First Measurements of Jet Production Rates in Deep-Inelastic Lepton-Proton Scattering

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The first measurements of forward multijet rates in deep-inelastic lepton scattering are presented. Data were taken with a 490-GeV muon beam incident on a hydrogen target. The jets were defined using the JADE algorithm. The measured rates are presented as a function of the jet resolution parameter y_{cut}, and as a function of the virtual-photon–proton center-of-momentum energy W, in the range $13 \leq W \leq 33$ GeV. Comparisons are made to the predictions of the Lund Monte Carlo programs, and good agreement is obtained when QCD corrections are included in the model.

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Previous studies of deep-inelastic lepton scattering (DIS) from nucleons have provided many unique results that have helped formulate today's standard model. Measurements of DIS cross sections using electrons [1], muons [2], and neutrinos [3] have been used within the quark-parton model (QPM) to extend our understanding of the theory of strong interactions, quantum chromodynamics (QCD). Fits to the various structure functions have yielded measurements of the strong coupling constant α_s, as well as the underlying parton distribution functions [4,5]. Multijet production in deep-inelastic lepton scattering may also be used to study these fundamental quantities. Events with more than one jet in the forward direction are expected if the observed Q^2 dependence of the structure functions is due to processes involving gluons in the initial or final states. This paper presents measurements of forward multijet rates produced by deep-inelastic lepton scattering, made possible for the first time by the high center-of-momentum energy available at Fermilab.

At the energies considered, the deep-inelastic muon-nucleon scattering process is dominated by single virtual-photon exchange, which at fixed beam energy can be completely described using two independent variables, for example Q^2, the negative square of the virtual-photon four-momentum, and ν, the energy of the virtual photon in the laboratory frame. The total available hadronic center-of-momentum energy squared is $W^2=M^2-Q^2+2M\nu$, where M is the mass of the target proton. The topology of this process is characterized in the naive QPM by the production of two hadronic jets, one moving forward in the hadronic center-of-momentum frame resulting from the hadronization of the struck quark (antiquark) and a second, moving backwards, originating from the target remnants. Therefore, in the naive QPM, only single-forward-jet events are expected.

Leading-order QCD corrections include two new processes, gluon bremsstrahlung and photon-gluon fusion, each of which manifests itself as a three-jet event (in the majority of events, two of these jets will be forward). The production rates of these multiple jet events have been calculated in perturbative QCD [6], and are dependent on both α_s and the parton distributions. In contrast, three-jet events in e^+e^- collisions [7] arise only from gluon bremsstrahlung and the rate depends only on α_s.

The experiment E665 [8] was performed in the NM beam line at Fermilab and used a beam of 490-GeV muons that struck a 1.15-m-long hydrogen target. Charged particles reconstructed in the tracking system and fitted to the primary vertex and neutral particles reconstructed in the electromagnetic calorimeter were used. The following kinematic cuts were applied to define the event sample: $Q^2>4.0$ $(\mathrm{GeV}/c)^2$, $\nu>40$ GeV, $x_{\mathrm{Bj}}=Q^2/2M\nu>0.003$, and $0.05<\nu/E_{\mathrm{beam}}<0.95$. A further cut was used to reduce the contribution from coherent photon bremsstrahlung: Events with no charged tracks apart from the scattered muon, $\nu>200$ GeV and $E_{\mathrm{cal}}/\nu>0.35$ were considered to be bremsstrahlung and removed, where E_{cal} is the total energy observed in the calorimeter. Only particles going forward in the virtual photon-proton center-of-momentum system were considered. To select well-reconstructed charged particles, tracks were required to have a χ^2 fit probability greater than 0.001 and fractional momentum resolution less than 0.1. Neutral particles were reconstructed from isolated calorimeter clusters, selecting only clusters with energy greater than 2 GeV. A 5.0-cm isolation cut was applied to remove charged-hadron-induced showers. The final total sample was 12573 events. The average observed total multiplicity for events with $W\geq 13$ GeV was 6.6 particles per event (2.3 charged plus 4.3 neutrals).

