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ABSTRACT

Measurements of multi-jet production rates in deep-inelastic Muon-Proton scattering at Fermilab-E665 are presented. Jet rates defined by the JADE clustering algorithm are compared to perturbative Quantum Chromodynamics (PQCD) and different Monte Carlo model predictions. The applicability of the jet-parton duality hypothesis is studied. We obtain hadronic jet rates which are approximately a factor of two higher than PQCD predictions at the parton level. Possible causes for this discrepancy are discussed.

1. Introduction

Jet physics, once exclusively studied at e^+e^- and hadron-hadron colliders, has entered a new age with the use of high energy muon-beams at the Tevatron (E665)[1] and, now with even higher center-of-mass energies at the HERA electron-proton collider.[2] Jet production in deep-inelastic lepton-hadron scattering (DIS) can be used to study the fundamental structure (parton distributions) and forces (strong coupling constant, α_s) inside hadrons. PQCD corrections to the DIS Born cross-section include processes which produce several isolated partons. These partons should manifest themselves as multiple jets of hadrons at sufficient enough center-of-mass energies. The production rates for such processes have been calculated to first order in α_s (LO),[3] and more recently to second order α_s^2 (NLO).[4]

A study of events with three jets in the final state, including the proton-remnant jet and two jets from the hard QCD interaction, the so-called (2+1)-jet topology, is reported in this paper. These events are produced, at LO, by gluon bremsstrahlung from the initial and final partonic states and by photon-gluon fusion.

The following standard DIS notation will be used throughout this paper: Q^2 is the negative square of the virtual-photon four-momentum; W is the total hadronic center-of-mass energy and ν is the energy of the virtual-photon in the lab frame.

2. Jet Rates

The E665 collaboration[5] used a muon beam of 490 GeV average energy which struck a 1.15 m long hydrogen target. Charged particles reconstructed in the forward spectrometer and neutral particles reconstructed in the electromagnetic calorimeter are used in this analysis. The event sample is defined by applying the following kinematical cuts: $4.0 \leq Q^2 \leq 25.0(GeV/c)^2$, $\nu > 40GeV$, $x_{Bj} = Q^2/2M\nu > 0.003$ and $0.05 < \nu/E_{Beam} < 0.95$. E_{Beam} is the energy of the beam and M is the mass of the target (proton). Events from coherent photon bremsstrahlung are identified as such if $\nu > 200GeV$ and $E_{Calorimeter}/\nu > 0.035$ and are removed from the sample. A further cut on $W \geq 20GeV$ is applied to reduce the effects of hadronization (as will be discussed later in this paper). A total of 3207 events remain with a narrow distribution about an average x-Bjorken of $< x_{Bj} >= 0.01$. Only particles going forward in the virtual photon-proton center-of-mass system are considered since the forward spectrometer had very small acceptance in the backward center-of-mass direction.

To define the number of jets in an event we use the JADE jet finding algorithm.[6] The JADE algorithm is based on the invariant mass prescription (IMP). Such a prescription has been used in perturbative QCD calculations to overcome soft and collinear singularities present when exclusive final states are defined.[3] The scaled invariant mass for any two particles (partons in PQCD) of the event is used as isolation criterion (test variable). All possible combinations of two-particle invariant masses are required to be greater than a given cut for those particles to be considered as isolated final states, thus restricting the available phase space for the final states.

