DESY 94-063

# Observation of jet production in deep inelastic scattering with a large rapidity gap at HERA

ZEUS Collaboration

11 April 1994

### Abstract

Events with a large rapidity gap in deep inelastic scattering with $Q^2 \geq 10$ GeV$^2$ have been studied in the ZEUS detector. The properties of these events with $W > 140$ GeV are consistent with a leading twist diffractive production mechanism. In the laboratory frame, with $E_T^{jet} \geq 4$ GeV, 15% of the events are of the 1-jet type with negligible 2-jet production. The single jet is back-to-back in azimuth with the scattered electron. No energy flow is observed between the jet and the proton direction. With a lower jet transverse energy cut 2-jet production is observed both in the laboratory and the $\gamma^* p$ centre-of-mass systems, demonstrating the presence of hard scattering in the virtual photon proton interactions that give rise to large rapidity gap events.

# 1 Introduction

In a recent publication [1], we reported on the observation of events with a large rapidity gap in electron proton deep inelastic scattering (DIS). Their general properties were found to be inconsistent with the dominant mechanism of DIS, where colour is transferred between the scattered quark and the proton remnant, and suggested that the underlying mechanism was of a diffractive nature and also leading twist. Preliminary results of a similar nature have been shown by the H1 Collaboration [2].

Diffractive processes are generally understood to proceed through the exchange of a colourless object with the quantum numbers of the vacuum called the pomeron. Because of the absence of colour flow diffractive processes should exhibit a high proportion of rapidity gap events at sufficiently high energies. However, the true nature of the pomeron is far from clear. Ingelman and Schlein [3], following earlier work of Low and Nussinov [4] and Donnachie and Landshoff [5], proposed that the pomeron behaves like a hadron and suggested that it may have a partonic structure which could be probed by a hard scattering process. The UA8 experiment later observed events with two high $p_T$ jets in diffractive $\bar{p}p$ interactions [6]. These results could be explained in terms of a partonic structure with a hard parton distribution in the pomeron.

In this paper we report the observation of jets in large rapidity gap events in DIS. The data presented here were collected in the 1993 HERA running period and constitute an increase in statistics by a factor 20 over our initial study [1].

# 2 Experimental setup

## 2.1 HERA machine conditions

The experiment was performed at the electron-proton collider HERA using the ZEUS detector. During 1993 HERA operated with bunches of electrons of energy $E_e = 26.7$ GeV colliding with bunches of protons of energy $E_p = 820$ GeV, with a time between bunch crossings of 96 ns. HERA is designed to run with 210 bunches in each of the electron and proton rings. For the 1993 data taking 84 paired bunches were filled for each beam and in addition 10 electron and 6 proton bunches were left unpaired for background studies. The electron and proton beam currents were typically 10 mA.

## 2.2 The ZEUS detector

ZEUS is a multipurpose magnetic detector whose configuration for the 1992 running period has been described elsewhere [7, 8]. Here we give a brief description concentrating on those parts of the detector relevant for the present analysis and those which were different for the 1993 running.

Charged particles are tracked by the inner tracking detectors which operate in a magnetic field of 1.43 T provided by a thin superconducting coil. Immediately surrounding the beampipe is the vertex detector (VXD) which consists of 120 radial cells, each with 12 sense wires. It uses a slow drift velocity gas (dimethylether)[9] and the presently achieved resolution is 50 $\mu$m in the central region of a cell and 150 $\mu$m near the edges. Surrounding the VXD is the central tracking detector (CTD) which consists of 72 cylindrical drift chamber layers, organised into 9 'superlayers' [10]. With the present understanding of the chamber, a spatial resolution of $\sim$ 280 $\mu$m has been achieved. In events with charged particle tracks, using the combined data from both chambers, resolutions of 0.6 cm in $Z$ and 0.1 cm in radius in the $XY$ plane[1] are obtained for the primary vertex reconstruction. From gaussian fits to the $Z$ vertex distribution, the rms spread is found to be 10.5 cm in agreement with the expectation from the proton bunch length.

The solenoid is surrounded by a high resolution uranium-scintillator calorimeter divided into three parts, forward (FCAL) covering the pseudorapidity[2] region $4.3 \geq \eta \geq 1.1$, barrel (BCAL) covering the central region $1.1 \geq \eta \geq -0.75$ and rear (RCAL) covering the backward region $-0.75 \geq \eta \geq -3.8$. Holes of $20 \times 20$ cm$^2$ in the center of FCAL and RCAL are required to accommodate the HERA beam pipe. The resulting solid angle coverage is 99.7% of $4\pi$. The calorimeter parts are subdivided into towers which in turn are subdivided longitudinally into electromagnetic (EMC) and hadronic (HAC) sections. The sections are subdivided into cells, each of which is viewed by two photomultiplier tubes. The calorimeter is described in detail in refs [11, 12, 13].

