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JETS IN DEEP INELASTIC SCATTERING

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ABSTRACT

The recent results of jet production in Deep Inelastic Scattering experiments are breifly reviewed.

QCD in DIS and Models

Quantum Chromodynamics (QCD) has been well tested in Deep Inelastic Scattering (DIS) experiments since the first measurement of QCD effects in the hadronic final states[1]. In a DIS Neutral Current event the incident lepton is scattered with high momemtum transfer to the one of the partons within the proton. The struck quark is subsequently hadronized in the non-perturbative regime. Partons can be reconstructed explicitly from measured hadrons in the form of jets via jet identification methods which have been developed in variety of manners for the last decade. The subsequent measurement of multi-jet production allows the quantitative test of QCD. Many important characteristics of QCD have been revealed successfully in e^+e^-[2].

Jet analyses have been carried out very recently in DIS from a fixed target experiment, E665[3]. Here a 490 GeV muon beam interacts with a liquid hydrogen target. The measurement of jet production is made with hadronic invariant masses up to 30 GeV and maximum momentum transfer squared of 25 GeV^2.

In 1992 the electron proton collider HERA, as a new machine of its kind, opened a new domain of kinematics in DIS. It is operating successfully, providing a specific luminosity at the design value. A large increase in energy is possible by colliding beams of 26.7 GeV electrons and 820 GeV protons. This allows invariant masses of the hadronic system larger than previous DIS experiments by an order of magnitude, thereby produces much cleaner jet structures, with a broad range of momentum transfer. The first results of the hadronic final state distributions from H1 and ZEUS are reported in [4, 5]. The presented data are based on luminosities of 23.5 and 25.0 nb^{-1}, respectively, both acquired during the 1992 data-taking period. The data spans Q^2 to a few hundred GeV^2 and x down to 10^{-4} with an average hadronic invariant mass of about 100 GeV.

In zeroth order QCD, equivalent to the naive quark parton model (QPM), a scattered quark leads to a 1+1 jet configuration where the target remnant is denoted by +1. The classical spectrum of p_t of the hadrons in the rest frame of the virtual boson and proton shows that the large excess of high p_t^2 cannot be explained by QPM unless it is corrected by QCD taking into account gluon emission[4, 6].

There are two main approaches in perturbative QCD: the finite order exact matrix element (ME)[7, 8]; and, the leading logarithmic approximation often called parton shower (PS)[9]. In QCD Compton processes the gluon can be emitted from the quark leg either before or after the interaction. This contrasts with e^+e^- where no initial state gluon radiation exists. The other order-α_s diagram is boson gluon fusion where a gluon-initiated process yields 2+1 jets. In the parton shower model soft gluons are simulated beyond first order α_s and therefore any number of partons can be produced[10, 11]. The amount of gluon emission is determined by the maximum starting virtuality scale which is not unique in DIS. Q^2, W^2, or any combinations of these scales is a possible choice. In this paper the choice of the virtuality scale will be quoted inside parenthesis. As an alternative to the parton shower, the color dipole model (CDM) describes gluon emission in a chain of radiating color dipoles connected between the struck quark and the proton remnant[12]. The O(α_s) ME and PS can be combined to cover regions which each model alone does not describe well. This model is referred to as MEPS[13].

Hadronic Final State Distributions

H1 performed the first analysis of the hadronic final state distributions based on 1.6 nb^{-1} of data taken during the first running period of HERA. The E_t weighted azimuthal angle distribution of the hadronic system is measured relative to the scattered electron in the laboratory system. The angle would be 180 degrees if in the struck quark direction. As shown in figure 1, the data is in good agreement with the MEPS model, however the PS model with scale $W^2(Q^2)$ gives too much(little) transverse energy flow away from the struck quark direction.

*Talk presented at International Europhysics Conference on High Energy Physics, Marseille, France, 22-28 1993.

The energy flow is measured by ZEUS in terms of the difference in pseudorapidity defined between the struck quark direction calculated from the measured QPM kinematics and the observed hadrons. At low x the struck quark is emitted in the opposite direction to the proton remnant so that the rapidity separation between the current jet and the proton remnant is large. A clear two peak structure is observed in the energy weighted pseudorapidity distribution relative to the struck quark for events with $x < 10^{-3}$ and $Q^2 > 10$ GeV^2 (figure 2). Small $\Delta\eta$ represent hadrons close to the struck quark, while large values correspond to the proton remnant. The peak is slightly shifted away from zero (the QPM direction) towards the proton remnant due to gluon radiation. The data is also compared to various QCD based models. None of the models describe the data completely, but MEPS agrees with the overall trends.

