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Meson-production mechanisms and single-spin hadron-hadron collisions

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It is shown that the inclusive measurement of pions and other mesons in high-energy single-spin experiments is a useful way to study meson-production mechanisms in general, and to identify mesons due to direct formation (quark-antiquark fusion) in particular. Further evidence supporting the picture proposed recently is presented. Predictions for future experiments are made.

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Striking left-right asymmetries (A_N) have been observed by the Fermilab E704 Collaboration [1] in high-energy single-spin inclusive meson production processes using transversely polarized proton and antiproton beams. Their data [1] show that A_N depends not only on x_F and x_T (here $x_F \equiv 2p_\parallel/\sqrt{s}$, $x_T \equiv 2p_\perp/\sqrt{s}$, $p_\parallel$ and $p_\perp$ are, respectively, the longitudinal and transverse momentum of the observed meson and $\sqrt{s}$ is the total energy, everything measured in the hadron-hadron c.m. frame) but also on *flavor*. Furthermore, comparison between these data and those at lower energies have been made [2]; and the result seems to suggest the existence of a significant energy-independent x_F-x_T correlation—an interesting new scaling behavior [2].

In a recent Letter [3], we suggested that the observed asymmetries in the fragmentation region of the polarized beam particles ($x_F \geq 0.4$) are due to the orbital motion of the valence quarks of the projectiles. Theoretical arguments and experimental indications supporting the proposed picture have been given, and the characteristic features of the proposed picture have been discussed. It is pointed out in particular that only part of the observed mesons are direct formation (fusion) products of orbiting valence quarks (of the projectile) and anti-sea-quarks (associated with the target). The purpose of this work is to discuss in detail the interplay between the different production mechanisms, to present the result of an independent test of the proposed picture,and to show why [4] the above-mentioned attractive new scaling behavior *cannot* exist.

We recall that $A_N(x_F,\pi|s)$ is the ratio of the difference and the sum of $N(x_F,\pi|s,\uparrow)$ and $N(x_F,\pi|s,\downarrow)$. Here, π stands for π^+, π^- and π^0, and

$$N(x_F,\pi|s,\uparrow) \equiv \frac{1}{\sigma_{\rm in}(s)} \int_{(R)} d^2\mathbf{p}_\perp \frac{d^3\sigma}{dx_F d^2\mathbf{p}_\perp}(x_F,\mathbf{p}_\perp;\pi|s,\uparrow) \tag{1}$$

is the number density of π observed in a given kinematical region R (for example, $p_\perp \geq 0.7$ GeV/c and in a given acceptance solid angle on the left-hand side looking downstream in the above-mentioned experiments [1]); $d^3\sigma/dx_F d^2\mathbf{p}_\perp(x_F,\mathbf{p}_\perp;\pi|s\uparrow)$ is the inclusive single-particle cross section for pions observed at x_F and $\mathbf{p}_\perp$ in $p(\uparrow)+p(0)\to\pi+X$ at total c.m.s. energy $\sqrt{s}$, and $\sigma_{\rm in}(s)$ is the total inelastic cross section. $N(x_F,\pi|s,\downarrow)$ is the corresponding density function for such pions observed in $p(\downarrow)+p(0)\to\pi+X$. Let us, as we did in Ref. [3], denote by $D(x_F,\pi,+|s,\uparrow)$ the number density for those pions which are directly formed by the valence quarks polarized in the same direction as the transversely polarized projectile proton, and $D(x_F,\pi,-|s,\uparrow)$ the corresponding number density for mesons formed by the valence quarks polarized in the opposite direction as the projectile proton. Then the N's in Eq. (1) *et seq.* can be written as

$$N(x_F,\pi|s,\uparrow) = \alpha D(x_F,\pi,+|s,\uparrow) + (1-\alpha)D(x_F,\pi,-|s,\uparrow) + N_0(x_F,\pi|s) , \tag{2}$$

$$N(x_F,\pi|s,\downarrow) = (1-\alpha)D(x_F,\pi,+|s,\downarrow) + \alpha D(x_F,\pi,-|s,\downarrow) + N_0(x_F,\pi|s) , \tag{3}$$