The C5 beam monitor, a small lead-scintillator counter, located at $Z$=-3.2 m was used to detect upstream proton beam interactions and to measure the timing and longitudinal structure of the proton and electron bunches. The vetowall detector, consisting of two layers of scintillator on either side of an 87 cm thick iron wall centered at $Z$=-7.3 m was also used to tag off-beam background particles.

For measuring the luminosity as well as for tagging very small $Q^2$ processes, we use two lead-scintillator calorimeters [14]. Bremsstrahlung photons emerging from the electron-proton interaction point (IP) at angles $\theta_\gamma \leq 0.5$ 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 or equal to 6 mrad and with energies $0.2E_e < E'_e < 0.9E_e$ are deflected by beam magnets and hit the electron calorimeter placed 35 m from the IP.

## 2.3 Trigger conditions

Data were collected with a three level trigger [7]. The First Level Trigger (FLT) is built as a deadtime free pipeline. The FLT for DIS events required a logical OR of three conditions on sums of energy in the EMC calorimeter cells: either the BCAL EMC energy exceeded 3.4 GeV; or the RCAL EMC energy, excluding the towers immediately adjacent to the beam-pipe, exceeded 2.0 GeV; or the RCAL EMC energy, including the beam-pipe towers, exceeded 3.75 GeV. For events with the scattered electron detected in the calorimeter, the FLT was essentially independent of the DIS hadronic final state. The FLT acceptance was greater than 97% for $Q^2 > 10$ GeV$^2$.

---

[1] The ZEUS coordinate system is defined as right handed with the $Z$ axis pointing in the proton beam direction, hereafter referred to as forward, and the $X$ axis horizontal, pointing towards the centre of HERA.

[2] Pseudorapidity $\eta$ is defined as $-\ln(\tan\frac{\theta}{2})$, where the polar angle $\theta$ is taken with respect to the proton beam direction from the nominal interaction point.

The Second Level Trigger (SLT) used information from a subset of detector components to differentiate physics events from backgrounds. The SLT rejected proton beam-gas events according to the event times measured in the rear calorimeter thereby reducing the FLT DIS triggers by an order of magnitude, but without loss of DIS events.

The Third Level Trigger (TLT) had available the full event information on which to apply physics-based filters. The TLT applied stricter cuts on the event times and also rejected beam-halo muons and cosmic muons. Events remaining after the above veto cuts were selected for output by the TLT if $\delta \equiv \Sigma_i E_i(1-\cos\theta_i) > 20\text{GeV} - 2E_\gamma$, where $E_i, \theta_i$ are the energy and polar angle (with respect to the nominal IP) of calorimeter cells and $E_\gamma$ is the energy measured in the photon calorimeter of the luminosity monitor. For fully contained events $\delta \sim 2E_e = 53.4$ GeV. Events from photoproduction processes peak at low values of $\delta$, because most of the scattered electrons remain within the rear beam pipe.

# 3 Kinematics of deep inelastic scattering

The kinematic variables used to describe deep inelastic scattering events

$$e\ (k)\ +\ p\ (P) \rightarrow e\ (k')\ +\ anything \tag{1}$$

are the following: the negative of the squared four momentum transfer carried by the virtual photon[3]:

$$Q^2 = -q^2 = -(k\ -\ k')^2; \tag{2}$$

the Bjorken variable:

$$x = \frac{Q^2}{2P \cdot q}; \tag{3}$$

the variable which describes the energy transfer to the hadronic final state:

$$y = \frac{q \cdot P}{k \cdot P}; \tag{4}$$

and $W$ the center-of-mass energy of the $\gamma^* p$ system, where:

$$W^2 = (q+P)^2 = \frac{Q^2(1-x)}{x} + M_p^2 \tag{5}$$

with $M_p$ the proton mass.

