the parameters of the A_1 resonance: $M_{A_1} = 1180 \pm 50$ MeV, $\Gamma = 400 \pm 50$ MeV (second-sheet pole values). Moreover, we have fairly precise knowledge of the $\rho\pi$ scattering amplitude itself. An interesting by-product is that we know the value of the axial-vector form factor, for which we provide an analytic parametrization.[4,5] This may be useful in various situations, for example, in tests of the second Weinberg sum rule.[9]

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[1]J. A. Jaros *et al.*, SLAC Report No. SLAC-Pub-2084, 1978 (unpublished).

[2]G. Alexander *et al.*, Phys. Lett. 73B, 99 (1978).

[3]Yu. M. Antipov *et al.*, Nucl. Phys. B63, 153 (1973); J. Pernegr *et al.*, to be published. Other recent data indicative of an A_1 with low mass include P. Gavillet *et al.*, Phys. Lett. 69B, 119 (1977); and A. Ferrer *et al.*, Orsay Report No. LAL 77/44, 1977 (unpublished).

[4]J.-L. Basdevant and E. L. Berger, Phys. Rev. D 16, 657 (1977). For other approaches, see M. Bowler *et al.*, Nucl. Phys. B97, 227 (1975); R. S. Longacre and R. Aaron, Phys. Rev. Lett. 38, 1509 (1977); R. Aaron *et al.* Northeastern University Report NUB-2340, 1977 (unpublished).

[5]O. Babelon, J.-L. Basdevant, D. Cailleries, and G. Mennessier, Nucl. Phys. B113, 445 (1976), and references cited therein.

[6]C. Baltay *et al.*, Phys. Rev. Lett. 39, 591 (1977); F. Wagner, M. Tabak, and D. M. Chew, Phys. Lett. 58B, 201 (1975); M. J. Corden *et al.*, Rutherford Laboratory Report No. RL-77-139 A, 1977 (unpublished).

[7]G. C. Fox and A. J. G. Hey, Nucl. Phys. B56, 386 (1973); H. E. Haber and G. L. Kane, Nucl. Phys. B129, 429 (1977); A. Irving and V. Chaloupka, Nucl. Phys. B89, 345 (1975).

[8]L. R. Ram Mohan, Nucl. Phys. B72, 201 (1974).

[9]S. Weinberg, Phys. Rev. Lett. 18, 507 (1967).

Can Existing High-Transverse-Momentum Hadron Experiments Be Interpreted by Contemporary Quantum Chromodynamics Ideas?

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It is shown that if in a calculation of high-transverse-momentum meson production in hadron-hadron collisions one includes not only the scale-breaking effects that might be expected from asymptotically free theories but also the effects due to the transverse momentum of quarks in hadrons, *then* the results are not inconsistent with the single-particle cross-section data.

In previous papers (hereafter called FF1 and FFF[1]), experimental results on the production of high-transverse-momentum mesons have been analyzed. It was supposed that the phenomena were due to the hard scattering between quarks, one from the beam and one from the target.[2] The longitudinal momentum distribution of the quarks in the proton, $G_{p\to q}(x)$, and the distribution of mesons from the outgoing quarks, $D_q^h(z)$, were taken from data on lepton-initiated processes and assumed to scale (i.e., depend only on the fractional momentum z or x and not otherwise on energy). If these functions scale, then the invariant cross section for producing a large-$p_\perp$ meson directly reflects the energy dependence of the quark-quark cross section $d\hat{\sigma}/d\hat{t}$. Thus if the latter behaves as $h(t/s)/s^n$, then the former behaves as $f(x_\perp, \theta_{\text{c.m.}})/p_\perp^{2n}$, where $x_\perp = 2p_\perp/W$ and $W=\sqrt{s}$. The expectation from field theories calculated to any finite order using perturbation theory is that $n \approx 2$, whereas existing experimental data behave like $1/p_\perp^8$ at fixed $x_\perp$. It appeared that if one wanted to describe existing data in terms of quarks, then $d\hat{\sigma}/d\hat{t}$ would have to be modified to agree with experiment. The form $d\hat{\sigma}/d\hat{t} = (2300 \text{ mb})/\hat{s}\hat{t}^3$ appeared to fit the large-$p_\perp$ meson data best.