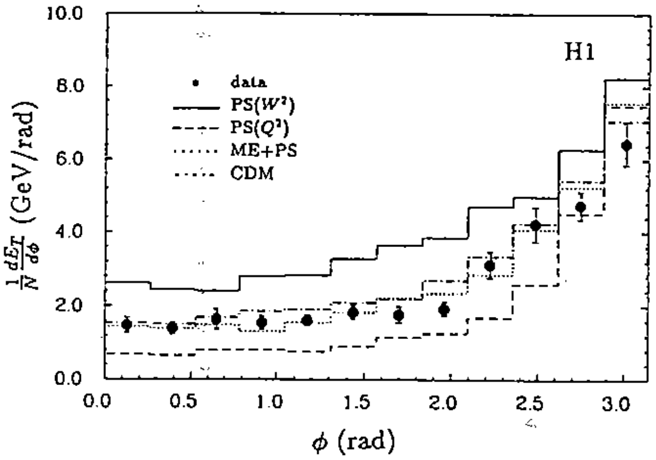

Figure 1: The H1 transverse energy flow in the laboratory frame as a function of azimuthal angle ϕ with respect to the scattered electron direction in the plane transverse to the beam direction.

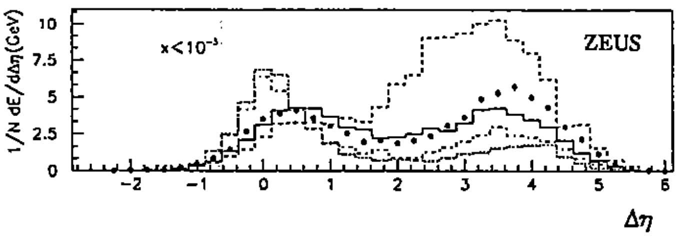

Figure 2: The energy weighted pseudorapidity difference $\Delta\eta$ of the hadronic system with respect to the struck quark from the quark-parton model. The ZEUS data ($x < 10^{-3}$) points are shown as the dots. The full histogram is MEPS, the dashed PS(W^2), the dotted PS(Q^2), the dash-dotted ME($O(\alpha_s)$).

Jet Production in DIS

Higher order QCD effects can be directly measured by analysing multi-jet events. The relative jet production rates is insensitive to the overall normalization errors in the total cross section measurement. The JADE algorithm successfully used in e^+e^-[14] is found to be suitable in DIS. The algorithm works in a Lorentz invariant way, allowing the experimental measurements to be made in the laboratory frame. Other algorithms[15] may require measurements in frames other than the laboratory frame which is not so straightforward in the early stages of HERA jet analyses.

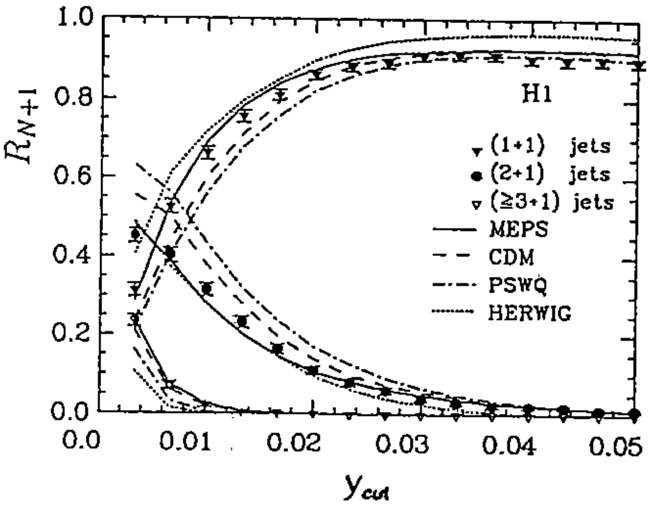

Figure 3: H1 multi-jet production rates as a function of y_{cut} for events with $x > 10^{-4}$, $Q^2 < 80$ GeV^2.