for the following reasons: There are upwards and downwards polarized valence quarks in the projectile $p(\uparrow)$, and both kinds may contribute to the directly formed pions which enter the detector [the corresponding number densities are characterized by the plus or minus sign in $D(x_F,\pi,\pm|s,\uparrow)$]. Here, if we denote by α the relative chance for a directly formed pion (with $p_\perp \neq 0$) due to an upwards polarized valence quark to "go left," then the corresponding chance for it to "go right" is $1-\alpha$. Taken together with the trivial fact that the probability for a meson due to a downwards polarized valence quark to "go left" is the same as that for a meson due to an upwards polarized valence-quark to "go-right," we obtain Eqs. (2) and (3). $N_0(x_F,\pi|s)$ stands for the non-direct-formation part. It follows from Eqs. (2) and (3),

$$N(x_F,\pi|s,\uparrow) - N(x_F,\pi|s,\downarrow) = C[D(x_F,\pi,+|s,{\rm tr}) - D(x_F,\pi,-|s,{\rm tr})] , \tag{4}$$

where $C \equiv 2\alpha-1$, $D(x_F,\pi,+|s,{\rm tr})$ stands for $D(x_F,\pi,+|s,\uparrow) = D(x_F,\pi,+|s,\downarrow)$, and $D(x_F,\pi,-|s,{\rm tr})$ for $D(x_F,\pi,-|s,\uparrow) = D(x_F,\pi,-|s,\downarrow)$. The relation shown by Eq. (4) is just the relation between ΔN and ΔD that we mentioned in Ref. [3]. C is the proportional constant given there. Here, we recall that, in this picture [3–5], mesons directly formed through the fusion of upwards polarized valence quarks of the projectile and anti-sea-quarks of the target are "going-left," while those directly formed through the direct formation of downwards polarized valence quarks of the projectile and anti-sea-quarks of the target are "going right." This implies $1/2<\alpha<1$ which means $0<C<1$. Furthermore, since the probability density for direct formation has to depend on the chances of finding a valence quark and a suitable anti-sea-quark, $D(x_F,\pi,+|s,\mathrm{tr})$ and $D(x_F,\pi,-|s,\mathrm{tr})$ can be written [see Eq. (2) of Ref. [3]] as convolution integrals of the corresponding quark distributions.

Having in mind that $A_N(x_F,\pi|s)$ is the ratio of the difference and the sum of $N(x_F,\pi|s,\uparrow)$ and $N(x_F,\pi|s,\downarrow)$, we can now use Eq. (4) *et seq.* to calculate $A_N(x_F,\pi|s)$, $\pi=\pi^+,\pi^-,\pi^0$, from the empirical values for $N(x_F,\pi|s)$ [6] [recall that $2N(x_F,\pi|s)=N(x_F,\pi|s,\uparrow)+N(x_F,\pi|s,\downarrow)$] and those for the quark momentum distributions [7]. While the calculated [3] asymmetries are indeed in agreement with the experiments [1], the following questions remain to be answered: What do we know about $N_0(x_F,\pi|s)$ for $\pi=\pi^+$, π^- and π^0? Do we not expect $N_0(x_F,\pi|s)$ to be independent of the isospins of the produced pions? How does $N_0(x_F,\pi|s)$ influence $A_N(x_F,\pi|s)$ and $N(x_F,\pi|s)$? It is clear that $N_0(x_F,\pi|s)$, especially the interplay between this quantity and the corresponding $D(x_F,\pi|s)$, where

$$D(x_F,\pi|s)\equiv[D(x_F,\pi,+|s,\mathrm{tr})+D(x_F,\pi,-|s,\mathrm{tr}]/2\ , \tag{5}$$

for $\pi=\pi^+$ and π^-, plays a key role in understanding the pion production mechanisms in general, and in understanding the existence and/or nonexistence of x_F-x_T scaling in particular. Hence, we think it should be worthwhile to check the properties of $N_0(x_F,\pi|s)$ and use this as a further test of the proposed picture. We note

$$N(x_F,\pi|s)=N_0(x_F,\pi|s)+D(x_F,\pi|s)\ , \tag{6}$$

and this implies that we can obtain $N_0(x_F,\pi^+|s)$ and $N_0(x_F,\pi^-|s)$ simply by subtracting $D(x_F,\pi^+|s)$ and $D(x_F,\pi^-|s)$ from the corresponding data for $N(x_F,\pi^+|s)$ and $N(x_F,\pi^-|s)$, respectively. In Fig. 1, we show the differences ($\Delta\sigma$) between the measured cross sections (for a fixed $p_\perp$) and the direct-formation contributions as function of x_F. These differences are obtained

