Multiplicity and momentum distributions of hadrons in deep inelastic scattering at HERA energies

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The universality and scaling behaviour of hadronisation have been investigated in semi-inclusive neutral current deep inelastic *ep* scattering; specifically the multiplicity and scaled momentum spectra of charged hadrons have been measured and analysed. The measurements are performed in the current region of the Breit frame, as well as in the current fragmentation region of the hadronic centre-of-mass frame. The data collected at the HERA ep collider by the H1 and ZEUS experiments are compared with similar measurements obtained in e^+e^- annihilation and with previous *ep* measurements as well as with leading-logarithm parton-shower predictions.

1. INTRODUCTION

The study of parton fragmentation and hadronisation processes provides valuable insight into the non-perturbative regime of Quantum Chromodynamics (QCD). These processes are studied by the H1 and ZEUS Collaborations at HERA energies (about 300 GeV in the *ep* centre-of-mass frame) using the semi-inclusive charged particles produced in neutral current deep inelastic scattering (DIS). Two quantities describe the properties of hadron production: the invariant mass of the hadronic system W and the virtuality Q^2 of the exchanged boson. The best way to study hadronisation is to look from the point of view of the exchanged boson colliding with the incoming proton. In their centre-of-mass frame, called also the hadronic centre-of-mass frame (HCM), half of energy, $W/2$, is carried out by particles which have absorbed the boson and the other half by particles from the proton remnant. Naïvely one would expect particle production in the proton remnant region to be similar to particle production in *pp* collision. Among the particles which have absorbed the exchanged boson, a part of them is expected to have similar features to the ones observed in one hemisphere of e^+e^- annihilation. The separation is easily done in the Breit frame. In this frame the exchanged boson of $Q/2$ energy is absorbed by the scattered quark which converts into particles in the region called the current region of the Breit frame. Thus, depending on the rapidity of the emitted hadron its feature can be similar either to the one produced in e^+e^- annihilation or in *pp* collision. There is a region of rapidity in between the origin of the Breit frame and the HCM frame, called the central region, which is unique in its feature for *ep* scattering. This region is dominated by gluon emission. In asymmetric collisions such as *ep* scattering leakage between regions modifies this simplified picture.

The current region of the Breit frame is populated mainly by hadrons coming from the zero-order QCD process $\gamma q \rightarrow q$ and the first-order QCD process $\gamma q \rightarrow gq$. The other first-order QCD process is the boson-gluon fusion (BGF) $\gamma g \rightarrow q\bar{q}$ with hadrons populating the edge of the current and central region. This process with its higher orders as well as the initial state gluon radiation do not contribute to hadron production in e^+e^- and are the main source of differences between hadron features in e^+e^- and *ep*. The depopulation of the current region depends on Q^2.

In this short review fragmentation features in *ep* scattering are presented in form of the scaled momentum distributions measured in the current region of the Breit frame [1, 2] and of the average charged multiplicities [1, 3]. The sensitivity to the energy scale definition is discussed for scales given by Q, W and a sum of the emitted energies. The data are compared with predictions from Monte Carlo (MC) event generators. Two models, ARIADNE 4.12 [5] and LEPTO-MEPS 6.5.1 [6], are considered to describe the DIS processes. In ARIADNE the parton cascade is modelled with the colour-dipole model whereas LEPTO incorporates the leading-order matrix element with some next-to-leading (NLO) correction implemented in the parton shower. A soft colour interaction model (SCI) implemented in LEPTO is also considered. For these event generators, hadronisation is performed by the Lund string model [7]. In addition HERWIG is discussed due to its cluster hadronisation model [8] although this model did not describe similar data in the past.

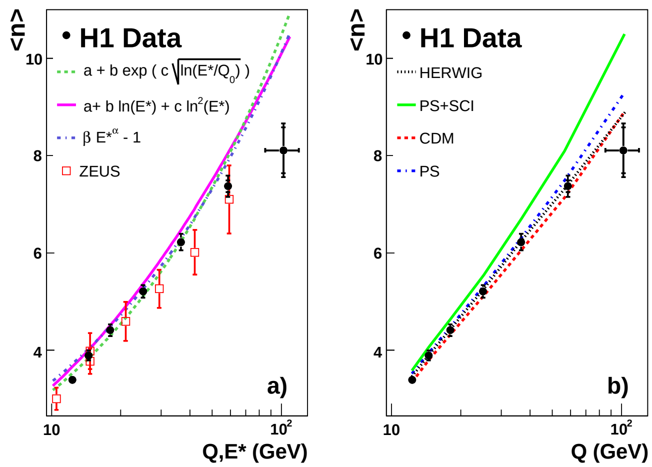

Figure 1: The average charged multiplicity $\langle n \rangle$ as a function of Q for DIS is compared with a parameterisation of the e^+e^- data [9] (left) and with MC predictions (right).

