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Published in:
Zeitschrift für Physik. C, Particles and Fields

DOI:
10.1007/s002880050075

Citation for published version (APA):
Derrick (et al.), M., Botje, M. A. J., Chlebana, F. S., Dake, A. P., Engelen, J. J., de Kamps, M., ..., van Woudenberg, R. (1996). Inclusive charged particle distributions in deep inelastic scattering events at HERA. Zeitschrift für Physik. C, Particles and Fields, 70, 1. DOI: 10.1007/s002880050075
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Received: 21 November 1995
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21 now with OPAL Collaboration, Faculty of Physics at Univ. of Freiburg
22 now at SAS-Institut GmbH, Heidelberg
23 now at GSI Darmstadt
24 also supported by NSERC
25 now at Institute for Cosmic Ray Research, University of Tokyo
26 partially supported by CAM
27 now at Park Medical Systems Inc., Lachine, Canada
28 partially supported by DESY
29 now at Philips Natlab, Eindhoven, NL
30 now at Carleton University, Ottawa, Canada
Abstract. A measurement of inclusive charged particle distributions in deep inelastic $ep$ scattering for $\gamma^* p$ centre-of-mass energies $75 < W < 175$ GeV and momentum transfer squared $10 < Q^2 < 160$ GeV$^2$ from the ZEUS detector at HERA is presented. The differential charged particle rates in the $\gamma^* p$ centre-of-mass system as a function of the scaled longitudinal momentum, $x_F$, and of the transverse momentum, $p_T^* \gamma$ and $<p_T^* >$, as a function of $x_F$, $W$ and $Q^2$ are given. Separate distributions are shown for events with (LRG) and without (NRG) a rapidity gap with respect to the proton direction. The data are compared with results from experiments at lower beam energies, with the naive quark parton model and with parton models including perturbative QCD corrections. The comparison shows the importance of the higher order QCD processes. Significant differences of the inclusive charged particle rates between NRG and LRG events at the same $W$ are observed. The value of $<p_T^* >$ for LRG events with a hadronic mass $M_X$, which excludes the forward produced baryonic system, is similar to the $<p_T^* >$ value observed in fixed target experiments at $W \approx M_X$.

1 Introduction

Inclusive particle distributions have been widely studied in deep inelastic scattering (DIS) [1] and $e^+ e^-$ annihilation to investigate the nature of the quark fragmentation and effects of higher order QCD processes. The formation of hadrons in DIS is a complicated process which cannot be fully calculated in the framework of perturbative QCD. In order to model this process it is convenient to distinguish two phases of the hadron formation. These correspond to a perturbative phase for QCD processes on the parton level followed by a non-perturbative fragmentation phase describing the confinement of the partons to observable hadrons.

In this paper the charged hadron multiplicity distributions are analysed in the virtual-photon proton centre-of-mass system ($\gamma^* p$ cms), which corresponds to the centre-of-mass system of the produced hadronic final state with the invariant mass $W$. In the naive quark parton model (QPM) the virtual photon hits a quark in the proton and transfers a four momentum, $q$. The struck quark and the target remnant system each have an energy of $W/2$ in the $\gamma^* p$ cms and move back-to-back with a ‘velocity’, which corresponds to a rapidity $y_{\text{max}}$ proportional to $\pm \ln W$. The outgoing quark and target remnant hadronise into multi-particle final states with limited $p_T^*$, where $p_T^*$ is the hadron momentum component transverse to the virtual photon direction as measured in the $\gamma^* p$ cms. The width of the rapidity distributions of the produced hadrons is proportional to $\ln W$, while its height is approximately independent of $W$. From the measurement of jet profiles in DIS it is known that the width of a quark jet is typically two units of rapidity [2]. At high values of $W$, the rapidity range populated by hadrons can be divided into three regions: the current jet region from $(y_{\text{max}} - 2)$ to $y_{\text{max}}$, the region of the target remnant fragmentation from $-y_{\text{max}}$ to $(-y_{\text{max}}+2)$ and a plateau region in between. When analysing hadron distributions as a function of the scaled longitudinal momentum in the $\gamma^* p$ cms, $x_F$, the current jet region defined above corresponds to the $x_F$ range $x_F > 0.05$. If no QCD branching processes on the parton level are considered, the $x_F$ and $p_T^*$ distributions for $x_F > 0.05$ are predicted to scale in $W$.

In fixed target DIS experiments [3, 4, 5] effects of scale-breaking in the $x_F$ distributions from QCD corrections, which are expected to soften the observed spectrum with increasing $W$, are small and could not be unambiguously identified. On the other hand, the mean square of $p_T^*$, $<p_T^* >$, has been found to be very sensitive to higher order QCD effects [6]. However, the details of the $p_T^*$ spectra are also sensitive to non-perturbative fragmentation effects [5, 7, 8]. With the high energies reached in $e\gamma$ collisions at HERA it is possible to extend the studies of $x_F$ and $p_T^*$ distributions to larger values of $W$, where the influence of perturbative QCD effects is expected to be much larger and the final state hadron distributions should reflect the dynamics of the subprocesses on the parton level.

In a recent analysis the scaled momentum and charged multiplicity distributions of the hadronic final state were measured in the current region of the Breit frame as a function of the negative square of the four-momentum transfer, $s = -q^2$.
Q^2, and the Bjorken-scaling variable x [9]. The charged particle spectra were observed to evolve with Q^2 in a way similar as in e^+e^- annihilation. In this paper we study inclusive charged hadron production as a function of x_F and <p_T^2> in the current region of the γ^*p cms frame. The objective of the analysis is to investigate the influence of perturbative QCD effects on the hadronic final state by studying the W dependence of these distributions in HERA ep collisions and in fixed target DIS data. The data are also compared with e^+e^- results as well as with predictions of Monte Carlo programs. The comparison is also performed for a subclass of DIS events, which are characterised by a rapidity gap between the observed hadronic final state and the proton beam direction [10], and which are therefore candidates for diffractive scattering.

