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Experimental Tests of Quantum Chromodynamics in High-$p_\perp$ Jet Production in 200-GeV/c Hadron-Proton Collisions

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Data on inclusive jet production in the transverse-momentum ($p_\perp$) range 0–8 GeV/c for 200-GeV/c p, π^-, π^+, K^-, K^+, and $\bar{p}$ incident on a hydrogen target are presented. The jet cross section is fully corrected for losses and biases, and compared with the predictions of a model based on quantum chromodynamics. Both the absolute cross section and the inclusive charged-particle distributions inside and outside the jet are in qualitative agreement with the model.

We have investigated 200-GeV/c hadron-proton collisions with a large-aperture spectrometer by triggering on jets of particles of high collective transverse momentum at 90° in the c.m. system. Earlier results from this experiment and details of the apparatus are described by Bromberg *et al.*[1-4] Trigger jets are defined, in this analysis, as the collection of all particles in a 1.5-sr cone near 90°, and are discussed in greater detail by Rohlf[5] and by Bromberg *et al.*[6] The results reported here are insensitive to the exact size of this cone. The incident hadron was tagged with four Čerenkov counters and contaminations in the beam flavor selection were negligible.

Previous data on jet production[1,2,7] have shown the cross section to be at least two orders of magnitude larger than that for a single particle with the same transverse momentum. More precise statements are hampered by uncertainties in interpretation of the data. Difficulties include trigger biases, and ambiguities of jet definition resulting from low-momentum particles. These questions can only be answered in the context of a model.[8-10] We have modeled the interactions as

$$\text{beam} + p \rightarrow \text{four jets}.$$

The initial step in this formulation was to use the quantum-chromodynamic (QCD) approach discussed by Feynman, Field, and Fox,[11] which relates hadron jet production to a sum of contributions of quark (q) and gluon (g) two-body scatterings such as

$$qq \rightarrow qq, \quad qg \rightarrow qg, \text{ etc.}$$

The importance of including the gluon contributions has been pointed out by others.[12,13] The model's success in describing other high-$p_\perp$ phenomena justifies its use in our experiment. The model is not an exact formulation of the QCD predictions. Known simplifications include the approximate handling of the parton transverse-momenta wave functions and the neglect of inelastic processes, such as $qq \rightarrow qqg$.

In the model, there are four jets in the final state, which arise from the two scattered constituents, the beam remains, and the target remains; each of these is fragmented into hadrons by use of a jet generator developed by Field and Feynman.[14-16] The function $D(z)$, which denotes the probability that a quark (gluon) fragments into a hadron with a fraction z of the quark (gluon) momentum, is fixed to agree with lepton experiments.[17,18] Only mesons are produced in this model, and scale breaking in the fragmentation is not included.

The four-jet Monte Carlo events were tracked through the spectrometer windows and the calorimeter response was modeled.[5,6] The events were then written out on magnetic tape, in the same format as the real data, and processed by the same software as the real events. A partial comparison of the data with the four-jet simulation is given in Fig. 1, where final-state charged-particle distributions are plotted versus $z = \vec{p} \cdot \vec{p}_{\rm jet}/|\vec{p}_{\rm jet}|^2$, where $\vec{p}$ is the individual charged-particle momentum, and $\vec{p}_{\rm jet}$ is the trigger jet momentum (4 GeV/$c < |\vec{p}_{\rm jet}| <$ 5 GeV/c for these plots). The plots are divided into (a) trigger side, $z > 0$; and (b) away side, $z < 0$. The total charged-particle multiplicities come out about the same. The average values are 10.3 for the data, and 9.5 for the Monte Carlo simulations. The z distributions on the trigger side match reasonably well, the difference being a somewhat softer distribution in the data. Moreover, the away-side agreement is striking. Comparable agreement was obtained in both rapidity and $p_\perp$ distributions. The discrepancies between theory and experiment could easily be due to the aforementioned simplifications in the formulation of the model.

These Monte Carlo events were used to study different approaches to the definition of a jet, and calculate the jet acceptance of our apparatus, including both geometrical and calorimeter resolution effects. The calorimeter size in this experiment was found to be well suited for measuring these jets.[5,6] The collective $p_\perp$ of all particles entering the trigger calorimeter was on the average only about 100 MeV/c less than the generated trigger-jet $p_\perp$, when we apply the fiducial cuts, $|y| < 0.2$ and $|\varphi| < 20°$, where y is the c.m. rapidity and φ is the azimuthal angle of the jet. The observed $p_\perp$ is decreased by trigger-jet particles missing the calorimeter but increased by beam, target, or away-side jet particles entering the calorimeter. For our calorimeter these effects roughly cancel.