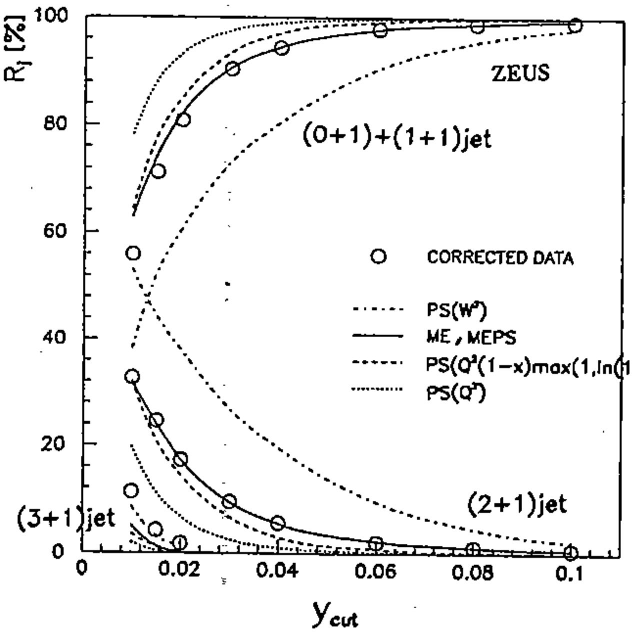

Figure 4: ZEUS multi-jet production rates as a function of y_{cut} for events with $x > 10^{-3}$ and $Q^2 > 10$ GeV^2.

Another practical advantage of the JADE scheme is that the theoretical calculations are avaliable up to the next to leading order(NLO)[8]. In this algorithm the distance measure between two adjacent particles, y_{ij}, is defined as the invariant mass* scaled by a reference mass scale typically chosen to be W^2 in DIS. Measured

*The mass of particles is neglected.

hadrons are clustered iteratively until the smallest y_{ij} for all pairs of clusters exceeds an arbitrary parameter y_{cut}. Therefore, jets are defined in terms of y_{cut}, which is analogous to the QCD theoretical cutoff which must be introduced to define the finite jet cross sections.

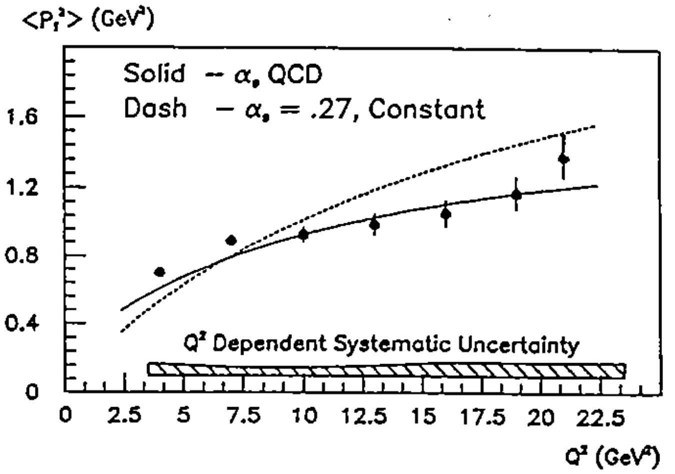

Figure 5: The average p_t^2 of jets identifed by the JADE algorithm as a function of Q^2. The solid line is the calculation of $< p_t^2 >$ using a running α_s, the dotted line uses a constant α_s.

The rate of 2+1 jets is measured as function of the jet resolution parameter y_{cut} by E665 in the hadronic invariant mass range from 15 to 30 GeV[3]. At HERA the jet structure of the final state is much cleaner and is studied in a wide range of kinematics. However, many hadrons are strongly boosted in the proton remnant direction which is not completely measured due to the presence of the beam pipe. Therefore, the JADE algorithm is slightly modified at HERA to minimize the effect of the beam pipe, where a first step is to calculate the missing longitudinal momentum, creating a pseudo-particle. This emulates the unmeasured component of the proton remnant which allows the measured component to be correctly assigned.

Figure 3 shows the uncorrected jet production rates of H1 as a function of y_{cut}. The ZEUS data, corrected for detector acceptance and the effect of initial state photon radiation, is illustrated in figure 4. Only statistical errors are shown in the plots. The correction factor from the detector to the hadron level depends on y_{cut} and varies from 5% to 20%. The difference between the hadron and parton level is below 10% in most of the kinematical regions for the presented analysis. The 2+1 jet rate increases with finer jet resolution (smaller y_{cut}). The LEPTO MEPS model fits the data but the PS models do not. The ME model reproduces the data up to 2+1 jet equally well, implying that hard gluon emission is required, which is consistent with e^+e^-. However, the HERWIG program with PS scale Q^2 also describes the data.