In the experimental implementation of the algorithm, the test variable is defined as, $y_{ij} = 2E_iE_j(1 - cos\theta_{ij})/(\epsilon W)^2$ and calculated for each pair of hadrons, i and j. $E_{i,j}$ are the particle energies, θ_{ij} the angle between them and ϵ an efficiency factor applied to W defining the energy scale. We have found that using $\epsilon = 0.5$ when applying the algorithm to the raw data minimizes the detector efficiency and acceptance corrections. All quantities are calculated in the virtual photon-proton center-of-mass system. The minimum y_{ij} is compared to the jet resolution parameter, y_{cut}. If $y_{ij}^{min} < y_{cut}$ the two particles four-momenta are added to form a new particle k, such that $p_k^\mu = p_i^\mu + p_j^\mu$. The procedure is repeated until y_{ij}^{min} is larger than or equal to y_{cut}. The resulting combined particles are called jets. All charged particles are assumed to be pions and all neutral particles to be photons. We should notice that the experimental implementation of the IMP is not necessary equivalent to its implementation at the parton level. Hadronization has ocurred and particles have acquired masses and different kinematical characteristics. Several e^+e^- experiments have studied different IMP clustering algorithm schemes,[7] adopting the JADE algorithm as the most suitable for PQCD analysis. For that reason we have chosen the JADE algorithm for this study. Since we only consider forward-going particles, we define the forward n-jet rates, R_{nF}, as the ratios between the number of events with forward n-jets and the total number of events.

A GEANT[8]-based Monte Carlo simulation of our detector is used to correct the data distributions for geometrical acceptance, reconstruction efficiency and resolution. The Lund Monte Carlo (LEPTO 5.2 and JETSET 6.3)[9] is used as the physics generator.

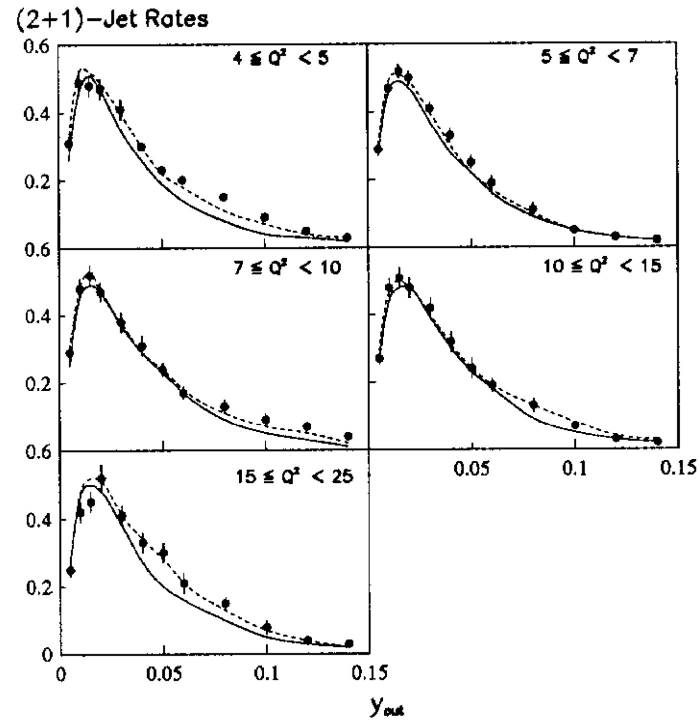

Figure 1: (2+1)-jet rates versus y_{cut}, for five different Q^2 bins. Also shown are the predictions of the Lund (Lepto 5.2) Monte Carlo, Matrix Elements (solid) and Parton Shower (dashed) options.

In both Lund options the default values for the parameters and Morfin & Tung-LO parton distributions[10] are used. Both versions of the Lund generator, matrix elements (ME) and parton showers (PS), are able to reproduce many aspects of the observed data with similarly good accurancy. However, the PS Monte Carlo jet rate predictions agree better with the data; therefore they were used for the corrections. The data distributions were corrected bin by bin using:

$$R_{n+1}^{corrected}(y_{cut}, W) = \frac{R_{n+1}^{MC\ true}}{R_{nF}^{MC\ recon}} R_{nF}^{data}(y_{cut}, W)$$

where $R_{n+1}^{MC\ true}$ was obtained applying the JADE algorithm with $\epsilon = 1.0$ to all primary hadrons generated by the Monte Carlo and $R_{nF}^{MC\ recon}$, the rate of n forward jets, was obtained from Monte Carlo generated events subjected to the identical analysis as to the data. Therefore, the final results are corrected also for the choice of scale at the observed level and are presented for $\epsilon = 1.0$.

