Scaled momentum spectra in deep inelastic scattering at HERA

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Charged particle production has been studied in neutral current deep inelastic *ep* scattering with the ZEUS detector at HERA using an integrated luminosity of $0.44\,\text{fb}^{-1}$. Distributions of scaled momenta in the Breit frame are presented for particles in the current fragmentation region. The evolution of these spectra with the photon virtuality, Q^2, is described in the kinematic region $10 < Q^2 < 41000\,\text{GeV}^2$. Next-to-leading-order and modified leading-log-approximation QCD calculations as well as predictions from Monte Carlo models are compared to the data. The results are also compared to e^+e^- annihilation data.

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1. Introduction

Multiplicity distributions of charged hadrons in the current region in the Breit frame are presented as functions of the virtuality of the exchanged boson, Q^2 per unit of the scaled momentum, $x_p = 2P_{\rm Breit}/Q$, and the variable $\ln(1/x_p)$ in bins of Q^2. Here, $P_{\rm Breit}$ denotes the momentum of a hadron in the Breit frame.

The data sample collected with the ZEUS detector between 1996–2007, comprising $0.44\,{\rm fb}^{-1}$, enables the study to be extended to Q^2 as high as $41\,000\,{\rm GeV}^2$. This analysis was restricted to events with $Q^2 > 160\,{\rm GeV}^2$. A well reconstructed neutral current DIS sample was selected by standard cleaning cuts.

Predictions from next-to-leading-order (NLO) QCD calculations that combine full NLO matrix elements with fragmentation functions (FF) obtained from fits to e^+e^- annihilation data [6, 7, 8, 9, 10, 11] were compared to the measurements. Predictions from MLLA+LPHD [5, 12, 13] were also considered.

The predictions from several Monte Carlo (MC) models were compared to the data. Neutral current DIS events were generated using the leading-order QCD ARIADNE 4.12 program [19]. The QCD cascade was simulated using the colour-dipole model (CDM) [20] inside ARIADNE. Additional samples were generated with the MEPS model of LEPTO 6.5 [21]. Both MC programs, ARIADNE and LEPTO, were also used to calculate detector acceptances and to correct the data to the hadron level.

In addition, the measurements are compared to previous ep results [1, 2, 3, 4] and to e^+e^- annihilation data [14, 15, 16, 17]. The hadronisation in the current region in the Breit frame in ep scattering can be compared directly to the hadronisation in one hemisphere of e^+e^- annihilation events. There, particle momenta are scaled to half of the centre-of-mass energy, $E^* = \sqrt{s}/2$.

2. Scaled momentum spectra

Scaled momentum spectra were measured in the current region in the Breit frame as a function of Q^2 in the kinematic range $160 < Q^2 < 40960\,{\rm GeV}^2$ and $0.002 < x < 0.75$. The normalised spectrum, $1/N\; dn^{\pm}/d\ln(1/x_p)$, with N being the number of events and $n^{\pm}$ being the number of charged particles, is shown in Figs. 1–2. These scaled momentum spectra exhibit a hump-backed form with an approximately Gaussian shape around the peak. The mean charged multiplicities are given by the integrals of the spectra. As Q^2 increases, the multiplicity increases and, in addition, the peak of the spectrum moves to larger values of $\ln(1/x_p)$.

In Fig. 1, the predictions of ARIADNE and LEPTO are compared to the data. They reproduce the main features of the data but do not agree in detail. For the highest Q^2 bin, both models predict too many charged particles at medium and low values of $\ln(1/x_p)$. LEPTO also predicts too many particles for medium-Q^2 bins while ARIADNE predicts too few for low-Q^2 bins.

In Fig. 2, the MLLA+LPHD predictions[5, 12] are compared to the data. Too many particles are predicted for the highest- and lowest-Q^2 bins, while at medium Q^2 the data is reasonably well described.

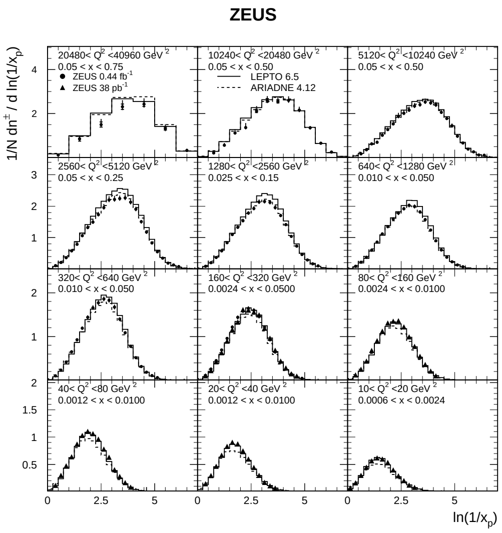

Fig.1 The scaled momentum spectra, $1/N\ dn^{\pm}/d\ln(1/x_p)$, for different (x,Q^2) bins. The full and dashed lines represent the LEPTO and the ARIADNE predictions, respectively.

