Hadronic final states at HERA

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Recent results are reviewed in hadronic final states obtained by the H1 and ZEUS collaborations at HERA. Concentrating on DIS processes, we examine properties of fragmentation and jet production.

1. INTRODUCTION

The HERA Collider at DESY collides 27.5 GeV electrons or positrons with 920 GeV protons. The virtuality Q^2 of the exchanged virtual photon varies from extremely small values up to values of many GeV^2 that provide Deep Inelastic Scattering (DIS), the subject of this review. Many aspects of QCD have been studied over the years by the H1 and ZEUS collaborations. Recent results have built upon and extended this physics programme, and here we survey some of the past year's studies of hadronic final states formed in HERA DIS collisions.

1.1. Charged multiplicities

The DIS Breit Frame is defined such that in the simplest (Born-level) processes, an incoming quark in the proton has its direction reversed on absorbing the exchanged boson, emerging as a jet whose properties should resemble those of jets in e^+e^- collisions. This kinematic region of the hadronic final state is referred to as the current region, while the rest of the event, containing the proton remnant, is known as the target region.

ZEUS have extended their studies of charged particle multiplicities in the Breit Frame, making comparisons with results from other types of collider experiment. To define the kinematic region under study, cuts are made on scattered electron energy E', transverse track momentum p_T and track pseudorapidity η. The multiplicity rises with energy scale, but the presence of higher-order QCD processes means that the choice of energy scale may affect the comparison with other experiments. Agreement is good if the energy of the current jet or the total centre of mass energy is used (fig. 1). ZEUS find reasonable agreement the theoretical models ARIADNE (colour dipole model) and LEPTO, both of which use Lund type colour strings for fragmentation, ARIADNE giving a better description. These results support a universal mechanism for fragmentation.

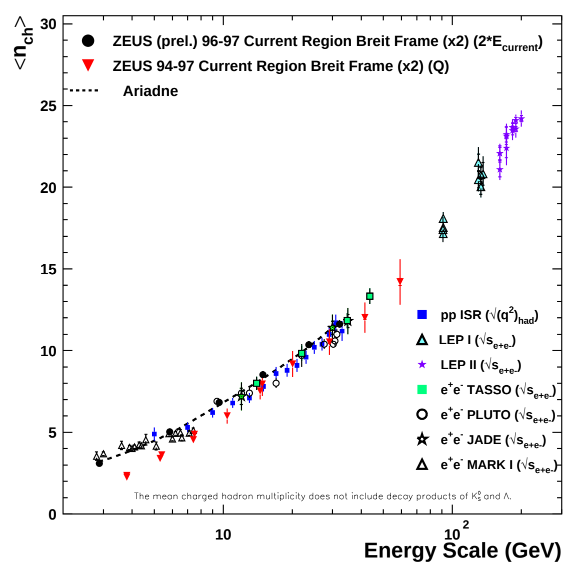

Figure 1. ZEUS measurements of mean charged multiplicity compared with other experiments. ZEUS selections: $E' > 12$ GeV, p_T of tracks > 150 MeV, $\eta_{\rm lab} > 1.75$.

1.2. Neutral strange particles in DIS

A different type of fragmentation study has been performed by ZEUS in measuring the properties of K^0 and Λ particles produced in DIS jets with $Q^2 > 25$ GeV^2 in a central laboratory rapidity range. Preliminary results indicate that the cross sections for these particles are well described by the ARIADNE model. As part of the investigation, the polarisation of the Λ is being studied. Two polarisation measures are available, each given by the coefficient P in the formula $dN/d\Omega = (1 \pm \alpha P \cos\theta)/4\pi$.
The longitudinal and transverse polarisations define θ, respectively, as the angle between the proton and the Λ, and the angle between the proton and the plane of the electron and the Λ. ZEUS measure these quantities in the laboratory frame, detecting the K^0 in its $\pi^+\pi^-$ decay and the Λ in its $p\pi^+$ decay, and charge conjugate.

Within uncertainties of approximately 5-10%, the polarisations are consistent with zero. Studies will be continued in the Breit Frame.