2 The experiment

2.1 HERA

The data were collected during the 1993 running period using the ZEUS detector at the electron-proton collider HERA, where a 26.7 GeV electron beam and a 820 GeV proton beam were brought to collision providing an ep centre-of-mass energy of 296 GeV. 84 bunches were filled for each beam and in addition 10 electron and 6 proton bunches were left unpaired for background studies. An integrated luminosity of 0.55 pb^{-1} was collected.

2.2 The ZEUS detector

ZEUS is a multi-purpose magnetic detector which has been described elsewhere [11, 12]. Here a brief description is given which concentrates on those parts of the detector relevant for the present analysis.

Charged particles are tracked by the inner tracking detectors which operate in a magnetic field of 1.43 T provided by a thin superconducting solenoid. Immediately surrounding the beam pipe is the vertex detector (VXD) which consists of 120 radial cells, each with 12 sense wires [13]. The achieved resolution is 50 μm in the central region of a cell and 150 μm near the edges. Surrounding the VXD is the central tracking detector (CTD) which consists of 72 cylindrical drift chamber layers, organised into 9 'superlayers' [14]. These superlayers alternate between those with wires parallel (axial) to the collision axis and those inclined at a small angle to give a stereo view. The hit efficiency of the CTD is greater than 95% and the resolution in transverse momentum for full length tracks is σ_p_T / p_T = 0.005 p_T \times 0.016 (p_T in GeV), where \( \bigotimes \) means addition in quadrature.

The solenoid is surrounded by a high resolution uranium-scintillator calorimeter (CAL), which is divided into three parts: forward^2 (FCAL), barrel (BCAL) and rear (RCAL) [15]. It covers 99.7% of the solid angle. Holes of 20 × 20 cm^2 in the centre of FCAL and RCAL accommodate the HERA beam pipe. Each of the calorimeter parts is subdivided into towers which in turn are segmented longitudinally into electromagnetic (EMC) and hadronic (HAC) sections. These sections are further subdivided into cells, which are read out by two phototubes each.

For measuring the luminosity as well as for tagging very small Q^2 processes, two lead-scintillator calorimeters are used [12, 16]. Bremsstrahlung photons emerging from the electron-proton interaction point (IP) at angles θ_γ ≤ 0.5 mrad with respect to the electron beam axis hit the photon calorimeter at 107 m from the IP. Electrons emitted from the IP at scattering angles less than 6 mrad and with energies between 20% and 90% of the nominal beam energy are deflected by beam magnets and hit the electron calorimeter placed 35 m from the IP.

Two small lead-scintillator sandwich counters partially surround the beam-pipe at the rear of the RCAL. These counters were used to reject background produced by beam-gas interactions with the incoming proton beam and to measure the timing and longitudinal spread of both the proton and the electron beams of HERA. Two layers of scintillation counters mounted on either side of an iron veto wall, situated upstream of the detector, were also used to reject background particles.

3 Data taking conditions

The ZEUS trigger is organised in three levels [11] and reduces the input event rate from the bunch crossing rate of 10 MHz to 3-5 Hz. For DIS events, the first level trigger (FLT) requires at least one of three conditions for energy sums in the EMC calorimeter cells: the BCAL EMC energy exceeds 3.4 GeV; or the RCAL EMC energy (excluding the innermost towers surrounding the beam pipe) exceeds 2.0 GeV; or the RCAL EMC energy (including those towers) exceeds 3.75 GeV.

The second level trigger (SLT) rejects proton beam-gas events by using the event times measured in the rear calorimeter cells. The DIS trigger rate of the SLT is about one-tenth the FLT DIS trigger rate. The loss of DIS events at the SLT is negligible.

The third level trigger (TLT) has the full event information available and applies physics-based filters. It requires tighter timing cuts to suppress beam-gas-background further and also rejects beam halo muons and cosmic muons. The TLT selects DIS event candidates by calculating:

\[ \delta = \sum_i E_i \cdot (1 - \cos \theta_i) > 20 \text{ GeV} - 2 E_\gamma, \]

where \( E_i \) and \( \theta_i \) are the energy and the polar angle of the energy deposits in the calorimeter. The summation runs over all calorimeter cells. \( E_\gamma \) is the energy measured in the photon calorimeter of the luminosity monitor. For fully contained DIS events \( \delta \approx 2E_e = 53.4 \text{ GeV} \), where \( E_e \) is the energy of the incident electron. Photoproduction events have low values of \( \delta \) compared to DIS events because the scattered electron escapes in the hole of the calorimeter which contains the beam pipe.

^2 The proton beam direction is the forward +Z direction

^3 The proton beam direction is defined as the Z-axis in the HERA laboratory frame
For events with the scattered electron detected in the calorimeter, the trigger is essentially independent of the DIS hadronic final state. The trigger acceptance is greater than 97% for \(Q^2 > 10 \text{ GeV}^2\) and independent of \(Q^2\) [17]. A total of about \(7 \cdot 10^6\) events passed the TLT and was written to tape during the 1993 running period.

4 Event kinematics

In deep inelastic \(ep\) scattering events the incoming electron couples to a \(\gamma\) or a \(Z\) (neutral current NC) or to a \(W^+\) (charged current CC), which scatters off the proton. In the \(Q^2\) range explored here, the contribution from \(W\) and \(Z\) exchange is negligible. The kinematic variables used to describe the inclusive DIS process are defined in Table 1.