These variables, only two of which are independent, can be determined either from the scattered electron or from the hadronic system. The variable $y$, calculated from the electron variables, is given by the expression

$$y_e = 1 - \frac{E'_e}{E_e}\,\frac{1-\cos\theta'_e}{2} \tag{6}$$

---

[3] In the $Q^2$ range covered by this data sample, $ep$ interactions are described to sufficient accuracy for this analysis by the exchange of a virtual photon.

where $E'_e$, $\theta'_e$ denote the energy and angle of the scattered electron. This relation is valid for colliding beams in the zero mass approximation. Alternatively, $y$ can be determined from the hadronic system, using the Jacquet-Blondel technique [15]:

$$y_{JB} = \frac{\sum_i (E_i - p_{zi})}{2 \cdot E_e} \tag{7}$$

where $p_{zi} = E_i \cdot \cos\theta_i$ and $\theta_i$ is the polar angle determined using the Z-coordinate of the reconstructed IP in an event. The sum runs over the calorimeter cells associated with the hadronic system.

Studies of the HERA kinematics have shown that it is advantageous, for the present analysis, to use the so-called double angle (DA) method, in which the angles of the scattered electron and the hadron systems are used to determine $x$ and $Q^2$. Quantities determined in this way will be identified with the subscript DA. Formulae to calculate $Q^2_{DA}$, $W_{DA}$, $x_{DA}$ and $y_{DA}$ are given in [16].

The invariant mass of the hadronic system X detected in the calorimeter, $M_X$, can be determined from the calorimeter cell information as follows [1]. Denote the energy, momentum and polar angle of the final hadronic system to be $E_H$, $p_H$ and $\theta_H$ respectively; and $\vec{p_i}$ as the vector constructed from the energy $E_i$, angle $\theta_i$ and the corresponding azimuthal angle $\phi_i$ of cell $i$, then:

$$\cos\theta_H = \frac{\sum_i p_{z_i}}{|\sum_i \vec{p_i}|} \tag{8}$$

$$p_H^2 = \frac{Q^2_{DA}(1 - y_{DA})}{\sin^2\theta_H} \tag{9}$$

$$E_H = p_H \cos\theta_H + 2E_e y_{DA} \tag{10}$$

from which $M_X$ is determined by the definition $M_X = \sqrt{E_H^2 - p_H^2}$.

# 4 DIS data selection criteria

The off-line selection of DIS events was similar to that described in our earlier publications [1, 17]. Scattered electron candidates were selected by using the pattern of energy deposition in the calorimeter. The electron energy was required to be more than 5 GeV. The electron finder algorithm used in this analysis was optimised to have high efficiency at low energies at a cost of somewhat lower purity compared to the one used in our earlier study. The efficiency for finding isolated electrons in this energy range was greater than 97%. Furthermore we demanded:

- $Q^2_{DA} \geq 10$ GeV$^2$;
- $y_{JB} \geq 0.04$, to give sufficient accuracy for DA reconstruction;
- $\delta \geq 35$ GeV, to control radiative corrections and photoproduction background;
- $y_e \leq 0.95$, to reduce photoproduction background;
- scattered electrons whose impact points $(X, Y)$ in the RCAL are inside a square of $32 \times 32$ cm$^2$ centered on the beam axis were rejected;

- a vertex, as reconstructed from VXD+CTD tracks, was required with $|Z| \leq 30$ cm and a radial distance from the beam line $R \leq 10$ cm.

A total of 38192 events was selected in this way corresponding to a total integrated luminosity of 0.55 $\text{pb}^{-1}$. This sample was estimated to have a contamination from beam gas background of less than 0.5%, as determined from the number of events produced by unpaired electron and proton bunches. The background in the total DIS sample due to photoproduction was estimated to be about 16% from a fit to the shape of the $\delta$ distribution before the above cut on $\delta$ was applied [17]. An additional source of background is elastic QED Compton scattering. Seventy-eight such events were removed by a suitable algorithm, which finds two electromagnetic clusters in the calorimeter and one track in the CTD.

# 5 The Monte Carlo simulation

The expected final states from DIS were modelled using two different sets of generators, the first one for the description of standard DIS processes and the second to model pomeron exchange reactions. We shall use the term pomeron exchange as a generic name to describe the process which is responsible for creating large rapidity gap events.

Events from standard DIS processes with first order electroweak corrections were generated with HERACLES [18]. This was interfaced using DJANGO [19] to ARIADNE 4.0 [20] for modelling the QCD cascade. The fragmentation into hadrons was performed with the Lund string hadronization model [21] as implemented in JETSET [22]. The proton parton densities were chosen to be the MRSD-′ set [23] which represents closely our structure function results [17]. Note that these Monte Carlo codes do not contain explicit contributions from diffractive $\gamma^* p$ interactions.