As in all jet measurements, one must employ an algorithm to define jets. We have chosen for this analysis the method introduced by the JADE collaboration [9]. The JADE algorithm was devised to closely resemble the criterion used to resolve partons in perturbative QCD calculations. To overcome collinear and infrared singularities in these calculations, an invariant mass cut is introduced to define the resolvability of the parton pairs. In the experimental implementation of this algorithm, each event is boosted to the virtual-photon–proton center-of-momentum frame, and for each pair of particles (i and j) the quantity $y_{ij}=M_{ij}^2/\tilde{w}^2$ is formed, where $M_{ij}^2=2E_iE_j(1-\cos\theta_{ij})$, $E_{i,j}$ are the particle energies, θ_{ij} is the angle between the particles, and $\tilde{w}$ is an energy scale. The minimum y_{ij} in the event is compared to the jet resolution parameter, y_{cut}, and if $y_{ij}^{\mathrm{min}}<y_{\mathrm{cut}}$, the two particles, i and j, are combined by adding their four-momenta. The procedure is repeated until y_{ij}^{min} is larger than y_{cut}, and the resulting combined particles are called jets. We have assumed all charged particles to be pions and all neutral particles to be photons. The rate for n jets, R_n, is defined to be the ratio of the number of events with n forward jets divided by the total number of events.

We have found that using the energy scale $\tilde{w}=W/2$ when applying this algorithm to the raw data minimizes the corrections to the jet rates for geometrical acceptance and reconstruction efficiency. However, the final results were corrected for this initial choice of scale, and are presented for the scale $\tilde{w}=W$. We have confirmed that the final rates depend only weakly on the original choice of $\tilde{w}$.

A GEANT-based Monte Carlo [10] simulation of our detector was used to correct the data distributions for geometrical acceptance, reconstruction efficiency, and resolution. The Lund Monte Carlo programs (LEPTO 5.2 and JETSET 6.3) [11] were used as the physics generator. Particle decays, secondary strong and electromagnetic interactions, and a detailed simulation of the detector were included. Electromagnetic radiative corrections, based on calculations by Mo and Tsai [12], were also applied. This Monte Carlo simulation was able to accurately reproduce many aspects of the data, including the uncorrected jet rates. As an example of the agreement between data and Monte Carlo simulation, Fig. 1 shows the average visible energy in the center-of-momentum frame versus W.

The Monte Carlo generated events were subjected to

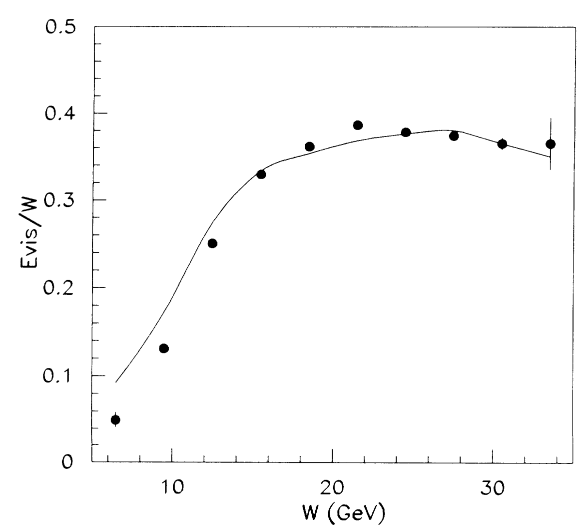

FIG. 1. The average visible energy, E_{vis}, divided by the total center-of-momentum energy, W, vs W for the event sample; the solid curve is the result of the Monte Carlo simulation.