2. JETS IN DIS

The Breit Frame provides an convenient basis for measuring many jet cross sections. At the Born level, in this frame, the recoil jet simply moves along the $-z$ axis. However in higher level processes, jets can appear at finite values of p_T, and in these hard QCD processes there are important dependences on the value of the strong coupling α_s. Jets are identified at HERA by means of the longitudinally-invariant k_T cluster algorithm. The dominant experimental systematic uncertainty arises from the measured jet energy scale.

2.1. Inclusive jet cross sections

ZEUS have continued to study inclusive jets in order to achieve improved measurements of α_s. Jets are reconstructed here from the signals from the ZEUS uranium-scintillator calorimeter. Good agreement is obtained between the shapes of the experimental jet cross sections, measured as a function of Q^2, jet E_T and η, and the NLO theoretical calculation of DISENT. On this basis, the value of α_s can be tuned to give optimum quantitative matching between experiment and theory. There is a theory uncertainty due to the parton structure of the proton, and also a QCD renormalisation scale uncertainty. Results are shown in fig. 2, showing the running of α_s with jet E_T. The cross sections as a function of Q^2 give the most accurate result for $\alpha_S(M_Z)$, namely:

$0.1201 \pm 0.0006\ \text{(stat)}\ ^{+0.0033}_{-0.0038}\ \text{(exp)}\ ^{+0.0049}_{-0.0032}\ \text{(th)}.$

This is in good agreement with the world average of 0.1187 ± 0.0020, and with competitive errors compared to other methods.

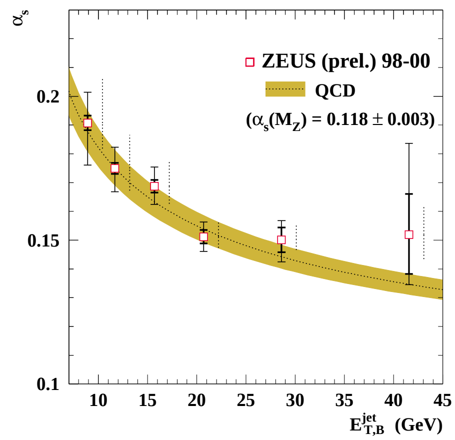

Figure 2. Value of $\alpha_s(M_z)$ as function of jet E_T from ZEUS. Main selections: $Q^2 > 125$ GeV^2, $-0.7 < \cos\gamma < 0.5$ where γ = angle of LO emerging parton; $-2 < \eta < 1.8$ and $E_T > 8$ GeV for jet in Breit Frame.

2.2. Multi-jet cross sections

Both HERA collider experiments have measured cross sections for two- and three-jet production in DIS. The ratio of the three- to two-jet cross sections provides a direct measurement of α_S. Results are compared with the calculation of NLOJET. The variation of the proton PDF's with α_S must be taken into account. Again, good results for α_S are obtained using this method. H1 and ZEUS respectively find values of:

$0.1175 \pm 0.0017\text{(stat)} \pm 0.0050\text{(sys)}^{+0.0054}_{-0.0068}\text{(th)},$

and

$0.1179 \pm 0.0013\ \text{(stat)}^{+0.0028}_{-0.0046}\ \text{(exp)}\ ^{+0.0064}_{-0.0046}\ \text{(th)}.$