This simple model (called the quark-quark scattering "black-box" model) succeeded in predicting the large-$p_\perp$ π^+/π^- and K^+/K^- ratios. However, an analysis of the correlations between two or more particles produced at large $p_\perp$ shows that effects due to the transverse-momentum distribution of the quarks in the initial hadrons, $\langle k_\perp\rangle_{h\to q}$, and the transverse momentum of the hadrons from the outgoing quark jets, $\langle k_\perp\rangle_{q\to h}$, cannot be neglected. In FFF $\langle k_\perp\rangle_{h\to q} = 500$ MeV and $\langle k_\perp\rangle_{q\to h} = 330$ MeV were used, but even these values were a bit smaller than indicated by experiment. One consequence of including the transverse momentum of quarks in hadrons and of hadrons from quarks (called smearing) is to require modification of the quark-quark cross section. Smearing effects break "scaling"; for a given $d\hat{\sigma}/d\hat{t}$, smearing increases the small-$p_\perp$ cross section sizably but has less effect at high $p_\perp$ (see Fig. 8 of FFF).

As reported in the summary of FFF, there were some encouraging features of the quark-quark "black-box" model with smearing but also some problems. Predictions depending strongly on $\langle k_\perp\rangle_{h\to q}$ were not very successful. The data of Della Negra *et al.*[3] showed that the total number of away-side (opposite side of trigger) hadrons with $z_p \geq 0.5$ per trigger, $N(z_p \geq 0.5)$,[4] decreases from 0.22 for a trigger $p_\perp = 2.1$ GeV/c to about 0.07 at trigger $p_\perp = 3.6$ GeV/c whereas the theory yielded $N(z_p \geq 0.5) = 0.17$ independent of $p_\perp$ over this range. There are now two experiments[5] that confirm this drop with increasing trigger momentum *but* they do show that $n(z_p)$ does begin to "scale" for $p_\perp \gtrsim 3.5$ GeV. However, the experimental values for the away-side multiplicity $n(z_p)$[4] in the "scaling" region $p_\perp \gtrsim 3.5$ are about 3 times smaller than predicted in FFF.[5] This is a serious problem for the model. It means that the away hadrons are not fragmenting from a quark with the same $D_q^h(z)$ function as determined in lepton processes or they are not quarks. In addition, larger values of $\langle k_\perp\rangle_{h\to q}$ means that the "black-box" $d\hat{\sigma}/d\hat{t}$ must be severely modified from our initial choice. In fact, to agree with the observed $1/p_\perp^8$ behavior of $Ed\sigma/d^3p$, the input $d\hat{\sigma}/d\hat{t}$ must behave more like $1/\hat{p}_\perp^6$. Della Negra *et al.*[3] have shown that their correlation data imply large smearing effects and that such a large smearing can go part of the way towards a $1/p_\perp^8$ behavior from an input $d\hat{\sigma}/d\hat{t}$ of the form $1/\hat{p}_\perp^4$.

Because of the above problems with the "black-box" model and because recent experiments on both the production of hadrons at large $p_\perp$ *and* the production of muon pairs of large mass indicate that $\langle k_\perp\rangle_{h\to q}$ may be larger than anticipated, the decision was made to start over at the beginning and include all the ingredients expected from contemporary quantum chromodynamics (QCD). I find that QCD might provide an adequate explanation of all the experimental results that I discussed in previous papers!