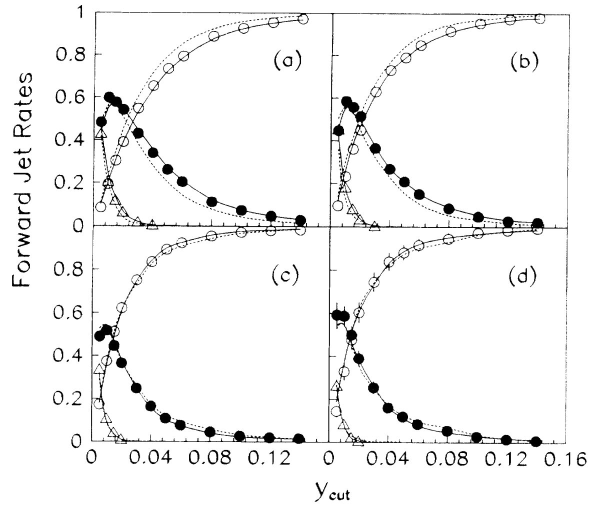

FIG. 2. Forward jet rates for one jet (open circles), two jets (solid circles), and more than two jets (open triangles) vs y_{cut} for different W bins: (a) $13 \leq W < 18$ GeV, (b) $18 \leq W < 23$ GeV, (c) $23 \leq W < 28$ GeV, and (d) $28 \leq W < 33$ GeV. The data have been corrected for acceptance, resolution, and reconstruction efficiency. Lund model predictions are also shown [matrix elements (solid curve) and parton showers (dashed curve)].

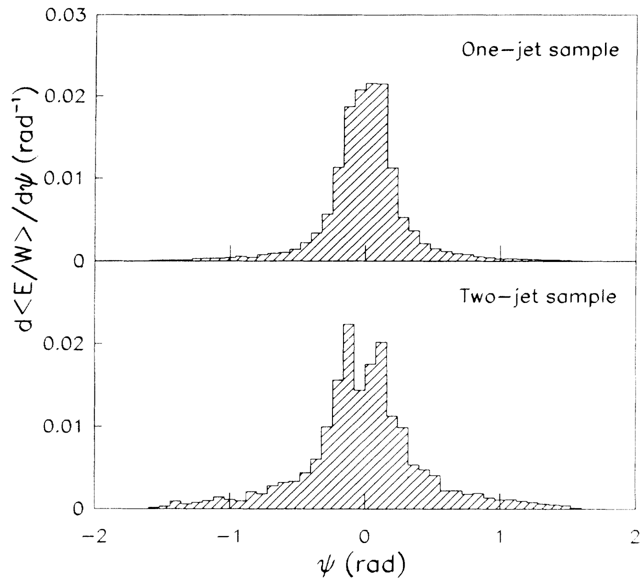

FIG. 3. The energy flow per event for the one- and two-forward-jet samples with $y_{\mathrm{cut}}=0.04$. ψ is the angle between the virtual-photon direction and the hadron momentum projected into the hadronic plane.

the identical analysis as the data, yielding reconstructed Monte Carlo jet rates $R_n^{\mathrm{MC\,recon}}$. In addition, the JADE algorithm was applied to the primary forward hadrons generated by the Monte Carlo simulation, resulting in true jet rates $R_n^{\mathrm{MC\,true}}$. Note that for both the data and the Monte Carlo simulation, the energy scale $\tilde{w}=W/2$ was used for the reconstructed rates, whereas the scale $\tilde{w}=W$ was used for the true rates. The data distributions were then corrected bin by bin using

$$R_n^{\mathrm{corrected}} = \frac{R_n^{\mathrm{MC\,true}}}{R_n^{\mathrm{MC\,recon}}} R_n^{\mathrm{data}} .$$

Thus, the final corrected jet rates are presented as if $\tilde{w}=W$ had been used in the definition of y_{ij}.

Figure 2 shows the rates of one, two, and more than two forward jets versus y_{cut}, for four different W bins. The data show the typical dependence on the jet resolution parameter y_{cut}, with the resolvability of multiple jets diminishing with increasing y_{cut}. Also shown in Fig. 2 are the predictions of the Lund model. This model includes two options for implementing QCD corrections to the quark-parton model, one employing leading-order QCD matrix elements (ME) and a second using QCD parton showers (PS). Both options use the same Lund string model to perform the fragmentation of the final partons. We have used the leading-order parton distributions from Morfin and Tung [4] and have set all of the Lund parameters to their default values.