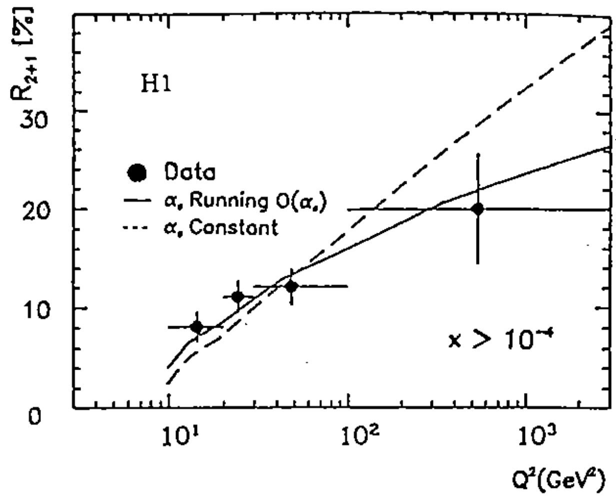

Figure 6: The Q^2 dependence of the H1 2+1 jet rate at $y_{cut} = 0.02$, integrated over x larger than 10^{-4}, in comparison with the MEPS model with a running α_s (solid line) and a constant α_s (dotted line). The error bars correspond only to the statistical errors of data.

Test of Non-Abelian theory

The most distinct feature of QCD is its non-Abelian nature which introduces the running of α_s with Q^2 and the existence of the triple gluon vertex. These characteristics have been tested extensively from the study of multi-jet production in e^+e^-[2]. Very recently E665 has shown evidence of the running of α_s in a single experiment. The average transverse momentum squared, p_t^2, of jets reconstructed by the JADE algorithm at $y_{cut} = 0.04$ is shown in figure 5 as a function of Q^2. Data is in good agreement with the running of α_s, while the hypothetical model of constant α_s cannot fit the data. The average p_t^2 is related to α_s and thus allows the extraction of a leading-order α_s value at each Q^2 point[16].

The Q^2 dependence of the 2+1 jet rate for $y_{cut} = 0.02$ is shown in figures 6 and 7 for (uncorrected) H1 and (corrected) ZEUS data, respectively. The correction for the ZEUS data now includes hadronization effects. The increasing 2+1 jet rate as a function of Q^2 measured by H1 reflects the fact that the selected event kinematics are not fixed in x. The ZEUS data is corrected up to the partonic level and thus is capable of being compared to the theoretical calculation in a direct way. Moreover, the narrow window in x is chosen at the expense of statistics in order to have the 2+1 jet rate behave in the same way as $\alpha_s(Q^2)$ (decreasing with increasing Q^2).

In both experiments the curve with a running coupling constant gives a slightly better description of the data. However it is hard to draw any conclusion from the present statistics. This year's large data samples

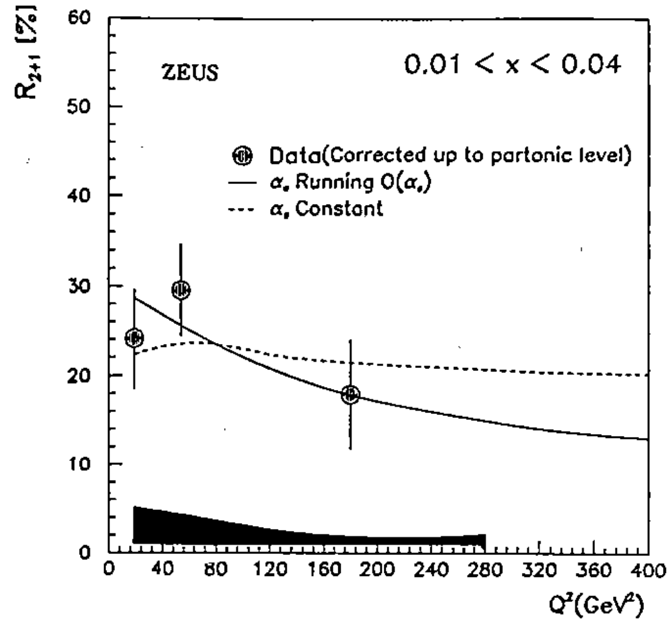

Figure 7: The Q^2 dependence of the ZEUS 2+1 jet rate, with fixed kinematics ($0.01 < x < 0.04$), in comparison with the leading-order calculation with a running α_s (solid line) and a constant α_s (dotted line). The systematic errors are estimated and shown at the bottom of the plot.

will allow this important feature of QCD to be tested. Finally, it is useful to note that the corrections from the next-to-leading order calculations are small, at the level of 5%, if y_{cut} is chosen above 0.02 at HERA[17].

Conclusion

E665 has shown evidence of running of α_s in the range of Q^2 between 3 GeV^2 and 25 GeV^2, in a single experiment. The studies of multi-jet production from H1 and ZEUS in a new domain of kinematics will provide a unique opportunity to test QCD by expanding Q^2 up to approximately 10^5 GeV^2. Various QCD based models have been tested in terms of the final state distributions and jet production rates. Systematic errors are found to be under control and second-order calculations are available.

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