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HADRON PRODUCTION AT LARGE TRANSVERSE MOMENTUM AND QCD

B.L. Combridge ^{*)}, J. Kripfganz ^{**)} and J. Ranft ⁺⁾
CERN -- Geneva

A B S T R A C T

The predictions of a QCD-based hard-scattering model for large p_T hadronic processes are investigated. Not only quark-quark scattering but all contributions in lowest order are considered. At low x_T , gluon-gluon and quark-gluon scattering are found to dominate the quark-quark term. At present energies the QCD predictions lie below the data but already come very close at the highest ISR energy. Predictions for higher p_T values and higher energies are made.

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^{*)} NATO Science Fellow.

^{**)} On leave of absence from Karl-Marx-University, Leipzig, GDR.

⁺⁾ Visitor from Karl-Marx-University, Leipzig, GDR.

Largely because of its property of asymptotic freedom, quantum chromodynamics (QCD) - the $SU_c(3)$ gauge theory of coloured quarks and gluons - is widely considered to be a promising candidate for a theory of strong interactions. Unfortunately, although short-distance and light-cone arguments allow predictions for a few processes such as deep-inelastic scattering and e^+e^- annihilation, such methods are not immediately applicable to a wider class of "parton-model" processes, including large-angle hadronic scattering, lepton-pair production in hadronic processes and hadron production at large p_T , as these are not dominated by light-cone singularities in a straightforward way. However, a perturbative approach is still believed to be valid in these cases and thus, despite some uncertainties in their description (the incorporation of scaling violations, for example), these processes may still provide important tests of QCD.

In the case of hadron production at large p_T , it has already been shown ^{1),2)} that lowest-order quark-quark scattering in a QCD framework gives contributions which are generally below, and usually small compared with, the data ^{*)}. The size of the QCD running coupling constant, its Q^2 dependence, and the Q^2 dependence of the hadrons' structure functions all contribute to this result. One can take the view that the data do not contradict QCD, but that there exist other (presumably non-asymptotic) contributions which are actually dominant at present energies and p_T ranges.

In the present paper, we reinvestigate QCD predictions for large p_T physics, taking into account all lowest order contributions to the supposed basic $2 \rightarrow 2$ hard-scattering subprocesses. These processes are listed in the Table. Since gluons carry a sizeable fraction of the proton's momentum, we expect important contributions from hard scatterings involving gluons. As we show below, it turns out that quark-gluon and gluon-gluon elastic scatterings are the important processes besides quark-quark scattering.

We calculate inclusive distributions in the usual way ^{1),2)}, requiring as input expressions for the various hard-scattering differential cross-sections $d\sigma/d\hat{t}$, structure functions $F(x, Q^2)$ and fragmentation functions $G(z, Q^2)$ ^{**)}.

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*) However, a fit to the data is possible with a modified but still logarithmic description of scale breaking and an unusually large quark-gluon coupling constant ³⁾.

**) We emphasize again that such a factorizing ansatz involves model assumptions going beyond our present knowledge of the structure of QCD.

We have calculated the differential cross-sections

$$\frac{d\sigma}{d\hat{t}} = \frac{\pi \alpha^2}{\hat{s}^2} \sum \quad (1)$$

for all lowest-order [i.e., $O(g^4)$] processes in QCD. Our results for Σ are listed in the Table. As examples, we show in Fig. 1 the individual graphs contributing to quark-gluon and gluon-gluon scattering.

For α we use the running coupling constant appropriate to four-flavour QCD [see, for example, Ref. 4]

$$\alpha(Q^2) = \frac{12 \pi}{25 \log \frac{Q^2}{\Lambda^2}} \quad (2)$$

Guided by estimates ^{4),5)} from deep-inelastic data, we take $\Lambda = 0.3$ GeV. In this way our normalization is completely fixed.

QCD predictions for quark and gluon distributions in nucleons, particularly their Q^2 dependence, have been recently studied in some detail, leading to analytic parametrizations ^{5),6)}. We shall follow Ref. 5). Simple expressions of the form

$$F(x, Q^2) = A(Q^2) x^{a_1(Q^2)} (1-x)^{a_2(Q^2)} \quad (3)$$

reproduce the predicted Q^2 dependence of the moments of the structure function up to a few per cent over a large Q^2 range [for details, see Ref. 5]. The agreement with the deep-inelastic data is very good.

For the quark fragmentation functions, we use expressions introduced in Ref. 7), which behave essentially like $(1-z)$ for z near 1. fulfil the relevant sum rules, and give a reasonable description of the data on inclusive hadron production in e^+e^- annihilation and deep inelastic scattering. For the unknown gluon fragmentation function we use

$$G_g^{\pi^0}(z) = \frac{1}{3} (n_g + 1) (1-z)^{n_g} \quad (4)$$

where, for the moment, n_g is a free parameter.

