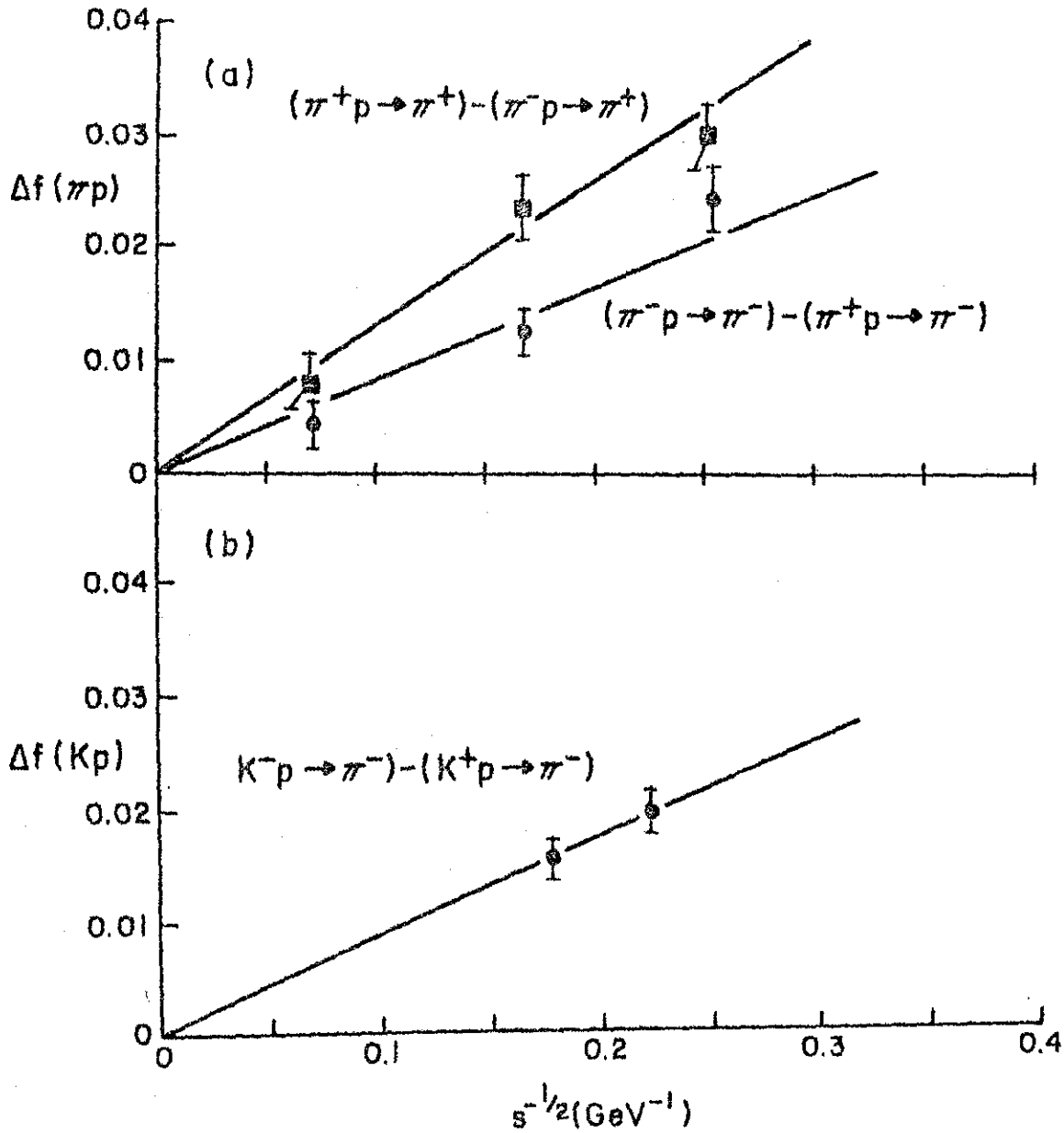
(a)
$(\pi^+p \to \pi^+)-(\pi^-p \to \pi^+)$
$(\pi^-p \to \pi^-)-(\pi^+p \to \pi^-)$
$\Delta f(\pi p)$
0.04
0.03
0.02
0.01
0
(b)
$K^-p \to \pi^-)-(K^+p \to \pi^-)$
$\Delta f(Kp)$
0.04
0.03
0.02
0.01
0
0
0.1
0.2
0.3
0.4
$s^{-1/2}(GeV^{-1})$

Figure 2