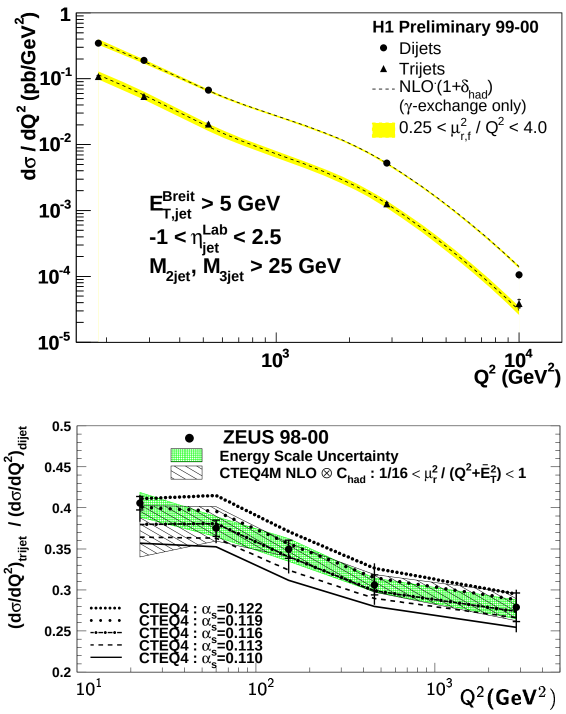

Figure 3. Upper: two- and three-jet cross sections in DIS from H1. Selections are shown on the plot. Lower: Three/two jet ratio from ZEUS [1].

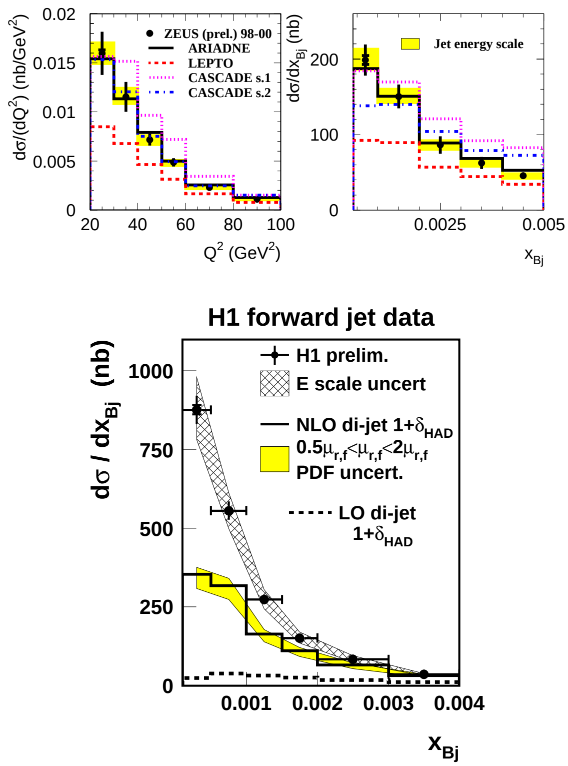

Figure 4. Upper: forward jet cross sections in ZEUS compared with theoretical expectations. Lower: H1 [2], compared with DISENT.

2.3. Forward jet production

The QCD calculations in the above results have been done on the basis of the DGLAP method for evolving cross sections as a function of Q^2. A different type of QCD dynamics is expected to be apparent when processes at fixed Q^2 are evolved as a function of x_{Bj}, namely BFKL processes. H1 and ZEUS have sought evidence for these by measuring jets in the forward (proton) direction with $E_{\rm jet}/E_p \gg x_{Bj}$ and $P_T^2 \approx Q^2$. Both experiments select on $E' > 10$ GeV, with Q^2 ranges of 5-85 (H1) and 20-100 (ZEUS) GeV^2, DIS y ranges of 0.1-0.7 (H1) and 0.4-0.7 (ZEUS) and jet $E_T > 3.5$ GeV (H1) and > 5 GeV (ZEUS). H1 measure down to lower x_{Bj} than ZEUS.

DGLAP evolution is incorporated in LEPTO and the NLO programs NLOJET and DISENT. ARIADNE contains the colour dipole model, while the CCFM model, combining BFKL and DGLAP, forms the basis of the CASCADE Monte Carlo. The goal is to find consistent deviations from the DGLAP calculations which BFKL can accommodate. ZEUS (fig. 4, upper plots) find agreement with ARIADNE and CASCADE, though not with LEPTO, and also agreement with DISENT because of the very large renormalisation uncertainties involved with this calculation. H1 obtain similar results (fig. 4), but see a clear disagreement with DISENT, which is not fully accounted for by the lower x_{Bj} values attained. Thus there appears to be a disagreement between the experiments in their evaluation of the DISENT results. It is not possible, meanwhile, to claim that the BFKL process has been unambiguously observed.