The ZEUS detector is almost hermetic, allowing the kinematic variables \(Q^2, x\) and \(y\) to be reconstructed in a variety of ways using combinations of electron and hadronic system energies and angles. In the analysis presented here the double angle method (DA) was chosen, in which the scattered electron angle and the angle \(\gamma_H\) is used [18]. In the naive quark parton model (QED) Compton scattering events and residual cosmic and beam-related muons were rejected by algorithms, which identify these types of events by their pattern of energy deposits in the calorimeter cells.

A total of 26100 events was selected by the above cuts. Of these events about 10% [10] contain a large rapidity gap in the hadronic final state. They are characterised by \(\eta_{\text{max}} < 1.5\), where \(\eta_{\text{max}}\) is the pseudorapidity of the most forward calorimeter cluster in the event, relative to the proton direction. The pseudorapidity is defined by \(\eta = -\ln (\tan (\theta/2))\) and a cluster is an isolated set of adjacent calorimeter cells with summed energy above 400 MeV. This sample is called the ‘large-rapidity-gap’ (LRG) event sample. The remaining events are denoted by ‘non-rapidity-gap’ (NRG) events. The invariant mass of the hadronic final state excluding the scattered proton in the LRG events is calculated from the energy deposits measured in the calorimeter (excluding the electron cluster) by \(M_X = \sqrt{\sum_{\text{had}} (E^2 - p_X^2 - p_y^2 - p_Z^2)}\). The values of \(p_X\), \(p_Y\) and \(p_Z\) are the cell energies \(E\) projected on the axes of the HERA laboratory frame. The polar angles of these pseudovectors are calculated from the geometric centres of the cells and the primary event vertex position. The measured value of \(M_X\) is corrected to the hadron level as described in Sect. 6.

5 Data selection

5.1 Event selection

The offline selection of DIS events was similar to that described in earlier publications (e.g. [9, 20, 21]). Scattered electron candidates were selected by using the pattern of energy deposition in the calorimeter. The electron identification algorithm was tuned for purity rather than for efficiency. The purity is defined as the number of electrons generated and reconstructed in a bin divided by the total number of electron candidates measured in the bin. In studies with Monte Carlo DIS events and test beam data the purity was estimated to be \(> 96\%\) for \(E_{\text{DA}} > 10\) GeV.

The requirements for the final event selection were:

- \(E_{\text{DA}} > 10\) GeV, to minimise beam gas background contamination;
- \(Q^2_{\text{DA}} > 10\) GeV;
- \(y_e > 0.85\), to reduce the photoproduction background, where \(y_e\) is the scaling variable \(y\) as determined from the energy and polar angle of the scattered electron;
- \(y_{\text{JB}} > 0.04\), to guarantee sufficient accuracy for the DA reconstruction method;
- \(\delta = \sum_i E_i (1 - \cos \theta_i) \geq 35\) GeV, where the sum runs over all calorimeter cells. For fully contained events \(\delta \approx 2E_e = 53.4\) GeV. This cut is used to remove photoproduction events and to control radiative corrections.

Furthermore we required:

- a primary vertex position, determined from VXD and CTD tracks, in the range \(-50 \leq Z_{\text{vtx}} \leq 40\) cm;
- the impact point \((X, Y)\) of the scattered electron in the RCAL to lie outside a square of \(32 \times 32\) cm² centered on the beam axis, to ensure that the electron is fully contained within the detector and its position can be reconstructed with sufficient accuracy.

After these cuts, the remaining photoproduction background was estimated to be \(\approx 1\%\). The contamination from beam-gas background was estimated to be below 0.5% as calculated from unpaired electron and proton bunches. Finally, QED Compton scattering events and residual cosmic and beam-related muons were rejected by algorithms, which identify these types of events by their pattern of energy deposits in the calorimeter cells.

5.2 Track reconstruction and selection

Tracks were recognised and fitted using two programs which were developed independently and follow different strategies for pattern recognition and track fitting. For the results shown in this paper the first approach is used and the second method was used for estimating the systematic error.

In the first approach the track finding algorithm starts with hits in the outermost axial superlayers of the CTD. As
In the analysis, the efficiency for identifying the scattered electron was further tightened to 150\%.

The scattered electron was removed from the track sample by rejecting those tracks which match the cluster in the calorimeter assigned to the scattered electron by the electron finding algorithm. Only tracks which have been selected for this analysis have $p_T^{l,\text{lab}} > 0.2\,\text{GeV}$ and a polar angle in the HERA laboratory frame in the range of $25^\circ < \theta < 155^\circ$. This is a region of the CTD, where the detector response and systematics are best understood. For tracks defined by these cuts the track reconstruction efficiency is $\approx 95\%$.

The scattered electron was removed from the track sample by rejecting those tracks which match the cluster in the calorimeter assigned to the scattered electron by the electron finding algorithm. Only tracks which reach at least the third superlayer and hence have a projected length in the plane perpendicular to the beam axis of more than 30 cm are kept to achieve the required transverse momentum resolution. For $\theta > 150^\circ$ the efficiency for identifying the scattered electron by matching the CTD tracks to energy deposits in the calorimeter decreases rapidly due to the limited acceptance and resolution of the CTD in the very rear part of the detector. Therefore the upper cut on $\theta$ of the hadrons considered in the analysis was further tightened to $150^\circ$.

Due to the cuts in $\theta$ and $p_T^{l,\text{lab}}$, the analysis in the $\gamma^* p$ cms is restricted to the range $10 < Q^2 < 160\,\text{GeV}^2$ and $75 < W < 175\,\text{GeV}$, where the acceptance for charged hadrons is larger than 60%.

In Fig. 1 the distribution of the selected events in the $Q^2$-$x$ plane is shown. For comparison the kinematic region which has been investigated in fixed target experiments is also shown.