The acceptance-corrected cross section for $pp \to \text{jet} + X$ is shown in Fig. 2. The jet $p_\perp$ is measured with very good resolution.[19] Data were taken with six different calorimeter trigger thresholds; in addition, a sample of events were recorded in which no calorimeter requirements were made. This enabled us to measure the cross section over a range of nine orders of magnitude. Different bias regions (which have different acceptances due to different trigger efficiencies) overlapped and thus served as a check of the net acceptance correction. The data have a $p_\perp$ dependence of $\exp(-3.2p_\perp)$ over the entire measured range. The single-particle data of Antreasyan *et al.*[20] are shown, with the numbers indicating the jet/single-particle ratios. Also shown in Fig. 2 are the QCD predictions.[11] The upper curve is the cross section for producing a jet (quark, gluon) of a given energy. The bottom

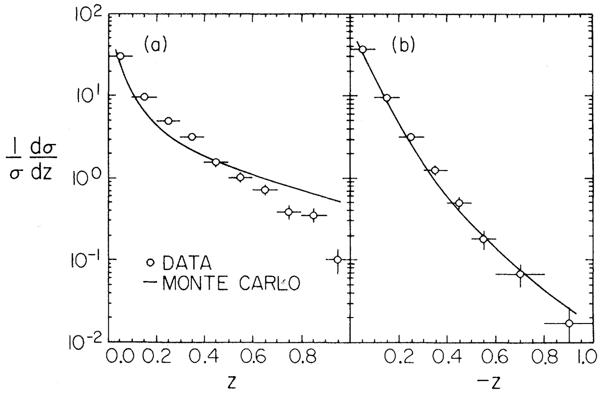

FIG. 1. Comparison of charged-particle z distributions between data and QCD-based four-jet model on (a) trigger side and (b) away side.

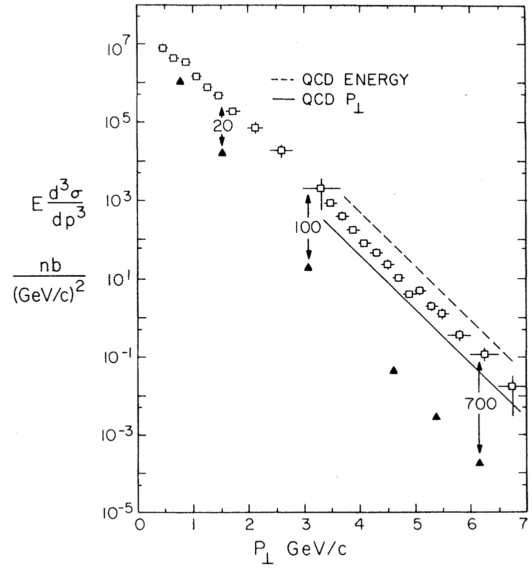

FIG. 2. Invariant cross section (empty squares) for $pp \to \text{jet} + X$ compared with QCD predictions. Also shown are the single-particle data, $(\pi^+ + \pi^-)/2$, from Ref. 20 (full triangles). The numbers incidate the jet/single-particle ratio. (See text for a discussion of the QCD predictions).

curve, which is about a factor of 15 lower, is the cross section for producing a jet of given $p_\perp$, with some energy going into mass of the jet particles, and transverse momentum of these particles about the jet (quark, gluon) axis. The lower curve, which is the prediction for what we have measured, is about a factor of 3 lower than the data, independent of $p_\perp$. Notice that the large jet cross section is characteristic of QCD[10,11] and we know of no other theories (e.g., a phase model as discussed in Ref. 1) that gives this.