We do not include any Q^2 dependence (scaling violations) in these fragmentation functions, since there is neither reasonable theoretical understanding nor detailed data on this. Present e^+e^- annihilation data [see, e.g., Ref. 8] show only a weak energy dependence for $z > 0.5$, and our results are sensitive to the behaviour at large z only. If the $G(z)$ were to significantly decrease with Q^2 in this region, this would steepen the slopes of our predicted single-particle distributions.

Another question which arises is what should be chosen for the effective large momentum squared Q^2 . If, for example, for each of the graphs in Fig. 1a, we would use the true momentum carried by the internal propagator, the sum would be no longer gauge invariant because of the three different α 's. Because of this, and to simplify the calculation, we have chosen a common effective Q^2

$$Q^2 = \sqrt[3]{\hat{s}\hat{t}\hat{u}} \quad (5)$$

where $\hat{s}$, $\hat{t}$, $\hat{u}$ refer to the subprocess. We have found few significant quantitative differences with other choices of Q^2 . For example, going from $Q^2 = \sqrt[3]{\hat{s}\hat{t}\hat{u}}$ to $Q^2 = 1/3(\hat{s}-\hat{t}-\hat{u})$, $-\hat{t}$ or $\hat{s}$, typically changes the total single particle yield by not more than about $\pm 25\%$.

Our results for the pion and total jet (quark+gluon) inclusive distributions at centre-of-mass angle $\theta = 90^\circ$ are shown in Figs. 2-5 for various energies and ranges of p_T .

Figure 2 compares the model with data taken at the highest CERN-ISR energy. The two curves for the predicted π^0 cross-section correspond to choosing $n_g = 1$ and 3 in Eq. (4). We are in good agreement with the few data points above $p_T \simeq 6$ GeV/c but tend to fall below the data as p_T decreases from this value. In the latter region, gluon effects are important and the predicted curve is sensitive to the choice of n_g . However, even with $n_g = 1$, we do not reach the data. For the remainder of this paper we take $n_g = 2$. We have also investigated the effect of taking different (initially less steep, for example) gluon distributions, but still with a Q^2 evolution in accordance with the methods of Ref. 5). It remains difficult to fit the medium p_T data of Fig. 2.

Figure 2 also shows the quark-quark scattering term alone. Our result for this contribution is comparable, though not identical, with that obtained earlier by Cutler and Sivers ²⁾ in a similar model.

Figure 3 is a comparison of our results and Fermilab 400 GeV/c data. The predicted pion curve is now substantially below the data. This is related to the observation that the model does not reproduce the $p_T^{-N} f(x_T)$, $N=8$, behaviour found experimentally. The scale-breaking, incorporated in the model via the running constant and the structure functions, does increase N from its scaling value of 4, but typically by only one or two units in the appropriate range.

We have also calculated the total jet cross-section at 200 GeV/c momentum and find that it falls roughly two orders of magnitude below recently reported data ¹¹⁾.

Thus present data require either the presence of extra contributions, or, possibly, the existence of some mechanism which would give substantial enhancements to our cross-sections, particularly at lower energies.

In both cases it would seem that these must be non-asymptotic effects, in our picture. As Figs. 2 and 3 indicate, the basic QCD processes should be visible at higher energies, and possibly also at larger p_T 's.

Investigating the higher p_T possibility first, we display in Fig. 4 the model predictions of the inclusive cross-section up to $p_T = 20$ GeV/c for the highest ISR energy point, $\sqrt{s} = 62.4$ GeV. The data points included in the plot are Fermilab data, extrapolated as $p_T^{-8} f(x_T)$. The predicted curve does indeed lie above these points for $p_T > 10$ GeV/c. However, the difference is not too substantial.

The situation changes dramatically in going to higher energies. In Fig. 5 we show the QCD predictions at $\sqrt{s} = 540$ GeV, the energy of a proposed $p\bar{p}$ experiment at the CERN SPS. Our predictions are now orders of magnitude above the Fermilab extrapolation. This effect should not only be easily visible, but also could be important for background estimates for $W^\pm$ and Z^0 production.

Figures 2, 4 and 5 also show the individual contributions to the π^0 cross-section of quark-quark, quark-gluon and gluon-gluon (elastic) scattering. The other contributions given in the Table are not particularly important. At very low x_T ($\lesssim 0.04$) the gluon-gluon term is dominant. Above this region, but still at low x_T , the quark-gluon contribution takes over. Quark-quark scattering is the dominant mechanism for all large and medium x_T ($\gtrsim 0.15$). The cross-over points depend to some extent on the gluon fragmentation and structure functions.