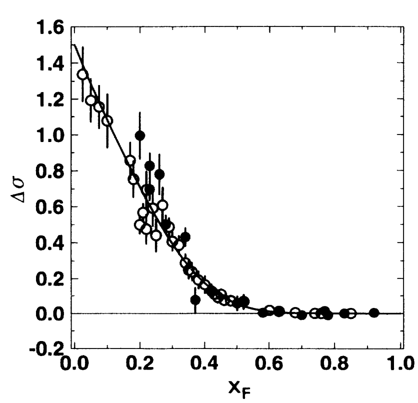
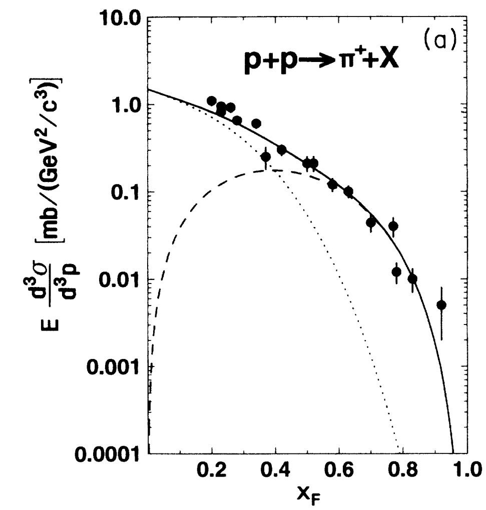


FIG. 1. The non-direct-formation parts of the inclusive pion production cross section for $p(0)+p(0)\rightarrow\pi^++X$ (solid dots) and $p(0)+p(0)\rightarrow\pi^-+X$ (open circles) are shown as functions of x_F. The data are taken from Ref. [6]. The quark distribution functions are taken from Ref. [7]. The solid line shows the explicit parametrization $1.5(1-x_F)^3\exp(-10x_F^3)$ which has been used to calculate the A_N's. See text for further details.



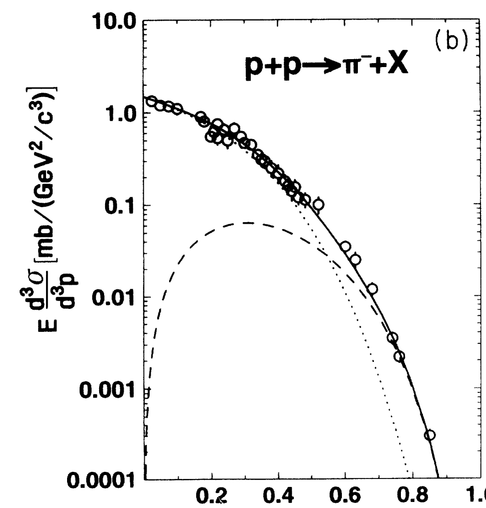


FIG. 2. The measured x_F distribution for $p(0)+p(0)\rightarrow\pi^++X$ (a) and that for $p(0)+p(0)\rightarrow\pi^-+X$ (b) are shown as the sum of the following two parts: (1) the isospin-independent non-direct-formation part (parametrization mentioned in Fig. 1 shown as dotted curves), (2) the corresponding isospin-dependent parts $\kappa_\pi u_v(x_F)\bar{q}_s(x_0/x_F)x_F$ for π^+ and $\kappa_\pi d_v(x_F)\bar{q}_s(x_0/x_F)x_F$ for π^- (shown as dashed curves).

by subtracting from single-pion inclusive cross sections $Ed^3\sigma/d^3p$ for the reactions $p(0)+p(0)\to\pi^+ +X$ and $p(0)+p(0)\to\pi^- +X$ for $p_\perp=0.8$ GeV/c at standard CERN Intersecting Storage Rings (ISR) energies (data are taken from Ref. [6]), the corresponding contributions due to direct formation: namely, $\kappa_\pi u_v(x_F)\bar{q}_s(x_0/x_F)x_F$ and $\kappa_\pi d_v(x_F)\bar{q}_s(x_0/x_F)x_F$. Here, as well as in Ref. [3], the quark distribution functions are taken from Ref. [7]. κ_π is the constant given in Eq. (4) of Ref. [3] which is the relative probability for a valence quark and an anti-sea-quark or appropriate flavor to form pion via direct formation. In this figure, we see that the obtained results $\Delta\sigma(p+p\to\pi^+ +X)$ and $\Delta\sigma(p+p\to\pi^- +X)$ (they are denoted by the solid dots and open circles, respectively) fall approximately on one curve. The solid line shows an explicit parametrization $1.5\,(1-x_F)^3\exp(-10x_F^3)$. In Fig. 2, we not only see that the above-mentioned differences are indeed small for $x_F>0.5$, but also see how the $p(0)+p(0)\to\pi^+ +X$ and $p(0)+p(0)\to\pi^- +X$ cross sections can be reproduced as the sums of two parts: the direct-formation part (shown as dashed curves) and the non-direct-formation part (shown as dotted curves). The solid lines are the corresponding sums [8].