### Table 1. Definition of the variables used to describe the kinematics of the inclusive DIS process

| Variable | Description |
|----------|-------------|
| $l$ ($l'$) | Four-momentum of the incident (scattered) lepton |
| $p, M_p$ | Four-momentum of the proton and its mass |
| $Q^2 = -q^2 = -(l-l')^2$ | Negative invariant mass squared of the exchanged virtual boson |
| $\nu = (P \cdot q)/M_p$ | Energy of the exchanged boson in the proton rest frame |
| $x = Q^2/(2M_p \nu)$ | Bjorken scaling variable |
| $y = (P \cdot q)/(P \cdot l)$ | Inelasticity parameter |
| $W^2 = (P + q)^2$ | Invariant mass squared of the hadronic final state |

$W^2 = (P + q)^2 = Q^2(1/x) + M_p^2$
program [25, 26] (CDMBGF) and b) LEPTO 6.1 with the option of combined matrix element and parton shower calculation (MEPS). The fragmentation was simulated using the LUND string model [27] as implemented in JETSET [28] (see Table 2).

Both models were interfaced to the program HERACLES [29], which computes the electro-weak radiative corrections for DIS events. In the case of hard QED Bremsstrahlung the four-momentum vector of the virtual photon which probes the proton is significantly different from the virtual photon momentum reconstructed from the momenta of the incident and scattered lepton. In this case the $x_F$ and $p_t^* \gamma$ distributions are also distorted and have to be corrected for this effect. In this analysis, however, the virtual photon momentum was reconstructed using the double angle method, which is insensitive to radiative effects. Events with hard QED initial state Bremsstrahlung photons ($E_{\text{brems}} \gtrsim 7\text{ GeV}$) are rejected by the cut on $\delta > 35\text{ GeV}$ (see Sect. 5.1). Monte Carlo calculations show that the QED radiative corrections are 5–10%.

For both Monte Carlo simulations the $M_{\text{RSDD}^*}$ parameterisation of the parton densities in the proton was chosen [30], which gives a reasonable description of the structure function measured at HERA [31, 32].

The properties of LRG events are characteristic of diffractive interactions [10]. Two Monte Carlo event samples have been used to model the hadronic final state of LRG events. The first was generated using the POMPYT Monte Carlo program [33], which is based on a factorisable model for high energy diffractive processes. Within the PYTHIA [34] framework, the incident proton emits a pomeron, whose constituents take part in a hard scattering process with the virtual photon or its constituents. The structure of the pomeron is assumed to be described by either a hard or a soft quark density function $f(\beta)$, where $\beta$ denotes the fraction of the pomeron momentum carried by the quark.

The second sample was generated following the model of Nikolaev and Zakharov (NZ) [35], which was interfaced to the Lund fragmentation scheme [36]. In the NZ model it is assumed that the exchanged virtual photon fluctuates into a $q\bar{q}$ pair, which interacts with a colourless two-gluon system emitted by the incident proton. Both diffractive Monte Carlo samples were generated with default parameter settings. QED radiative processes were not simulated for these events. With the event selection cuts described in Sect. 5, however, the QED radiative corrections are expected to be of the same size as for the NRG events.

Event samples produced by the Monte Carlo generators marked in Table 2 by an asterisk were also processed by the CDMBF Monte Carlo program interfaced to HERACLES. Note that the results are not corrected for the selection inefficiency of the $\eta_{\text{max}}$ cut.

6.2 Data correction procedure

The measured hadron multiplicity distributions are distorted with respect to those of the true hadronic final state due to trigger biases, event and track selection cuts and the acceptance and resolution of the detector. The output of the trigger and detector simulation program together with the samples produced by the different event generators have been used to estimate the distortion of the distributions and to correct for them by multiplying the measured distributions by a correction function $c(v)$ in each bin of $Q^2$ and $W$, where $v$ is the hadron variable under study and $c(v)$ is calculated as a bin-by-bin ratio:

$$c(v) = \left( \frac{1}{N_{\text{evt,rec}}} \frac{\Delta N_{\text{had}}(v)}{\Delta v} \right)_{\text{gen}} \left( \frac{1}{N_{\text{evt,gen}}} \frac{\Delta N_{\text{had}}(v)}{\Delta v} \right)_{\text{rec}} . \quad (4)$$

The subscripts $\text{gen}$ and $\text{rec}$ refer to the quantities as given by the event generator programs and the reconstructed quantities from the output of the detector simulation program, respectively. The number of events in a bin of $Q^2$ and $W$ is denoted by $N_{\text{evt}}; \Delta N_{\text{had}}$ is the number of hadrons in a bin of $v$. The generated hadron distributions do not include the charged particle decay products of $R^{0}$s and $\Lambda$'s and of weakly decaying particles with a lifetime $> 10^{-8}$ s. For the expression in the numerator the event rate and hadrons are sorted in bins of the generated kinematic variables and for the denominator in bins of the reconstructed variables. In this way the distributions have been corrected for losses of events and hadrons as well as for the effects of event migration, finite resolution and trigger biases.

The bin size in the hadron variables $v$ was chosen to be comparable with the estimated resolution in $v$ and it was checked that the correction factor neither deviates by more than 40% from unity nor depends strongly on $v$ [38]. For models which adequately describe the data, the dependence of the correction factors on the model input was found to be small. The difference in $c(v)$ for different models was included in the systematic error.

The mean square of $p_t^* (\leq p_t^{*2})$ was corrected by:

$$<p_t^{*2}> = <p_t^{*2}>_{\text{meas}} <p_t^{*2}>_{\text{MC,gen}} <p_t^{*2}>_{\text{MC,rec}} , \quad (5)$$

where $<p_t^{*2}>_{\text{meas}}$ is the mean value of $p_t^{*2}$ determined from the uncorrected data. The terms in the correction factor are defined as in equation 4. This method of correction is numerically more stable than the determination of $<p_t^{*2}>$ from the acceptance corrected $p_t^{*2}$ distributions.