At first sight this would seem quite impossible since when one plots $p_\perp^8$ times $Ed\sigma/d^3p$ at fixed

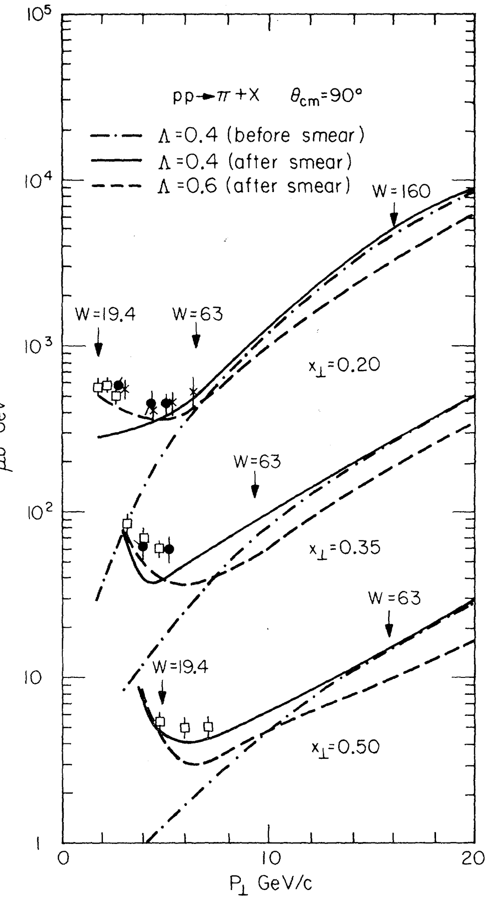

FIG. 1. $p_\perp^8 Ed\sigma/d^3p$ vs $p_\perp$ for large-$p_\perp$ pion production data at $\theta_{\text{c.m.}} = 90°$ and at *fixed* $x_\perp = 0.2$, 0.35, and 0.5, compared with the predictions (with absolute normalization) of a model that incorportates all the features expected from QCD. The dot-dashed and solid curves are the results before and after smearing, respectively, using $\Lambda = 0.4$, and the dashed curves are the results using $\Lambda = 0.6$.

$x_\perp$ versus $p_\perp$, the data are roughly independent of $p_\perp$ for $2 \leq p_\perp \leq 6$ GeV/c and $0.1 \leq x_\perp \leq 0.5$ (Fig. 1 shows the data at $x_\perp = 0.2$, 0.35, and 0.5). How could this agree with QCD which yields roughly $p_\perp^{-4}$ behavior? The difference in the two would, over the range $p_\perp = 2$ to 6 GeV/c, mean a difference by a factor of 3^4 or 81. The answer is that there are a number of effects consistent with the QCD ideas—each not particularly large in itself, but all acting in the same direction so that they conspire to produce the very large net effect needed to agree with experiment. The effects are as follows:

(a) The effective strong-interaction coupling constant falls with Q^2, where Q is some characteristic momentum in a collision.[6] Let us take $\alpha_s(Q^2)=12\pi/(25\ln Q^2/\Lambda^2)$, with $\Lambda=0.4$ GeV and $Q^2=2\hat{s}\hat{t}\hat{u}/(\hat{s}^2+\hat{t}^2+\hat{u}^2)$. (This form for Q^2 is purely arbitrary. It was chosen to be symmetric in $\hat{s}$, $\hat{t}$, and $\hat{u}$ and to be $\hat{t}$ in the case $\hat{t}\ll\hat{s}$.) At $x_\perp=0.2$, the dependence of α_s on Q^2 increases $n_{\rm eff}$ from 4.0 to 4.8, where $n_{\rm eff}=-\ln(\sigma_1/\sigma_2)/\ln(p_{\perp_1}/p_{\perp_2})$ with σ_1 and σ_2 the invariant cross sections (at fixed $x_\perp$) at $p_{\perp_1}=2.0$ and $p_{\perp_2}=6.0$ GeV/c, respectively. At $x_\perp=0.5$, $n_{\rm eff}$ is changed from 4.0 to 4.7 over the range $4.0\le p_\perp\le 8.0$ GeV/c.