In order to model the DIS hadronic final states with a large rapidity gap we have studied three Monte Carlo event samples, two of which were generated by POMPYT [24]. POMPYT is a Monte Carlo realisation of factorisable models for high energy diffractive processes, where within the PYTHIA [25] framework, the beam proton emits a pomeron, whose constituents take part in a hard scattering process with the virtual photon or its constituents. The quark momentum density in the pomeron for this analysis was taken to be either hard:

$$\beta f(\beta) = constant \cdot \beta(1-\beta) \tag{11}$$

or soft:

$$\beta f(\beta) = constant \cdot (1-\beta)^5, \tag{12}$$

where $\beta$ denotes the fraction of the pomeron momentum carried by the quark. Note that the hard quark density in POMPYT is the same as that proposed by Donnachie and Landshoff [26], up to a normalisation constant. The third sample was generated following the Nikolaev-Zakharov (NZ) model [27] which was interfaced to the Lund fragmentation scheme [28]. The NZ model, which is not factorisable, assumes 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. The resulting effective $\beta$ distribution lies between the two parameterisations chosen above for POMPYT.

NZ events were produced within the following ranges of generator parameters: $0.0001 < x < 0.05$; $-1. < t < -0.0001$ GeV$^2$ where $t$ is the momentum transfer squared between the virtual photon and the proton and $3.0 < (M^*)^2 < 10000.$ GeV$^2$ where $M^*$ is the invariant mass of the hadronic system produced by the diffractive excitation of the virtual photon. POMPYT events were produced within the following ranges of generator parameters: $0.9 < x_F < 0.9997$ where $x_F$ is the ratio of the longitudinal momentum of the scattered proton to that of the beam proton; $-10. < t < 0.$ GeV$^2$ (most of the events have $-t < 2.$ GeV$^2$) and the invariant mass of the $M^*$ plus scattered electron system was required to be greater than 5 GeV. For both POMPYT and NZ events $Q^2 > 4$ GeV$^2$ was required at the generator level. With these parameter settings the cross section predictions of these models differ by an order of magnitude. In this paper we consider only the predicted shapes of distributions. Monte Carlo event statistics are comparable to those of the data. QED radiative processes were not simulated for diffractive events, but with the selection cuts of section 4, radiative corrections to the rates of DIS events are below 10% [17]. All Monte Carlo events were passed through the standard ZEUS detector and trigger simulations and the event reconstruction package [7].

# 6 Results

## 6.1 Events with a large rapidity gap

Following our previous study [1] we define $\eta_{max}$ as the maximum pseudorapidity of all calorimeter clusters in an event, where a cluster is defined as an isolated set of adjacent cells with summed energy above 400 MeV. The distribution of $\eta_{max}$ is shown in Fig. 1a, uncorrected for detector effects. Values of $\eta_{max} \geq 4.3$, which are outside the calorimeter acceptance, occur when energy is deposited in many contiguous cells around the beam pipe in the proton direction. The dip in the $\eta_{max}$ distribution at $\eta_{max} \sim 1.1$ is a detector effect. The bulk of the events is centered around $\eta_{max} \sim 4$. In addition to this region of large $\eta_{max}$, a second class of events is observed which has $\eta_{max} < 1.5$, called large rapidity gap events. A total of 1973 such events is found. The photoproduction background for these events is about 3% as inferred from the shape of the $\delta$ distribution restricted to events with $\eta_{max} < 1.5$. Other backgrounds for these events are negligible.

The standard DIS model, shown as a dotted histogram in Fig. 1a, gives a reasonable account of the shape of the $\eta_{max}$ distribution for values above 1.5 but cannot account for the excess of events at lower values. To investigate how well a combination of standard DIS processes and diffractive interactions could describe this distribution, the fractions of standard DIS Monte Carlo events and pomeron events are adjusted to give the best fit to the $\eta_{max}$ distribution, normalising the total number of Monte Carlo events to the data. In Fig. 1a the fit with the hard POMPYT model is shown as a solid histogram, that with the soft POMPYT model as dash-dotted histogram and that with the NZ model as a dashed histogram. We find that a qualitative description of the data can be obtained with about 10% of all events coming from either the hard POMPYT or the NZ model. The soft POMPYT model does not give a good representation of the data and will not be considered further. From these fits we also find that the background of DIS events in the large rapidity gap sample is about 7%.