We estimate the systematic uncertainties 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 values of ϵ between 0.3 and 1, and have found that the final corrected jet rate values (using $\epsilon = 1.0$) are very stable, at the ± 0.015 level. We estimate the uncertainty in the acceptance corrections coming from the physics generator used within the Monte Carlo by comparing the corrected rates using the ME and the PS options of the Lund Model. The differences in the resultant rates are Q^2 dependent but are always less than 0.02. The combined systematic uncertanties are estimated by adding the model dependent uncertainties to the sum in quadrature of all the others. This total systematic uncertainty is always less than $\Delta R_{(2+1)} = 0.03$.

Figure 1 shows the (2+1)-jet rates at the hadronic level, corrected by geometrical acceptance, reconstruction efficiency and resolution, versus y_{cut}, for five different Q^2 bins. Also shown are the predictions of the Lund ME and PS Monte Carlos. Good agreement is observed with the QCD based models at the hadronic level. Error bars represent only statistical errors (assumed to be binomial). We should notice that default parameters were used in both Monte Carlo models, tuned to exclusive hadronic distributions of DIS data in previous experiments at lower energies.[11]

3. Comparison with PQCD and Monte Carlo Models

Before attempting the extraction of any PQCD information (as, for example, α_s or the gluon distribution), the next step in the analysis is to establish a relation between properties of the observed jets and the partons. The so called, local parton-hadron duality (LPHD)[12] bridges over the hadronization process establishing, at least on average, that the properties of hadrons and partons are the same. To study PQCD through jet rates we will need to establish, more specifically, that the average numbers of jets and partons are equivalent, what we will call a jet-parton duality (JPD).

Figure 2.a shows the (2+1)-jet rates from E665 data at the hadron level versus Q^2 for a value of $y_{cut} = 0.04$. Also shown are the predictions of the (2+1)-jet rates at the partonic level from different options of the Lepto 6.1 Monte Carlo,[13] using MRS(D^-) parton distributions.[14] We observe that the data jet rates obtained at the hadronic level are a factor of two higher than the Lund-Matrix Element predictions obtained at the parton level.