(b) The parton distributions in the proton, $G(x,Q^2)$, do not scale. The influence of this on $\nu W_2(x,Q^2)$ for ep and μp scattering has been studied by Georgi and Politzer[7] and by Fox[8] and may account for the lack of scaling seen in ep and μp experiments over the range $4.0\le Q^2\le 10.0$ GeV^2. We use Fox's formulation to extrapolate these functions to the higher-Q^2 region needed in analyzing high-$p_\perp$ data ($Q^2=10-500$ GeV^2). The asymptotic-freedom formulation predicts that as Q^2 increases, there are fewer quarks at large x and more at small x. The scale breaking of $G(x,Q^2)$ increases $n_{\rm eff}$ from 4.8 to 5.2 at $x_\perp=0.2$, $2.0\le p_\perp\le 6.0$ GeV/c and from 4.7 to 5.4 at $x_\perp=0.5$, $4.0\le p_\perp\le 8.0$ GeV/c.

(c) Let us suppose that the fragmentation function $D_q^{\,h}(z,Q^2)$ is also Q^2 dependent (does not scale) in a manner similar to $G(x,Q^2)$. I have no data on this but performed an analysis on these functions using the procedure that Fox used to determine the expected Q^2 dependence of $G(x,Q^2)$. One obtains $D(z,Q^2)$ for any Q^2 in terms of that for a reference $Q_0^{\,2}$. We took $Q_0^{\,2}=4$ GeV^2 and supposed $D(z,Q_0^{\,2})$ to be the fragmentation functions of Field and Feynman.[9] The scale breaking of the D functions increases $n_{\rm eff}$ from 5.2 to 5.6 at $x_\perp=0.2$ and from 5.4 to 5.9 at $x_\perp=0.5$.

(d) The incoming partons have a large transverse momentum.[10] For the present, we use $\langle k_\perp\rangle_{h\to q}=848$ MeV and take it to be independent of Q^2 and x and generated as a Gaussian. This value is chosen to agree with the recent data on the production of muon pairs by hadron-hadron collisions that appears to imply that $\sqrt{2}\langle k_\perp\rangle_{h\to q}\approx 1.2$ GeV. (The value $\langle k_\perp\rangle_{q\to h}$ is increased to 439 GeV and generated as a Gaussian to agree with our recent quark-jet analysis.[9]) This effect increases $n_{\rm eff}$ from 5.6 to 7.6 at $x_\perp=0.2$ and $2.0\le p_\perp\le 6.0$ GeV/c, and from 5.9 to 8.1 at $x_\perp=0.5$ and $4.0\le p_\perp\le 8.0$ GeV/c, in agreement with experimental observations (see Fig. 1).

(e) As emphasized by Cutler and Sivers[11] and by Combridge, Kripfganz, and Ranft,[12] one cannot neglect effects due to gluons, g, in the proton (they carry about half the proton momentum). In addition to elastic $qq\to qq$, $\bar{q}q\to\bar{q}q$, and $\bar{q}\bar{q}\to\bar{q}\bar{q}$ scattering, we include $gq\to gq$, $g\bar{q}\to g\bar{q}$, $gg\to\bar{q}q$, $\bar{q}q\to gg$, and $gg\to gg$ contributions with each $d\hat{\sigma}/d\hat{t}$ calculated to first order in perturbation theory and with an effective coupling $\alpha_s(Q^2)$ as in (a).[11,12] The gluon distribution in a proton $G_{p\to g}(x,Q^2)$ was taken from Fox's analysis[8] and behaves like $(1-x)^4$ at large x at the reference momentum $Q_0^{\,2}=4$ GeV^2. The distribution of hadrons, $D_g^{\,h}(z,Q^2)$, in a jet generated by a gluon is completely unknown. We have chosen a form that behaves like $(1-z)^2$ at large z at the reference momentum $Q_0^{\,2}=4$ GeV^2. These choices are arbitrary; many results depend on them for the QCD quark-gluon and gluon-gluon cross sections are large. They, however, also behave as $p_\perp^{-4}$ at fixed $x_\perp$; therefore including gluons does *not* help to change $n_{\rm eff}$ from 4 to 8 but is important in bringing the *magnitude* (at low $x_\perp$) up to agree with data.