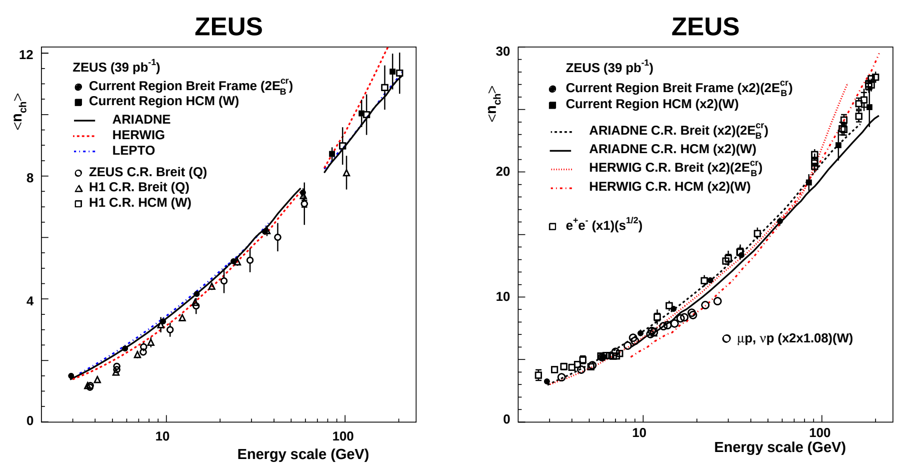

Figure 2: The average charged multiplicity $\langle n_{\rm ch} \rangle$ as a function of $2 * E_B^{cr}$ and W respectively for the Breit and HCM frames. Left: compared with the scale defined by Q and with MC predictions. Right: multiplied by 2 compared with the measurements from e^+e^- [9] and the fixed target experiments as well as with MC predictions.

2. MULTIPLICITY OF CHARGED HADRONS

The data collected with the H1 detector correspond to an integrated luminosity of 44 pb^{-1} [1] and with the ZEUS detector to 39 pb^{-1} [3, 4]. The measurements of the average multiplicity, $\langle n_{\rm ch} \rangle$, presented in Figs 1 and 2 are performed in the current region of the Breit frame and of the HCM frame. In the Breit frame the energy scale is related to the momentum of the scattered parton, $Q/2$. Its hadronisation features are compared in Fig. 1 with similar observables measured in one hemisphere of hadronic final states in e^+e^- annihilation described by half of the centre-of-mass energy E^*. The large uncertainties for these ZEUS measurements come from inclusion of the HERWIG hadronisation in systematic uncertainties [4]. In Fig. 2 an alternative energy scale to Q is considered to be the available energy in the Breit current region E_B^{cr} and in the current region of the HCM frame W. The E_B^{cr} values are multiplied by 2 for consistency with Q. In Figs 1 and 2 the MC models show good agreement with the data except the model with the soft colour interactions (SCI) (Fig. 1) and HERWIG at high energy scales (Fig. 2).

Three energy scales $2 * E_B^{cr}$, W and Q are considered. As shown in Fig. 2 (left) the average multiplicity depends on the scale definition at scale below 10 GeV. This can be understood in terms of higher order processes like BGF and migration of the emitted energy out of the Breit current region. In Fig. 1 the measurements are below the e^+e^- parameterisation at the highest Q^2 in the vicinity of the Z^0 resonance. The average charged multiplicities are also compared in Fig. 2 (right) with the e^+e^- data and with the fixed target DIS measurements (see [3]). The DIS data are scaled up by a factor 2 since they are equivalent to one hemisphere of e^+e^-. All the measurements exhibit approximately the same dependence of the average charged multiplicity on the respective energy scale except the data from the DIS fixed target experiments which deviate at energies above 15 GeV due to selection criteria. More information on multiplicity characteristics can be found elsewhere [3].

3. SCALED MOMENTUM DISTRIBUTIONS

The scaled momentum spectra have been studied using an integrated luminosity of about 0.5 fb^{-1} taken with the ZEUS detector [2] and 44 pb^{-1} with the H1 detector [1]. The scaled particle momentum x_p is defined as the momentum of a particle measured in the Breit frame scaled by the maximum momentum $Q/2$ of a quark in the current region. Figure 3 (left) shows the evolution of scaled momentum distributions as a function of the available energy defined in ep scattering by the exchanged boson virtuality Q^2. There is good agreement between different sets of ep data. Scaling violations are observed. The evolution is compared with the evolution of the similar distributions obtained from e^+e^- experiments [9]. The ep data show similar behaviour to the e^+e^- data providing a rough demonstration of fragmentation universality. However, a detailed comparison between e^+e^- and ep shows some discrepancies. At high values of Q^2 approaching the Z^0 exchange region and at $x_p < 0.1$ there are less charged particles observed in the ep data than in e^+e^- annihilation. Similar observations at $Q^2 < 100$ GeV^2 in previous measurements have been understood in terms of higher order QCD processes which deplete the current region in the Breit frame.