Figure 2.b shows the same (2+1)-jet rates from E665 data at the hadronic

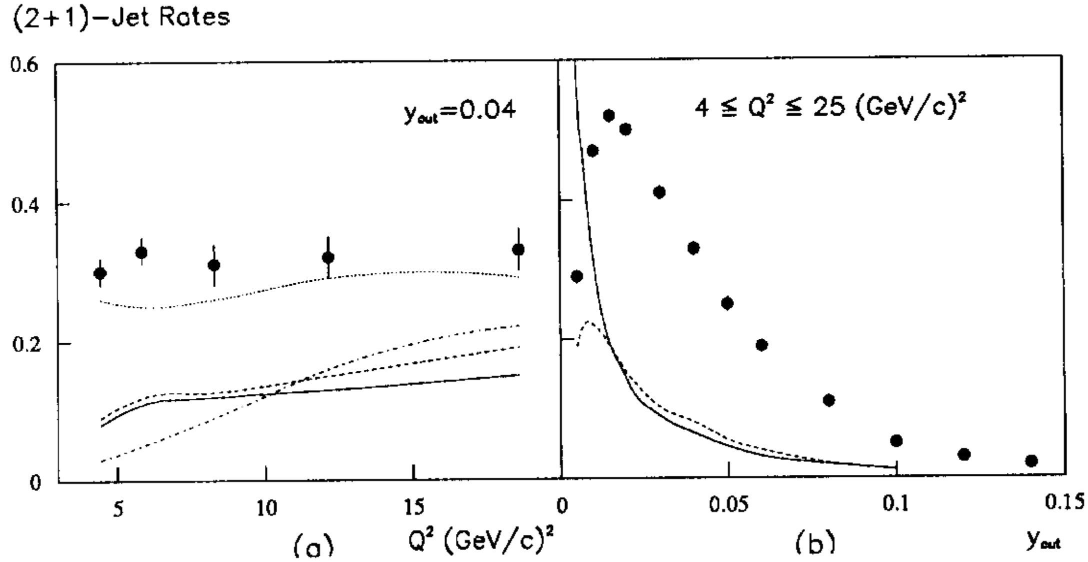

Figure 2: a) (2+1)-jet rates, at the hadron level, versus Q^2, for $y_{cut} = 0.04$. Also shown are the predictions, at the parton level, from various Lepto 6.1 Monte Carlo options: Matrix Elements (ME) (solid), Parton Shower (PS) with default maximum virtuality (dotted-dashed), ME+PS (dashed) and PS with W^2 as maximum virtuality (dotted). b) (2+1)-jet rates, at the hadron level, versus y_{cut}. Also shown are the PQCD predictions at the LO (solid) and NLO (dashed).[4]

level versus y_{cut}, for all Q^2. Also shown are the predictions of the (2+1)-jet rates from PQCD at the LO and next-to-leading order (NLO) (where only the transverse polarization of the photon is considered).[4] The (2+1)-jet hadronic data rates are also a factor of two higher than PQCD predictions. We have checked that the PQCD-LO predictions of references [3], [4] and the Lepto-Matrix Elements (after removing the effects for finite parton masses, intrinsic transverse momenta (k_T) and the recoiling remnant) all agree. We conclude that, using the JADE algorithm definition of jets, jet-parton duality is not observed in the jet rates.

We should notice that these results contradict expectations for DIS that could be extracted from e^+e^- results. Running at similar center-of-mass energies, experiments at PETRA[15] and PEP[16] observed that three jet rates at the hadronic level defined by the JADE algorithm agree quite well with PQCD-NLO predictions. Therefore, they were able to establish a working JPD for e^+e^- jet physics. We should also notice that former DIS experiments[17] have shown a good agreement between DIS and e^+e^- hadronic final state properties.

There are several possibilities why JPD using the JADE algorithm is not observed in these DIS data. We have investigated several of them. First, we checked if, at our energies, hadronization is still the prevalent factor for the topological structure of the event. Early studies at lower energies[11] and previous studies with our same data set[18] already have indicated a clear signal for PQCD topological characteristics in DIS data.

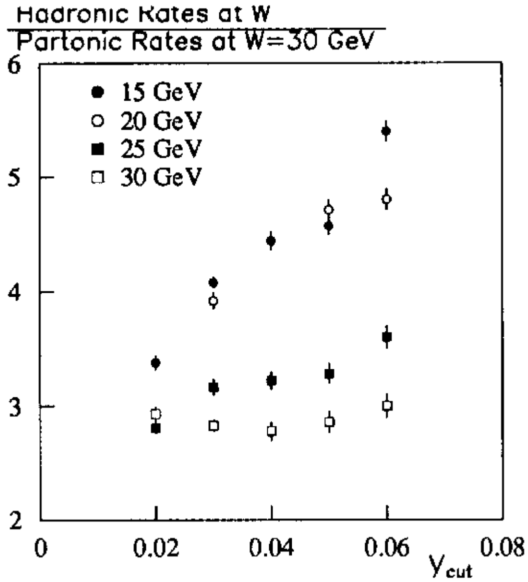

Figure 3: Ratios between data (2+1)-hadronic jet rates obtained at different energies (W) and partonic jet rates at W = 30 GeV versus y_{cut}.