In the present state of knowledge, we do not know if all of these choices, (a)–(e), are really consistent with the *correct* consequences of the QCD theory. Thus we cannot show that experiment is truly consistent with the theory. Instead, we must merely try to see if experiment is *inconsistent* with what we think we know theoretically. In this report, I have not made any adjustments of my initial choices in order to fit the high-$p_\perp$ data.

Figure 1 shows a comparison of the predicted and experimental behavior of $p_\perp^{\,8}$ times $Ed\sigma/d^3p$ at 90° and $x_\perp=0.2$, 0.35, and 0.5 versus $p_\perp$. The dashed curves are the results (after smearing) using $\Lambda=0.6$. For the range $2.0\le p_\perp\le 6.0$ GeV/c at $x_\perp=0.2$, and $4.0\le p_\perp\le 10.0$ at $x_\perp=0.5$, the results are roughly independent of $p_\perp$ (when multiplied by $p_\perp^{\,8}$). However, this $1/p_\perp^{\,8}$ behavior of the invariant cross section holds only over a small range in $p_\perp$ that depends on the value of $x_\perp$. The data on $Ed\sigma/d^3p$ at *fixed* $W=19.4$ and 53 GeV versus $p_\perp$ are compared with the theoretical predictions in Fig. 2. The agreement is remarkable. It is nearly as good as the "black-box" model (Fig. 13 of FF1) where we chose the normalization and behavior of $d\hat{\sigma}/d\hat{t}$ to fit the data. Figure 2 also shows the results before smearing (dot-dashed curves). Smearing has little effect for $p_\perp\ge 4.0$ GeV/c at $W=53$ GeV but has a sizable effect (even at $p_\perp=6.0$ GeV/c) at $W=19.4$ GeV due to the steepness of the cross section at this low energy.

One cannot at present say whether the slight

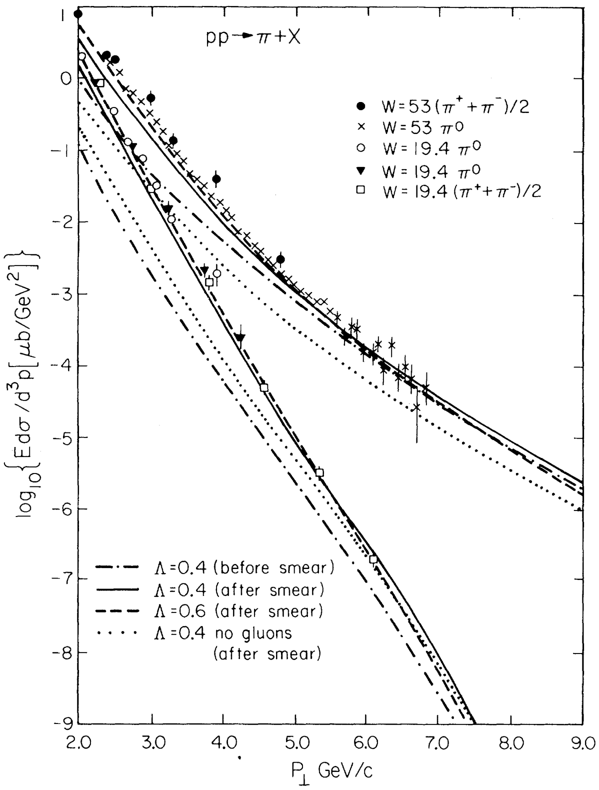

FIG. 2. Predictions of the model (normalized absolutely) compared with data on large-$p_\perp$ pion production at $\theta_{\rm c.m.}=90°$ and $W=\sqrt{s}=19.4$ and 53 GeV vs $p_\perp$. (The data are the same as Fig. 13 of FF1.) The dot-dashed and solid curves are the results before and after smearing, respectively, for $\Lambda=0.4$ and the dashed curves for $\Lambda=0.6$. The contributions from quark-quark scattering alone (after smearing) are shown by the dotted curves.