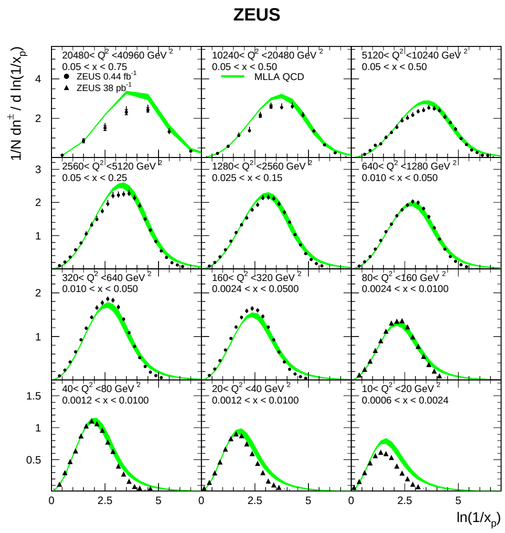

Fig.2 The scaled momentum spectra, $1/N\ dn^{\pm}/d\ln(1/x_p)$, for different (x,Q^2) bins. The band represents the range of the MLLA+LPHD predictions. Other details as in Fig. 1.

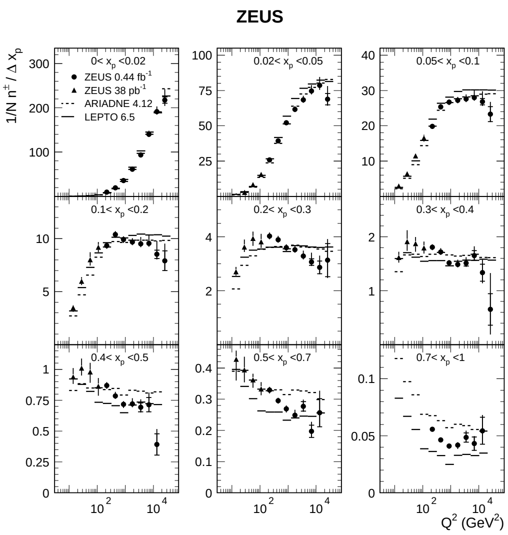

Fig.3 The number of charged particles per event per unit of x_p, $1/N\ n^{\pm}/\Delta x_p$, as a function of Q^2 in x_p bins of width Δx_p. Other details as in Fig. 1.

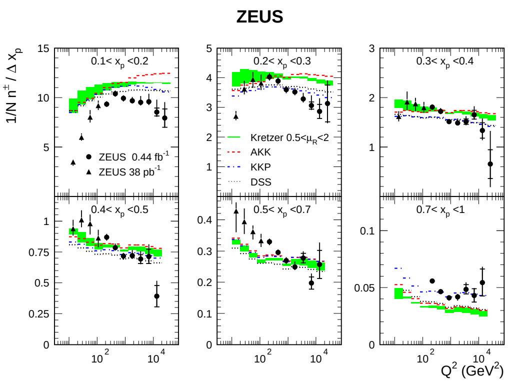

Fig.4 The number of charged particles per event per unit of x_p, $1/N\ n^{\pm}/\Delta x_p$, as a function of Q^2 in x_p bins with width Δx_p as in Fig. 3. The shaded band represents the NLO calculation by Kretzer [6] with its renormalisation scale uncertainty. Additional NLO calculations are shown: Kniehl, Kramer, Pötter [7](KKP), Albino, Kniehl, Kramer [8](AKK) and De Florian, Sassot and Stratmann [10, 11](DSS).