H1 also measure the rapidity separation $\Delta\eta_2$ between the forward jet and the next-forward jet when an additional jet pair is observed. This

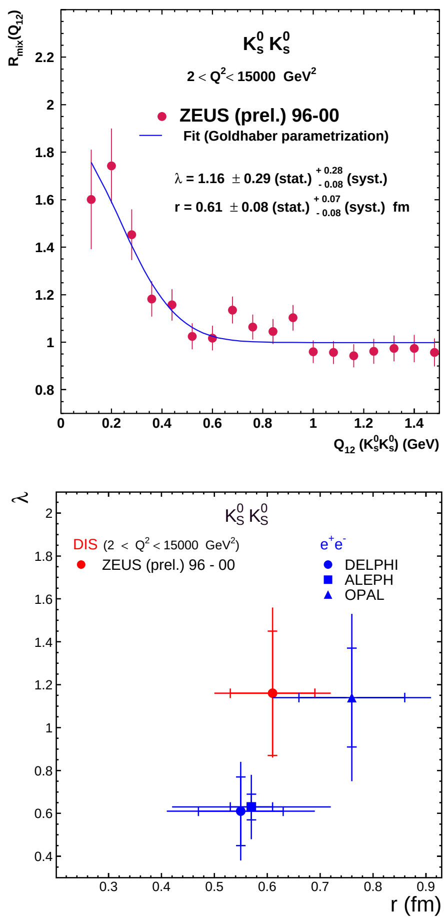

Figure 5. Upper: Bose-Einstein correlation function $R(Q^2)$ measured by ZEUS for neutral kaon pairs (upper) and the fitted parameters r and λ compared with other experiments (lower)

should enable a separation to be made between BFKL and resolved photoproduction processes. The NLOJET model gives a mixed agreement with the data, CASCADE gives poor agreement, while ARIADNE gives good general agreement. H1 conclude that increased transverse momentum ordering beyond DGLAP is required.

3. BOSE-EINSTEIN CORRELATIONS

The two-particle correlation function in multi-particle states is defined as

$$R(Q_{12}) = \frac{P(Q_{12})^{\text{Data}}}{P_{\text{mix}}(Q_{12})^{\text{Data}}} \Big/ \frac{P(Q_{12})^{\text{MC,noBEC}}}{P_{\text{mix}}(Q_{12})^{\text{MC,noBEC}}}$$

where Q_{12} is the 4-momentum difference and P is the probability density in Q_{12}, calculated for pairs of identical particles in the same and in different events ("mix"). Bose-Einstein correlation predicts a low-Q_{12} enhancement in R; this can be fitted in terms of the Goldhaber expression

$$R(Q^2) = \alpha \left(1 + \lambda e^{-Q_{12}^2 r^2}\right),$$

neglecting long-range effects: α = normalisation factor, r = radius of source, λ = strength term.

Following their studies with pion pairs, ZEUS have measured these quantities in DIS for charged and neutral kaon pairs. Results for the latter are shown in fig. 5, and demonstrate a prominent correlation effect whose r and λ parameters are in reasonable agreement with those from other experiments. For the charged kaons, a smaller effect is seen, with λ around 0.4 of the value from DELPHI and OPAL. The difference is being investigated by ZEUS, with a suggested reason being the effects of resonances.

4. CONCLUSIONS

A large number of QCD-based studies have been made possible by the high energies achieved at HERA-I. This talk has concentrated on the DIS regime, focussing on processes involving light quarks, but even this restricted set of processes provides a very wide range of physics. Measurements of α_s have been carried out using different methods, and a number of aspects of fragmentation have been examined.

The higher luminosities of the upgraded HERA-II collider will make more progress possible. Meanwhile, since in many cases the theoretical uncertainties dominate the present results, the motivation is strong for our theorist colleagues to advance further the calculations and techniques that they have so excellently made available so far.

REFERENCES

1. ZEUS Collaboration, hep-ex/0502007
2. H1 Collaboration, hep-ex/0508055