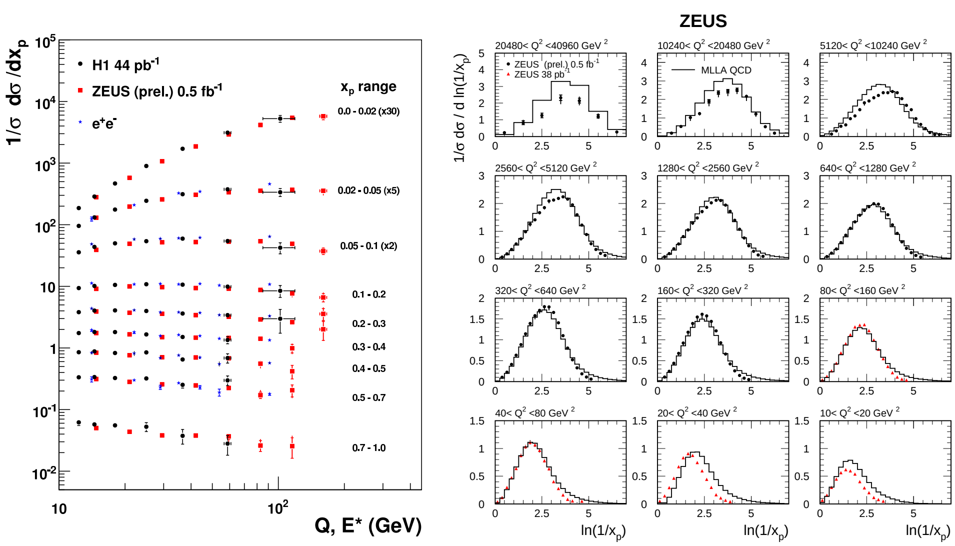

Figure 3: Left: the charged particle distribution shown as a function of Q^2 in x_p bins; similar measurements from e^+e^- are overlaid. Right: the normalized $\ln(1/x_p)$ distributions shown as the black dots for different Q^2 intervals; the full line represents the MLLA+LPHD predictions.

The fragmentation function (FF) represents the probability for a parton to fragment into a particular hadron carrying a fraction of the parton energy and incorporates the long distance, non-perturbative physics of the hadronisation process. Like structure functions, the FF cannot be calculated in perturbative QCD, but can be evolved from a starting distribution at a defined energy scale using the DGLAP evolution [10] equations. The fragmentation functions are universal and are the same in ep and e^+e^-.

The best way to exhibit the fragmentation features are hadron spectra as a function of $\ln(1/x_p)$ in Q^2 intervals as shown in Fig. 3 (right). The spectra become softer with Q^2 increasing. The main features of the data are reproduced by the MC predictions of ARIADNE and LEPTO (not show here) except normalisation at the highest Q^2 values. The modified leading log approximation (MLLA), presented also in Fig. 3 (right), describes basic properties of particle production by multi-gluon emission at leading order including colour coherence and gluon interference phenomena. The MLLA calculations include hypothesis of local parton hadron duality (LPHD) [11] with parameters fitted to reproduce the e^+e^- data. The analytical MLLA+LPHD predictions describe the data at medium Q^2 but not at the lower and highest Q^2. This can be partially explained by a significant migration of particles from (or to) the current region of the Breit frame due to the contribution of boson-gluon fusion processes. As Q^2 increases the peaks are shifted more than expected towards higher values of $\ln(1/x_p)$. As the energy scale Q increases the coupling constant α_s decreases and amount of the soft gluon radiation increases. This leads to a fast increase of the particle density with small fractional momentum x_p.

4. SUMMARY AND CONCLUSIONS

The average charged multiplicity has been investigated in inclusive neutral current deep inelastic ep scattering in the kinematic range $Q^2 > 25$ GeV^2 in terms of different energy scales. The virtuality of the exchanged boson Q and the scale $2 * E_B^{cr}$ were used in the current region of the Breit frame. In the current region of the HCM frame W was used. The energy scales $2 * E_B^{cr}$ and W give better agreement with measurements in e^+e^- annihilation than Q.

The comparison of the scaled momentum distributions of charged particles produced in ep scattering with the same observables measured in e^+e^- annihilation support broadly the concept of quark fragmentation universality. Some depletion of the scaled momentum distributions at low Q^2 can be attributed to higher order QCD processes like BGF occurring in ep but not in e^+e^-. At high Q^2 approaching the Z^0 exchange region a significant depletion is also observed. The x_p distributions support the concept of quark fragmentation universality in ep scattering and e^+e^- annihilation. The MLLA+LPHD calculations based on the e^+e^- data do not describe the distributions in the entire range of the measured Q^2.

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