These results show that $N_0(x_F,\pi^+|s)=N_0(x_F,\pi^-|s)$ for sufficiently large transverse momenta ($p_\perp\geq 0.7\sim 0.8$ GeV/c, say). That is, the nondirect formation part $N_0(x_F,\pi|s)$ is indeed [9] isospin independent, although for such large $p_\perp$ direct-formation processes are significant [1], especially in the fragmentation regions. Furthermore, we explicitly see the existence of a transition region in the inclusive cross sections near $x_F=0.4\sim 0.5$. This is because in this region, $N_0(x_F,\pi|s)$ and $D(x_F,\pi|s)$ switch their roles: While the former is the main contribution for $x_F<0.4\sim 0.5$, the latter begins to dominate for larger values of x_F. This means that for sufficiently large transverse momenta ($p_\perp>0.7\sim 0.8$ GeV/c, say), pointlike interactions between the constituents of the projectile and those of the target play a significant role in the projectile-fragmentation region ($x_F\geq 0.4$). Here, most of the produced mesons are products of direct (valence-) quark-anti(sea-) quark fusion. This observation is consistent with the earlier analysis of Ochs [10]. But, the results obtained here also show that, even for $p_\perp\geq 0.8$ GeV/c, contributions from direct quark-antiquark fusion are negligibly small for small x_F. This observation is in agreement with the well-known fact that, in general, the behavior of the mesons observed in the fragmentation regions and those in the central rapidity region are qualitatively different from each other [11,12], and that, in particular, the energy dependence and/or the $p_\perp$ dependence of these two kinds of contributions are not correlated. In summary, the results of this analysis and those given in Ref. [3] lead us to the following conclusions: The proposed picture agrees with the existing inclusive pion production data for single-spin, as well as for unpolarized, hadron-hadron collisions. The roles played by the variables x_F and x_T are very different from each other, and they are different in different kinematical regions. There is a transition region in the A_N vs x_F plot, but the location of this region depends in general on $\sqrt{s}$ as well as on $p_\perp$ (or x_T). In other words, the new scaling behavior [2] cannot exist.

Similar analyses can be carried out for other meson-production processes. We have chosen pions for this demonstration for the following reasons: (a) There are data [1] for pion production in scattering processes with polarized beam, as well as data [6] for the corresponding processes with unpolarized beams; (b) the new x_F-x_T-scaling behavior [2] has been discussed only in connection with pions.

It is clear that the existence or nonexistence of such a new scaling behavior (in connection with x_F and x_T dependence) of A_N for pions and/or for other mesons can be readily tested in future single-spin experiments. It is also clear that, in either case, such experiments will yield useful information on meson-production mechanisms, especially on their relationship in different kinematical regions.

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[8] It should be mentioned in this connection that, by using the explicit parametrization of $\Delta\sigma$ given here, we have recalculated the asymmetries A_N for $p(\uparrow)+p(0)\to\pi+X$. The results are, as expected, essentially the same as those shown in Fig. 1 of Ref. [3]. Plotted in the same figure, the difference can hardly be seen.

[9] From $N(x_F,\pi^0|s)=[N(x_F,\pi^+|s)+N(x_F,\pi^-|s)]/2$ and $D(x_F,\pi^0|s)=[D(x_F,\pi^+|s)+D(x_F,\pi^-|s)]/2$ which are direct consequences of isospin invariance [for explicit comparisons between the π^0 and the $(\pi^+ +\pi^-)/2$ data in

inclusive single-pion production processes $p+p \to \pi+X$, see, for example, P. Darriulat, Annu. Rev. Nucl. Part. Sci. **30**, 159 (1980), and the references given there], we obtain $N_0(x_F,\pi^0|s)=[N_0(x_F,\pi^+|s)+N_0(x_F,\pi^-|s)]/2$. Taken together with $N_0(x_F,\pi^+|s)=N_0(x_F,\pi^-|s)$, we reach the conclusion that $N_0(x_F,\pi^0|s)$ should also be the same.

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[11] See, for example, G. Belletini *et al.*, Phys. Lett. **45B**, 69 (1973).
[12] See, for example, Meng Ta-chung, in *Hadronic Multiparticle Production*, edited by P. Carruthers (World Scientific, Singapore, 1988), p. 648, and the references given therein.