The following sources of systematic uncertainties were studied:

- The model dependence of the correction factors $c(v)$ was estimated using two different models for the NRG and LRG event samples each. The CDMBF and MEPS models were used to correct the NRG event sample and for the LRG event sample the POMPYT model with a hard quark density function (see Table 2) and the NZ model were...
used. The relative systematic error of \(1/N_{\text{evt}} \cdot dN_{\text{had}}/dx_F\) is \(\sim 3\%\) and the one of \(<p_t^*{}^2>\) is \(\sim 7\%\).

- The sensitivity of the measurements on the track selection criteria has been investigated. The cut in the polar angle of the tracks was varied between 20° and 33° and/or it was required that superlayer 5 instead of superlayer 3 has to be reached by the track. The requirement of a minimum hadron momentum transverse to the beam direction in the laboratory frame, \(p_{t,\text{lab}}\), was omitted. No significant changes in the results (<1%) have been observed.

- The effect of a possible misestimation of the momentum resolution in the detector simulation program was studied by evaluating the correction function with a resolution of the measured transverse momentum artificially increased by 100%. The size of this effect on \(<p_t^*{}^2>\) and \(x_F\) was smaller than 1%.

The contributions of the above effects to the systematic error have been added in quadrature and are shown together with the statistical errors of the results in the tables and figures.

The shape of the correction factors to be applied to the measured hadron distributions of \(x_F\) and \(p_t^*\) as well as to \(<p_t^*{}^2>\) is shown in Fig. 2 separately for NRG and LRG events. The size of the correction for both event classes is very similar.

### 7 Results

#### 7.1 \(x_F\) and \(p_t^*\) distributions in NRG events

First the \(x_F\) and \(p_t^*\) distributions of charged hadrons in NRG events are discussed. In Fig. 3a the \(x_F\) distribution at \(<W> = 120\) GeV and \(<Q^2> = 28\) GeV\(^2\) is compared with different models for hadron production in DIS. The \(x_F\) distribution falls steeply with increasing \(x_F\). The results from the H1 experiment [39] agree well with this measurements.
The data agree with those models, in which higher order QCD processes are included, such as MEPS (solid line) and CDMEBF (dashed line), but not with the naive quark parton model (QPM) (dotted line).

In Fig. 3b the $p_t^2$ spectrum, which is integrated over $x_F > 0.05$ for the study of the current jet fragmentation, is compared with the same model calculations. The QPM model predicts a much steeper $p_t^2$ distribution than the data show, whereas the MEPS model agrees well with the data. However, for closer investigation it is advantageous to take the mean square of $p_t^2$, $< p_t^2 >$, a quantity which is more sensitive to the behaviour of the tail of the $p_t^2$ distribution.

Figure 3c shows the $< p_t^2 >$ distribution as a function of $x_F$ for $x_F \geq 0.05$. In any model, which allows for a transverse momentum of the partons, the rise of $< p_t^2 >$ with increasing $x_F$ is expected because a hadron with a higher value of $x_F$ carries also a larger fraction of the transverse momentum of the primary parton. Again the MEPS and CDMEBF models describe the data while the QPM strongly underestimates the value of $< p_t^2 >$.

In Fig. 3a,c the results from the H1 experiment are also shown [39]. The differential hadron multiplicities measured by ZEUS are listed in Table 3.

### Table 3. Differential multiplicities for charged hadrons as a function of $A$ and $B$.

| $x_F$ | $< x_F >$ | $1/N_{evt} \frac{dN_{had}}{dx_F}$ | $p_t^2$ | $< p_t^2 >$ | $< p_t^2 >$ GeV$^2$ |
|-------|------------|----------------------------------|--------|-------------|-------------------|
| 0.05  | 0.10       | 0.07                             | 0.00   | 0.45        | 0.45              |
| 0.10  | 0.20       | 0.15                             | 0.00   | 0.45        | 0.45              |
| 0.20  | 0.40       | 0.30                             | 0.00   | 0.45        | 0.45              |
| 0.40  | 0.80       | 0.60                             | 0.00   | 0.45        | 0.45              |
| 0.80  | 1.20       | 0.90                             | 0.00   | 0.45        | 0.45              |
| 1.20  | 1.50       | 1.33                             | 0.00   | 0.45        | 0.45              |
| 1.50  | 2.00       | 1.71                             | 0.00   | 0.45        | 0.45              |
| 2.00  | 2.75       | 2.30                             | 0.00   | 0.45        | 0.45              |
| 2.75  | 3.50       | 3.07                             | 0.00   | 0.45        | 0.45              |
| 3.50  | 5.00       | 4.04                             | 0.00   | 0.45        | 0.45              |

### 7.2 $x_F$ and $p_t^2$ spectra in LRG events

The $x_F$ and $p_t^2$ distributions from charged hadrons as well as $< p_t^2 >$ as a function of $x_F$ are shown in Fig. 4 separately for the samples of LRG and NRG events. The values for the LRG events are tabulated in Table 4. The value of $< W >$ is similar for both event samples, whereas $< Q^2 >$ for the LRG events is lower by 30% than for the NRG events. The $x_F$ distribution for the LRG events is falling less steeply when compared to that of the NRG events. The $x_F$ distribution for LRG events is falling less steeply compared to that of the NRG events. The $x_F$ distribution for the LRG events is falling less steeply when compared to that of the NRG events. The $x_F$ distribution for LRG events is falling less steeply when compared to that of the NRG events. The $x_F$ distribution for LRG events is falling less steeply when compared to that of the NRG events. The $x_F$ distribution for LRG events is falling less steeply when compared to that of the NRG events. The $x_F$ distribution for LRG events is falling less steeply when compared to that of the NRG events. The $x_F$ distribution for LRG events is falling less steeply when compared to that of the NRG events. The $x_F$ distribution for LRG events is falling less steeply when compared to that of the NRG events.