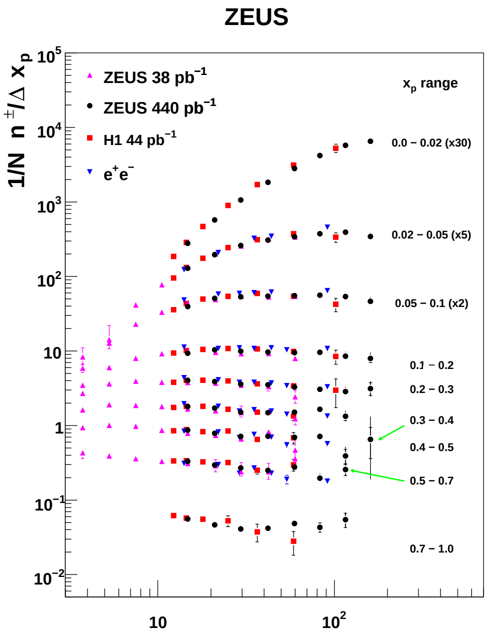

Fig.5 The number of charged particles per event per unit of x_p, $1/N\ n^{\pm}/\Delta x_p$, as a function of Q in x_p bins with width Δx_p. Also shown are data from H1 [4] and e^+e^- [14, 15, 17, 16]. The dots (triangles) represent the new (previous) ZEUS measurement, the squares the H1 data and the inverted triangles the e^+e^- data. The three lowest x_p bins are scaled by factors of 30, 5 and 2, respectively.

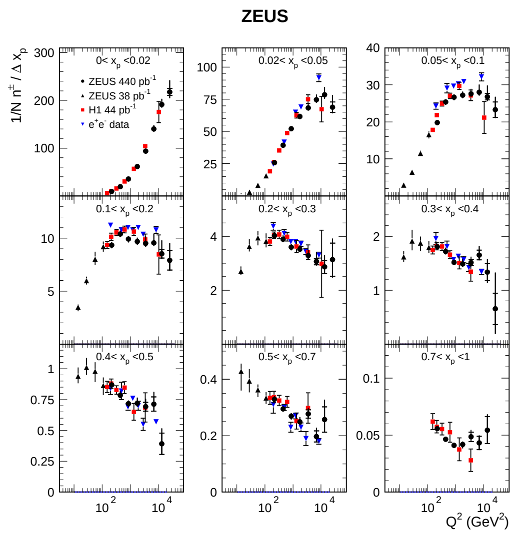

Fig.6 The number of charged particles per event per unit of x_p, $1/N\ n^{\pm}/\Delta x_p$, as a function of Q^2 in x_p bins with width Δx_p. Other details as in Fig. 5.

3. Scaling violation

As the energy scale, Q, increases, the phase space for soft gluon radiation increases, leading to a rise of the number of soft particles with small x_p. These scaling violations can be seen when the data are plotted in bins of x_p as a function of Q^2. Figure 3 show that the number of charged particles increases with Q^2 at low x_p and decreases with Q^2 at high x_p. Neither LEPTO nor ARIADNE provides a good description of this Q^2 dependence over the whole range of x_p. Figure 4 shows the data together with four NLO+FF QCD predictions [6, 7, 8, 9, 10, 11] for $x_p > 0.1$, where theoretical uncertainties are small and the predictions not too strongly affected by hadron-mass effects which are not included in the calculations [18]. The fragmentation functions (FF) used in all four calculations were extracted from e^+e^- data. The four predictions are similar in shape and have similar uncertainties. The uncertainties are only illustrated for the calculation of Kretzer [6]. The NLO calculations also do not provide a good description of the data. Too many particles are predicted at small x_p and too few at large x_p. In general, the scaling violations predicted are not strong enough.

Figure 5 shows the same data as Fig. 3 together with results from H1 [4] and from e^+e^- experiments [14, 15, 16, 17]. For a proper comparison, the the particle momenta from e^+e^- data were scaled to half of the centre-of-mass energy as discussed in the introduction and the scale was set to $Q = 2\ E_{\text{beam}}$, where E_{beam} is the beam energy. In addition, corrections for the different treatment of K^0 and Λ decays were applied. The overall agreement between the different data sets supports fragmentation universality. The presentation of the data using a linear scale as presented in Fig. 6 does, however, show some significant differences between e^+e^- and ep, in particular around the Z^0 mass at $0.02 < x_p < 0.2$ and at low Q^2 at $0.1 < x_p < 0.2$.

4. Conclusions

Scaled momentum spectra have been measured in NC DIS for the current region in the Breit frame over the large range of Q^2 from 10 GeV^2 to 40960 GeV^2. Large scaling violations are observed. Comparing the data to e^+e^- results generally supports the concept of quark-fragmentation universality. Neither MLLA+LPHD nor NLO+FF calculations describe the data well. A better, albeit not prefect description is provided by the ARIADNE program.

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