disagreement in the normalization of the theory seen in Figs. 1 and 2 at low $x_\perp$ (about a factor of 2 at $W=53$ GeV and $p_\perp=2.0$ GeV/c) is significant or simply due to the uncertainties in the inputs, (a)–(e). At these low $x_\perp$ and $p_\perp$ values the theory cannot be calculated precisely since the results depend very sensitively on the gluon distributions, the values of $\langle k_\perp\rangle_{h\to q}$ and $\langle k_\perp\rangle_{q\to h}$, the choice of Q^2, higher-order corrections, etc.

One important feature of the QCD approach is that the away-side multiplicity, $n(z_p)$,[4] is now substantially reduced from the predictions in FFF. Calculations indicate that $N(z_p \geq 0.5)$ at $p_\perp=5.0$ GeV/c, $W=53$ GeV, and $\theta_{\rm c.m.}=45°$ (to compare with Fig. 6 of Ref. 4) is now only about 0.05. This is three times smaller than the FFF result and in agreement with data. This sizable reduction is due to the increased $\langle k_\perp\rangle_{h\to q}$ (which also increase $\langle P$ out$\rangle$), the decreased values of $D(z,Q^2)$ at large Q^2, and the presence of *gluons*.

Every effort should be made both theoretically and experimentally to prove *or* disprove the QCD approach. An obvious way to verify the approach experimentally is to measure the single-particle cross section at higher $p_\perp$ and observe the rise predicted in Fig. 1.[11,12] Furthermore, a detailed comparison, over existing energies, of the predictions of the model with the charged-particle ratios (towards and away), two-particle correlation data, and jet-trigger experiments should provide evidence for *or* against the approach.

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[1](FF1) R. D. Field and R. P. Feynman, Phys. Rev. D 15, 2590 (1977); (FFF) R. P. Feynman, R. D. Field, and G. C. Fox, Nucl. Phys. B128, 1 (1977).

[2]A slightly longer version of this report with a more complete list of theoretical and experimental references is available [R. D. Field, California Institute of Technology Report No. CALT-68-633 (to be published)].

[3]M. Della Negra *et al.*, Nucl. Phys. B127, 1 (1977).

[4]The quantity $N(z_p \geq 0.5)=\int_{0.5}^{\infty} n(z_p)dz_p$, where $n(z)$ is the number of away-side hadrons between z_p and z_p+dz_p *per* trigger and $z_p=-p_x(\text{away})/p_\perp(\text{trig})$. See Eqs. (6.1) and (6.2) in FFF.

[5]See the discussion by G. C. Fox, in Particles and Fields—1977, edited by G. H. Thomas, A. B. Wicklund, and P. Schreiner (American Institute of Physics, New York, to be published).

[6]H. D. Politzer, Phys. Rep. 14C, 129 (1974).

[7]H. Georgi and H. D. Politzer, Phys. Rev. D 14, 1829 (1976).

[8]G. C. Fox, Nucl. Phys. B131, 107 (1977).

[9]R. D. Field and R. P. Feynman, California Institute of Technology Report No. CALT-68-618 (to be published).

[10]To avoid singularities at low momenta, we merely replace $\hat{s}$, $\hat{t}$, and $\hat{u}$ with $\hat{s}+1$, $\hat{t}-1$, and $\hat{u}-1$, respectively, in all scattering cross sections. In addition, for $Q^2 \leq Q_0^2$ we set $Q^2=Q_0^2=4.0$ GeV^2. The precise form of this "cutoff" procedure is important only for $2.0 \leq p_\perp \leq 3.5$ GeV/c which means that data in this region cannot at present serve to test the QCD hypothesis.

[11]R. Cutler and D. Sivers, Phys. Rev. D 16, 679 (1977), and 17, 196 (1978).

[12]B. L. Combridge, J. Kripfganz, and J. Ranft, Phys. Lett. 70B, 234 (1977).