The $p_t^2$ spectrum of LRG events is significantly less broad than that for the rest of the DIS events (Fig. 4b). This effect is highlighted in Fig. 4c. The mean values of $p_t^2$ in events with a large rapidity gap are smaller than for the NRG events by a factor of 2–5. From a comparison with DIS model calculations with and without simulating QCD radiation processes, it is found that the $< p_t^2 >$ values for LRG events resemble those for DIS events with only a small amount of gluon radiation. This observation is in good agreement with ZEUS results from the analysis of the energy flow [21]. However, $< p_t^2 >$ in LRG events is somewhat larger than predicted by the QPM (see dotted line in Fig. 4c), indicating that there is a non-zero contribution of higher order QCD processes in this class of events, too. This is confirmed
by the observation of DIS events with a large rapidity gap which exhibit a two-jet structure [40]. The model calculations for diffractive $e p$ scattering slightly underestimate the measured values of $<p_t^2>$.

The inclusive distributions of LRG events have been found to have the properties of a diffractive interaction of a highly virtual photon with a proton [10]. Diffractive interactions in hadron-hadron reactions and photoproduction have been successfully described in the framework of Regge theory by the exchange of a pomeron [41]. Several models have been developed to describe this reaction in terms of parton interactions (e.g. [42, 43]). In this context it is interesting to test the hypothesis that the diffractive DIS process can be viewed as the ‘emission’ of a pomeron from the proton, which carries the fraction $x_{pom}$ of the proton momentum, and a subsequent deep inelastic $\gamma^{*}$ pomeron scattering, which occurs at a higher value of $x' = x_{pom}$. In this picture the relevant scale for the invariant mass of the hadronic final state should be given by $M_X$ and not by $W$. In Fig. 5a $<p_t^2>$ as a function of $x_F$ from the LRG events is compared with the results of a fixed target DIS experiment [5], where the invariant mass of the total hadronic final state ($<W> = 14$ GeV) is only slightly higher than the invariant mass of the hadronic final state observed in the LRG events ($<M_X> = 8$ GeV). The values of $<p_t^2>$ and the $x_F$ distribution for both event samples agree reasonably well. This result supports the hypothesis that the transverse momentum space for the particle production is similar to DIS, where the scale of the invariant mass is given by $M_X$ rather than by $W$.

### Table 4. Differential multiplicities for charged hadrons as a function of $x_F$ and $p_t^2$

| $x_F$ | $<x_F>$ | $<p_t^2>$ | $N_{had}$ |
|-------|---------|-----------|-----------|
| 0.03  | 0.05    | 0.04      | 26.97     |
| 0.05  | 0.10    | 0.07      | 19.70     |
| 0.10  | 0.15    | 0.12      | 12.16     |
| 0.15  | 0.22    | 0.18      | 6.49      |
| 0.22  | 0.32    | 0.27      | 4.02      |
| 0.32  | 0.45    | 0.38      | 1.41      |
| 0.45  | 0.65    | 0.54      | 0.68      |
| 0.65  | 0.90    | 0.75      | 0.31      |

### Fig. 4. Charged hadron distributions for $10 \leq Q^2 \leq 160$ GeV$^2$ and $75 \leq W \leq 175$ GeV ($<Q^2> = 28$ GeV$^2$ and $<W> = 120$ GeV). a) The $x_F$ distribution, b) the $p_t^2$ distribution for $x_F > 0.05$ and c) $<p_t^2>$ as a function of $x_F$ are presented separately for NRG and LRG events. In all three figures the curves represent the results of the following model predictions: solid curve: POMPYT with a hard pomeron structure function (see Table 2); dashed curve: model of Nikolaev and Zakharov; dotted curve: QPM.

### Fig. 5. Comparison of a) $<p_t^2>$ as a function of $x_F$ and b) the $x_F$ distribution for the LRG event sample (ZEUS) and DIS at low energy (EMC, $<W> = 14$ GeV). The mean value of $M_X$ for the LRG event sample is $<M_X> = 8$ GeV.
range analysed here. The differential rates for hadron production in $e^+e^-$ annihilation were divided by two so that they correspond to a single hemisphere and can be directly compared with the results from DIS. The differential hadron multiplicity distribution in DIS at HERA energies agrees with that observed in $e^+e^-$ collision events for $x_F > 0.1$. This confirms the approximate independence of the hadron formation process from the type of the primary scattering objects, which most of the models assume [27, 45].

The $x_F$ and $<p_T^2>$ distributions from this analysis are compared with those of DIS events at lower values of $W$ [46, 47]. Since in fixed target experiments the DIS event sample has not been separated into NRG and LRG events, the NRG and LRG event samples have been combined for the comparison. The $x_F$ and $p_T^2$ distribution as well as $<p_T^2>$ as a function of $x_F$ for the NRG+LRG event sample are given in Table 5. The distributions have been corrected using a combination of Monte Carlo event samples generated by the POMPYT and the CDMBGF Monte Carlo generator. The relative normalisation of the Monte Carlo samples has been fixed by fitting the sum of the reconstructed $\eta_{\text{max}}$ distribution from the POMPYT and the CDMBGF Monte Carlo sample to the measured $\eta_{\text{max}}$ distribution [21].