The ratio of jet production by incident protons to that by incident π^- is shown in Fig. 3(a). No acceptance correction is used here, for it cancels upon taking the ratio. As seen in other experiments,[21,22] the ratio approaches the ratio of the total cross sections at low $p_\perp$ and falls sharply at high $p_\perp$. We expect pions to make high-$p_\perp$ jets more easily than protons because the pion has only two valence quarks, which therefore each carry on the average a larger fraction of the incident momentum than the three valence quarks of the proton. Also shown in Fig. 3(a) are the data from this experiment on the ratio of cross sections σ

$$\sigma(pp \to h + X)/\sigma(\pi^- p \to h + X),$$

where h is a single charged hadron produced at 90° in the c.m. system. The single-particle data agree with the jet data when the former $p_\perp$ scale is divided by about 0.8. This is consistent with the single high-$p_\perp$ hadron having originated from a quark or gluon which had on the average 15%–20% more momentum, as suggested by both the theoretical[11] and experimental[1] analyses of single-particle production. The datum point in the $p_\perp$ bin 7–8 GeV/c represents thirteen $\pi^- p$ events and no pp events from roughly equal beam fluxes. These highest-$p_\perp$ events are indeed jetlike; they have about 80% of the kinematically allowed energy going into about 15% of the hemisphere. Jet data from Ref. 21 is superimposed for comparison with this experiment. Figure 3 also shows the cross-section ratios

$$\sigma(K^- p \to \text{jet} + X)/\sigma(\pi^- p \to \text{jet} + X),$$

$$\sigma(K^+ p \to \text{jet} + X)/\sigma(\pi^+ p \to \text{jet} + X),$$

$$\sigma(\pi^+ p \to \text{jet} + X)/\sigma(\pi^- p \to \text{jet} + X),$$

$$\sigma(pp \to \text{jet} + X)/\sigma(\bar{p}p \to \text{jet} + X).$$

These cross sections are consistent with the hypothesis that high-$p_\perp$ jet production depends only on the number of valence quarks in the incident beam (with other parameters fixed). This has been observed for high-$p_\perp$ single-particle production.[4,22]

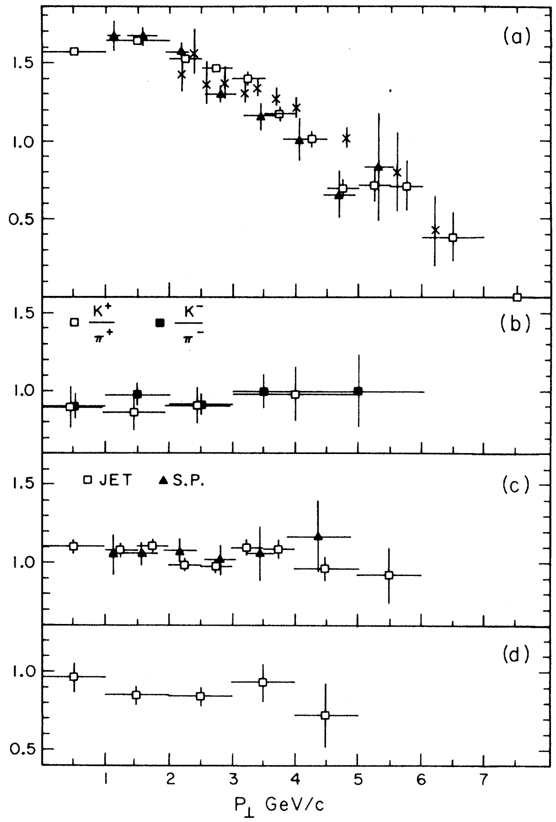

FIG. 3. (a) The beam ratio p/π^- for jet production (empty squares) compared with single-particle production (solid triangles) from this experiment ($p_\perp$ divided by 0.8) and the beam ratio p/π^+ for jet production from Corcoran *et al.*[21](crosses). (b) The beam ratios K^-/π^- and K^+/π^+. (c) The beam ratio π^+/π^- and the single-particle data from this experiment ($p_\perp$ divided by 0.8). (d) The beam ratio $p/\bar{p}$.

This Letter represents a comprehensive but qualitative test of QCD. The current theory still has many uncertainties[10,11] and this, plus the relatively low energy of our data, renders more quantitative comparisons impossible at present. We will discuss these points more fully in Refs. 5 and 6, and discuss there the discrepancies in Figs. 1 and 2 between theory and experiment. Still it should be realized that the data summarized in this Letter are being compared with absolute, parameter-free predictions of a fundamental theory of the strong interactions. Viewed in this light, we feel that the success of the theory is impressive.

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[19] The resolution depends on the jet structure (Refs. 1 and 6). For an average jet of $p_\perp = 5$ GeV/*c* made up of 60% charged particles, 15% hadronic neutrals, and 25% electromagnetic neutrals, the jet $p_\perp$ resolution is 6%.

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