In principle, the corrections to the jet rates are sensitive to the physics generator used within the Monte Carlo. We have attempted to estimate this sensitivity by comparing the corrected rates using the ME option to those obtained using the PS option. The differences in the resultant rates were always less than 0.04. We estimate the systematic error in the jet rates due to the event and particle selection criteria to be less than ± 0.01, and that due to our ability to model the acceptance and efficiency of the apparatus to also be less than ± 0.01. We varied the initial choice of energy scale in the definition of y_{ij} from $\tilde{w}=0.3W$ to $\tilde{w}=W$ and found that, although the corrections for acceptance changed dramatically, the final corrected rates were stable. Based on the observed variations, we estimate the systematic error due to the correction technique to be less than ± 0.015.

We have examined the topological properties of those events identified as one-jet and two-jets (e.g., thrust, sphericity, and planarity), and have confirmed that they agree with expectations. For example, Fig. 3 shows the scaled energy flow per event [13] for one-jet and two-jet events obtained with $y_{\mathrm{cut}}=0.04$. The energy flow per event is defined as

$$\frac{d\langle E/W\rangle}{d\psi} = \frac{1}{N_{\mathrm{events}}} \frac{1}{\Delta\psi} \sum_j^{\mathrm{events}} \sum_i^{\mathrm{particles}} \frac{E_i}{W_j} ,$$

where ψ is the angle between the virtual-photon direction and the hadron momentum projected into the hadronic plane and $\sum_i^{\mathrm{particles}}$ extends over all particles in the angular range $(\psi, \psi+\Delta\psi)$. We define the hadronic plane as the plane which contains the virtual photon and in which the sum of the squared transverse momenta of the hadrons is maximized. We have chosen the plane orientation such that the scattered muon has negative ψ. A two-lobed and broader structure is observed in the two-jet sample as compared to the one-jet sample.

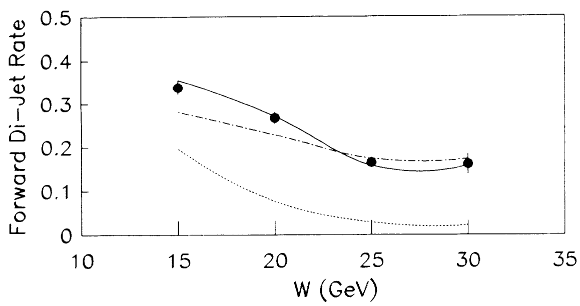

FIG. 4. Forward di-jet rate versus W for $y_{\mathrm{cut}}=0.04$. Lund model predictions are also shown [matrix elements (solid curve), parton showers (dot-dashed curve)]. In addition, the results using the quark-parton model with no QCD corrections (dashed curve) are included.

Figure 4 shows the forward di-jet rate versus W for a value of $y_{\mathrm{cut}}=0.04$. As predicted by leading-order perturbative QCD [14], the forward di-jet rate falls as W increases. Also shown are the Lund model ME and PS predictions. We also include the QPM predictions without QCD corrections, again using the Lund Monte Carlo programs. Good agreement is observed with the QCD based models, with the naive QPM prediction excluded. The drop in the rates as a function of W can be explained by three effects. The first is purely kinematical; for a fixed y_{cut}, increasing W implies an increasing cut on the effective invariant mass of the hadrons. The second is the running of the strong coupling constant, and the third is the variation of the parton distribution functions with W (i.e., x_{Bj} and Q^2). The relative importance of these effects in the observed di-jet evolution with W and the sensitivity of these results to α_s and the parton distributions will be addressed in a future paper.

In conclusion, the first measurements of multiple-forward-jet rates produced by deep-inelastic lepton scattering have been made in the kinematic region $13 \leq W \leq 33$ GeV. Comparisons have been made to QCD predictions by using two versions of the Lund Monte Carlo programs, one based on the leading-order QCD matrix elements, and the second using a leading-log parton shower approach. Good agreement is observed in these comparisons, whereas predictions of the bare quark-parton model (no QCD) are excluded by the data. A decrease in the resolved forward di-jet rate is also observed as a function of W, in qualitative agreement with perturbative QCD predictions.

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