Figure 6b shows that the $x_F$ distribution becomes significantly softer with increasing $W$. The prediction of the QPM, where no scale breaking effects due to QCD radiation are included, almost agrees with the result from the fixed target experiments [7, 46, 47] but is very different from the result at HERA energies (dotted line in Fig. 6b). The effects of scaling violation in the $x_F$ distribution of hadrons, which have been found to be small when measured in a limited interval of $W$ and $Q^2$ [3, 5], become evident when studied over a large range of $W$ and $Q^2$. Models in which higher order $\alpha_s$ processes are considered (e.g. the MEPS model indicated by the full line in Fig. 6b) agree reasonably with the ZEUS data.

The mean value of $p_T^2$ as a function of $x_F$ is shown in Fig. 7 for $x_F > 0.05$ going from $W = 14$ to 120 GeV (this analysis) and for $W = 120$ GeV from the EMC collaboration [46]. Comparing the results at low $W$ and high $W$ there is a strong increase of $<p_T^2>$ by a factor of about three over the whole range of $x_F > 0.05$ going from $W = 14$ to 120 GeV. The comparison of the prediction from the QPM and the models including higher order QCD processes shows that QCD effects are much larger at HERA energies than at energies reached in fixed target experiments.

For a further analysis of the $W$ and $Q^2$ dependence, $<p_T^2>$ was determined for two intervals in $x_F$ and four bins of $W$ at an average value for $Q^2$ of 28 GeV$^2$ (Fig. 8a) and four bins of $Q^2$ keeping $W$ fixed at an average value of 120 GeV (Fig. 8b). The value of $<p_T^2>$ increases both with $W$ and with $Q^2$. The results are tabulated in the Tables 6 and 7.

**Table 5. Differential multiplicities for charged hadrons as a function of $A$) $x_F$ and B) $p_T^2$ ($x_F > 0.05$) and C) $<p_T^2>$ as a function of $x_F$ for DIS events (combined NRG + LRG event sample) in the range of $10 < Q^2 < 160$ GeV$^2$ and $75 < W < 175$ GeV. Statistical and systematic errors are given separately.**

| $x_F$ | $<x_F>$ | $1/N_{\text{evt}} \frac{dN_{\text{had}}}{dx_F}$ GeV$^{-1}$ |
|-------|---------|-----------------------------------|
| 0.05  | 0.15    | 0.07                              |
| 0.10  | 0.20    | 0.15                              |
| 0.20  | 0.40    | 0.30                              |
| 0.40  | 0.60    | 0.49                              |
| 0.60  | 0.80    | 0.69                              |
| 0.80  | 1.20    | 0.96                              |
| 1.20  | 1.50    | 1.33                              |
| 1.50  | 2.00    | 1.71                              |
| 2.00  | 2.75    | 2.30                              |
| 2.75  | 3.50    | 3.07                              |
| 3.50  | 5.00    | 4.04                              |

| $p_T^2$ GeV | $<p_T^2>$ GeV$^2$ | $1/N_{\text{evt}} \frac{dN_{\text{had}}}{dp_T^2}$ GeV$^{-2}$ |
|-------------|------------------|---------------------------------------------------|
| 0.00 - 0.10 | 0.00 - 0.07      | 0.10 - 0.05 ± 0.01                                |
| 0.10 - 0.20 | 0.15             | 0.23 - 0.08 ± 0.05                                |
| 0.20 - 0.40 | 0.30             | 0.52 - 0.07 ± 0.05                                |
| 0.40 - 0.60 | 0.49             | 0.96 - 0.06 ± 0.04                                |
| 0.60 - 0.80 | 0.69             | 2.29 - 0.05 ± 0.03                                |
| 0.80 - 1.20 | 0.96             | 1.07 - 0.02 ± 0.04                                |
| 1.20 - 1.50 | 1.33             | 0.45 - 0.02 ± 0.08                                |
| 1.50 - 2.00 | 1.71             | 0.22 - 0.01 ± 0.03                                |
| 2.00 - 2.75 | 2.30             | 0.07 - 0.004 ± 0.004                              |
| 2.75 - 3.50 | 3.07             | 0.02 - 0.002 ± 0.004                              |
| 3.50 - 5.00 | 4.04             | 0.01 - 0.001 ± 0.001                              |

Figure 6a) $x_F$ distribution from this analysis (NRG events) compared to results from $e^+e^-$ annihilation on the $Z^0$ resonance ($W = 91$ GeV) [44]. b) $x_F$ distribution from this analysis (NRG + LRG events) compared with results from $\mu p$ DIS at $<W> = 14$ GeV [46] and at $<W> = 18$ GeV [47].
the colour dipole model without including the BGF process (solid line) and CDMBGF models (dashed line).

Also of Fig. 9. The target experiment are compared with model calculations in processes but the BGF process is not considered. The colour dipole model simulates higher order gluon radiation dependence is also described by the MEPS and CDMBGF curves show results from model calculations at HERA energy with the events) compared to results from ZEUS 1993.

The results from the ZEUS experiment and the fixed targets at low energies [5, 48]. The rise of \( \langle p_t^2 \rangle \) with \( W \), which had been observed already in the fixed target DIS experiments, continues in the range of \( W \) seen at HERA. However, the \( Q^2 \)-dependence in these two ranges of \( W \) is different. There is a large overlap of the \( Q^2 \) intervals covered. At HERA energies a rise of \( \langle p_t^2 \rangle \) with \( Q^2 \) is observed, while at low \( W \) almost no dependence on \( Q^2 \) was found [5].

These results are compared with those from a fixed target experiment at lower energies [5, 48]. The rise of \( \langle p_t^2 \rangle \) with \( W \), which had been observed already in the fixed target DIS experiments, continues in the range of \( W \) seen at HERA. However, the \( Q^2 \)-dependence in these two ranges of \( W \) is different. There is a large overlap of the \( Q^2 \) intervals covered. At HERA energies a rise of \( \langle p_t^2 \rangle \) with \( Q^2 \) is observed, while at low \( W \) almost no dependence on \( Q^2 \) was found [5].