Figure 3 shows the data (2+1)-jet rates at the hadronic level, for W= 15, 20, 25 and 30 GeV divided by the Lund 5.2-ME partonic rates at 30 GeV, versus y_{cut}. As in the case of e^+e^-,[15] at LO we can write: $R^{partons}_{(2+1)} = C(y_{cut}) \cdot \alpha_s$. In DIS there is a dependence on $W(Q^2)$ in the coefficient C, however we have found that it is very small. Therefore, the partonic ratios of rates at two different center-of-mass energies are independent of y_{cut} (the C's cancel). A dependence on y_{cut} in the ratios shown in figure 3 would be an indication that non-perturbative effects (hadronization) are present in the data. The data ratios only show a weak dependence on y_{cut} for center-of-mass energies greater than $W \cong 20GeV$ (remarkably similar to the e^+e^- values shown in reference [15]). That is why a cut on $W \geq 20\ GeV$ was made in the final data sample.

The departure from JPD could also arise from problems in the PQCD predictions. There are several unknowns in these calculations - the parton distributions, the value of Λ_{QCD} and an uncertainty on which scale to use in the perturbative expansions. We find that it would be necessary to modify the parton distributions and/or the value of Λ_{QCD} far beyond what has already been measured in our kinematical regime to account for the difference. Recent calculations by D. Graudenz[4] show that higher order corrections and scale dependences also can not reconcile the factor of two discrepancy observed on the rates.

Another possibility is that the JADE clustering algorithm at the hadronic level is not equivalent to the use of the IMP in the PQCD calculations. Several authors have already pointed out problems with the JADE clustering algorithm in e^+e^- physics.[19] These problems involve, in general, the fact that the final results depends upon the order in which the clustering is performed. These difficulties are accentuated when soft hadrons produced at wide angles are present in the event. The JADE clustering starts with the softer particles which are not present in truncated QCD perturbative expansions but are present in the observed hadrons. In our case, these problems result in the misidentification of real (1+1) events as (2+1) events and viceversa. At $y_{cut} = 0.04$, real (1+1) events are misidentified as (2+1) at the 20% level. This is enough to account for much of the roughly factor of two between (2+1) partonic and hadronic jet rates (the misidentification levels decrease with increasing y_{cut}). There are also other technical issues involving factorization using IMP techniques, as discussed in reference [19], that we will not address here. At present, we are studying different modifications of the JADE algorithm and various kinematical cuts on the jet and/or hadron phase spaces with the hope of improving the jet-parton duality.

Recently, we completed a study using E_T^2 (squared transverse energy of the jets) to weight the jet rates.[20] This variable seems to be less sensitive to the misidentification of events, and thus a much better JPD is observed allowing for the extraction of PQCD information. This study points to the possibility of using a clustering algorithm based on the relative transverse momenta instead of the invariant masses. The k_T algorithm, already sucessfully used in e^+e^-,[21] uses such a prescription. This algorithm has been extended to DIS[22] and results from PQCD calculations and application to the data are expected in the near future.

4. Conclusions

E665 has measured multi-jet rates defined by the JADE clustering algorithm at center-of-mass energies from 20 to 35 GeV. Hadronization effects in that sample are shown not to be prevalent. Monte Carlo models tuned to reproduce hadronic exclusive DIS properties reproduce several aspects of the data, including the observed jet rates at the hadronic level, quite well. Comparing hadronic jet rates with Monte Carlo (Matrix Elements) predictions at the partonic level and with LO and NLO perturbative QCD calculations, we observe that the hadronic jet rates are a factor of two higher than the predictions.

We have studied several possibilities that can create this discrepancy. We have found that the discrepancy is mostly due to the high sensitivity of the JADE clustering algorithm to the softer particles in the event. Soft hadrons at wide angles are expected to be produced in DIS by initial state gluon radiation and a more complicated hadronization of the proton remnant, making the JADE clustering more troublesome in DIS than in e^+e^- physics. Therefore, we find that the JADE clustering algorithm is not very efficient for the identification of perturbative jets in this DIS energy regime (about 60% for the (2+1)-jet events).

We are studying modifications of the JADE algorithm, various kinematical cuts on the jet and/or hadron phase spaces and the use of different algorithms based on other prescriptions (i.e., the relative transverse momenta) to try to improve the jet-parton duality for jet rates. Only after this duality is established, will we be able to extract PQCD information from jet rates.

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