To summarize : present data on large p_T hadron production are not fitted by the predictions of our scale-breaking hard-scattering model based on quantum chromodynamics. However, they do not rule out the existence of such a contribution, in the sense that our predictions never rise above the data. (This is a consequence of the smallness of the running coupling constant in QCD, together with the scale-breaking in Q^2 . Thus, in particular, there is no need to suppress these processes artificially, as has often been supposed.)

Data and prediction come tantalisingly close at the highest ISR energies. Experiments at higher energies, or possibly at higher p_T at present top energies, should reveal the existence of such a QCD mechanism through a change in the observed scaling behaviour of the large p_T cross-section.

Although this picture qualitatively resembles conclusions of previous similar analyses of just the quark-quark scattering term ^{1),2)}, we have shown that gluon effects are important, particularly at very high energy where gluon-gluon and quark-gluon scattering dominate most of the accessible p_T range. The variation in competing processes may be observable through p_T dependence of the associated event structure, particularly on the toward side. Also we note that, as expected in such models, using calorimeters to trigger on jets would give substantial increases in cross-sections, possibly allowing much wider p_T ranges to be probed.

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	Σ
$q_1 q_2 \rightarrow q_1 q_2,$ $q_1 \bar{q}_2 \rightarrow q_1 \bar{q}_2$	$\frac{4}{9} \frac{s^2 + u^2}{t^2}$
$q_1 q_1 \rightarrow q_1 q_1$	$\frac{4}{9} \left(\frac{s^2 + u^2}{t^2} + \frac{s^2 + t^2}{u^2} \right) - \frac{8}{27} \frac{s^2}{ut}$
$q_1 \bar{q}_1 \rightarrow q_2 \bar{q}_2$	$\frac{4}{9} \frac{t^2 + u^2}{s^2}$
$q_1 \bar{q}_1 \rightarrow q_1 \bar{q}_1$	$\frac{4}{9} \left(\frac{s^2 + u^2}{t^2} + \frac{t^2 + u^2}{s^2} \right) - \frac{8}{27} \frac{u^2}{st}$
$q\bar{q} \rightarrow gg$	$\frac{32}{27} \frac{u^2 + t^2}{ut} - \frac{8}{3} \frac{u^2 + t^2}{s^2}$
$gg \rightarrow q\bar{q}$	$\frac{1}{6} \frac{u^2 + t^2}{ut} - \frac{3}{8} \frac{u^2 + t^2}{s^2}$
$qg \rightarrow qg$	$-\frac{4}{9} \frac{u^2 + s^2}{us} + \frac{u^2 + s^2}{t^2}$
$gg \rightarrow gg$	$\frac{9}{2} \left(3 - \frac{ut}{s^2} - \frac{us}{t^2} - \frac{st}{u^2} \right)$

Hard scattering subprocesses in QCD and the associated differential cross-sections in lowest order. Σ is defined by Eq. (1). The initial (final) colours and spins have been averaged (summed). q and g denote quark and gluon, respectively. Subscripts 1, 2 denote distinct flavours. s, t, u are the Mandelstam variables of the subprocess.

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FIGURE CAPTIONS

- Figure 1   Lowest-order graphs contributing to
                  (a) quark-gluon scattering ;
                  (b) gluon-gluon scattering.
- Figure 2   Predictions for π^0 (solid curves) and total jet (dash-dot
                  curve) inclusive cross-sections in pp interactions at
 $\sqrt{s} = 62.4$ GeV, $\theta = 90^\circ$. The two solid curves correspond to
 $n_g = 1$ (upper) and $n_g = 3$ in Eq. (4). The quark-quark
                  scattering contribution alone is given by the dash-open
                  circle curve. The points are single pion data from Ref. 9).
- Figure 3   Predictions for π^0 (solid curve) and total jet (dash-dot
                  curve) inclusive cross-sections in pp interactions at
 $\sqrt{s} = 27.4$ GeV ($p_{\text{lab}} = 400$ GeV/c) and $\theta = 90^\circ$. The points
                  are single pion (π^-) data for θ near 90° taken from
                  Ref. 10).
- Figure 4   Predictions for π^0 (solid curve) and total jet (dash-dot
                  curve) inclusive cross-sections in pp interactions at
 $\sqrt{s} = 62.4$ GeV, $\theta = 90^\circ$. The individual contributions of quark-
                  gluon (short-dashed curve) and gluon-gluon (long-dashed curve)
                  scattering are also shown. For the sake of clarity, the
                  quark-quark scattering term, dominant for $p_T > 4$ GeV/c, is
                  not displayed here ; it is shown in Fig. 2. The points are
                  single-pion data for θ near 90° from Ref. 10), extrapolated
                  as $p_T^{-8} f(x_T)$.
- Figure 5   As Fig. 4, with $\sqrt{s} = 540$ GeV. The quark-quark scattering
                  contribution alone (dash-open circle curve) is also plotted.

FIG.1

FIG.2

FIG. 3

FIG.4

FIG. 5