The results from the ZEUS experiment and the fixed target experiment are compared with model calculations in Fig. 9. The \( W \)-dependence is reasonably described by the MEPS (solid line) and CDMBGF models (dashed line). Also the colour dipole model without including the BGF process (dotted line) qualitatively reproduces the \( W \) dependence of \( \langle p_t^2 \rangle \) but overestimates the absolute value. The \( Q^2 \)-dependence is also described by the MEPS and CDMBGF model but not by the colour dipole model (CDM) alone. The colour dipole model simulates higher order gluon radiation processes but the BGF process is not considered. The \( Q^2 \) dependence of \( \langle p_t^2 \rangle \) shows that it is necessary to include the explicit treatment of the BGF process as well in the simulation.

8 Conclusions

Measurements of differential charged hadron multiplicity distributions in DIS events have been presented in the centre-of-mass system of the virtual photon and the proton at a centre-of-mass energy of 296 GeV for \( 10 \leq Q^2 \leq 160 \text{ GeV}^2 \) and \( 75 \leq W \leq 175 \text{ GeV} \).

The transverse momentum, \( p_t^* \), and \( x_F \) distributions have been investigated separately for events with (LRG) and without a large rapidity gap (NRG) between the proton direction and the observed hadronic final state. In the whole range of \( x_F > 0.05 \) the values of \( \langle p_t^2 \rangle \) for NRG events are much larger than those for the LRG events. These results confirm that gluon radiation in LRG events is strongly suppressed as compared to 'standard' DIS events at comparable \( W \). A comparison of the data with the prediction of the QPM shows, however, that some QCD radiation is present also in LRG events.

The value of \( \langle p_t^2 \rangle \) in the LRG events is similar to that observed in deep inelastic \( \mu p \) scattering experiments on fixed targets at low \( W \) (\( < W > = 14 \text{ GeV} \)). This indicates that the multi-particle production in LRG events is similar to that in DIS at a scale of the final state invariant mass \( W = M_X \), where \( M_X \) is the invariant mass of the observed hadronic final state \( X \), excluding the proton.

The comparison of the \( x_F \) distributions in \( e^+e^- \) annihilation and in DIS events confirms the hypothesis that the hadron formation process in the current jet region is approximately independent of the type of the primary interacting particles.

The comparison of results presented here with those of DIS at low \( W \) from fixed target experiments allows a study of the development of QCD effects in the \( x_F \) and \( p_t^* \) distributions over a large range in \( W \) and \( Q^2 \). A significant increase of \( \langle p_t^2 \rangle \) with \( W \) is found. At HERA energies, the mean value of \( p_t^2 \) also rises with increasing \( Q^2 \) at fixed \( W \). This can be understood in terms of the increase of the momentum space allowing the formation of more multi-jet events.

### Table 6. \( \langle p_t^2 \rangle \) as a function of \( W \) in two intervals of \( x_F \). Statistical and systematic errors are given separately

| \( W \) GeV | \( < W > \) GeV | \( < p_t^2 > \) GeV² | \( < p_t^2 > \) GeV² |
|-----------------|-----------------|-----------------|-----------------|
| 77 - 95         | 86              | 0.59 ± 0.03 ± 0.07 | 1.08 ± 0.08 ± 0.13 |
| 95 - 122        | 108             | 0.67 ± 0.03 ± 0.04 | 1.19 ± 0.08 ± 0.10 |
| 122 - 141       | 132             | 0.74 ± 0.05 ± 0.04 | 1.07 ± 0.09 ± 0.18 |
| 141 - 173       | 157             | 0.78 ± 0.05 ± 0.09 | 1.44 ± 0.10 ± 0.12 |

### Table 7. \( \langle p_t^2 \rangle \) as a function of \( Q^2 \) in two intervals of \( x_F \). Statistical and systematic errors are given separately

| \( Q^2 \) GeV² | \( < Q^2 > \) GeV² | \( < p_t^2 > \) GeV² | \( < p_t^2 > \) GeV² |
|-----------------|-----------------|-----------------|-----------------|
| 10 - 20         | 14              | 0.59 ± 0.02 ± 0.03 | 1.05 ± 0.05 ± 0.07 |
| 20 - 40         | 28              | 0.77 ± 0.05 ± 0.03 | 1.27 ± 0.09 ± 0.04 |
| 40 - 80         | 54              | 0.86 ± 0.08 ± 0.10 | 1.46 ± 0.16 ± 0.17 |
| 80 - 160        | 110             | 0.96 ± 0.11 ± 0.15 | 2.12 ± 0.34 ± 0.77 |

### Fig. 7. \( \langle p_t^2 \rangle \) as a function of \( x_F \) from this analysis (NRG + LRG events) compared to results from \( \mu p \) DIS at \( \langle W > = 14 \text{ GeV} \) [46]. The curves show results from model calculations at HERA energy with the MEPS model (solid curve), the CDMBGF model (dashed curve) and the QPM (dotted curve).
Fig. 8. $<p_t^2>$ in two intervals of $x_F$ as a function of a) $W$ and b),c) $Q^2$ compared with results from $\mu p$ DIS experiments (EMC [5] and E665 [48]). The prediction of the MEPS Monte Carlo calculation is compared with the results of this analysis (solid curve) and of [5] (dashed curve).

Acknowledgements. The experiment was made possible by the inventiveness and the diligent efforts of the HERA machine group who continued to run HERA most efficiently during 1993. The design, construction and installation of the ZEUS detector has been made possible by the ingenuity and dedicated effort of many people from inside DESY and from the home institutes, who are not listed as authors. Their contributions are acknowledged with great appreciation. The strong support and encouragement of the DESY Directorate has been invaluable. We also gratefully acknowledge the support of the DESY computing and network services.

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