The correlation between $M_X$ and $W_{DA}$ is displayed in Fig. 1b where events with $\eta_{max} < 1.5$ are plotted with larger dots. Note, in this and all following figures, the data shown are uncorrected for detector effects and the $\eta_{max}$ cut. The large rapidity gap events are distinct from the standard events; they are characterized by small $M_X$ values, typically $M_X \leq 20$ GeV. In Fig. 1c the $M_X$ distribution is shown for events with $\eta_{max} < 1.5$. From the NZ and hard POMPYT models we learn that the reconstructed $M_X$ tends to overestimate the true value by about 7% at 10 GeV, the discrepancy increasing approximately linearly with $M_X$. The resolution of $M_X$ is roughly constant at a value of about 15%, for values of $M_X$ above 4 GeV. For both models the acceptance due to the $\eta_{max}$ cut is about 40% and high values of $M_X$ are preferentially suppressed. The hard POMPYT model, and to a lesser extent also the NZ model, are seen to predict fewer events for $M_X > 10$ GeV. We note that the 7% standard DIS Monte Carlo events populate mainly the region $M_X < 10$ GeV and do not account for the difference. In Figs. 1d-f the distributions of $W_{DA}$, $Q^2_{DA}$ and $x_{DA}$ are shown for $\eta_{max} < 1.5$. From Fig. 1 we see that neither the hard POMPYT nor the NZ models, with the parameter settings given in section 5, can describe all details of our data; however the gross features of the data are well enough described for the purposes of this analysis.

The features of large rapidity gap events displayed in Fig. 1 do not change if the threshold energy used in the cluster definition is varied by ±100 MeV.

We define the variable $\xi$ by the relation

$$\xi = \frac{M_X^2 + Q^2_{DA}}{W^2_{DA} + Q^2_{DA}}. \tag{13}$$

If large rapidity gap events are interpreted as due to pomeron exchange, then $\xi$ is the fraction of the proton's momentum carried by the pomeron. For the data with a large rapidity gap, due to acceptance cuts, $\xi$ lies in the range $5.6 \cdot 10^{-4}$ to $2.0 \cdot 10^{-2}$ with a mean value $< \xi >$ of $3.2 \cdot 10^{-3}$.

## 6.2 The $x$, $Q^2$ and $W$ dependence

In Regge phenomenology the amplitudes for two-body scattering by pomeron exchange are approximately independent of the centre-of-mass energy while Reggeon exchange amplitudes have inverse power law dependences. The contribution to $\gamma^* p$ scattering of a subprocess due to pomeron exchange should depend weakly on $W$, whereas $\pi$ or $\rho$ exchange would give a contribution falling approximately as $W^{-4}$ or $W^{-2}$. About the same $W$ dependences would be expected in $ep$ scattering for the relative contributions of these subprocesses to the total DIS sample. In order to examine the $W$ dependence we study the ratio $r$ of the number of events with $\eta_{max} < 1.5$ to the total number of DIS events. In this ratio several factors drop out, such as the flux of virtual photons, which are common for events with and without a large rapidity gap. The dependence of $r$ on $W_{DA}$ is shown in Fig. 2a. The figure also shows (as a histogram) the relative acceptance of the $\eta_{max}$ cut as a function of $W_{DA}$. For $W_{DA} \geq 140$ GeV it can be seen that the acceptance corrections are independent of $W_{DA}$. At smaller $W_{DA}$ values, the acceptance decreases since the final state hadronic system is boosted in the forward direction. The contribution of the large rapidity gap events to the DIS cross section is constant, within errors, for $W_{DA} \geq 140$ GeV, suggesting a diffractive type of interaction. For $W_{DA} \geq 140$ GeV the fraction of events with $\eta_{max} < 1.5$ is $7 - 8\%$ of the total DIS sample.

In Figs. 2b-d we show the ratio $r$ as a function of $Q^2_{DA}$ for three different intervals in Bjorken $x_{DA}$. The data were restricted to values $W_{DA} \geq 140$ GeV where Monte Carlo calculations show that the acceptance is flat in $Q^2_{DA}$. Since the total DIS sample shows a leading twist behaviour, the near constancy of $r$ with $Q^2_{DA}$ suggests that the production mechanism responsible for the large rapidity gap events should also be a leading twist effect.

## 6.3 Jet structure

In order to see whether the process leading to large rapidity gap events contains a hard component we studied the jet structure of the final state.

Two types of jet studies were performed. In the first study ($ep$), jet production was analysed in the laboratory system with respect to the beam axis to see how the transverse momentum of the electron was balanced by the hadronic system. The second study ($\gamma^* p$) was done in the virtual photon proton centre-of-mass system. We searched for jet structures using a cone based jet finding algorithm in pseudorapidity ($\eta$), azimuth ($\phi$) space [29, 30]. The cone radius $R = (\Delta\phi^2 + \Delta\eta^2)^{\frac{1}{2}}$ in the algorithm was set to 1 unit and calorimeter cells with EMC (HAC) energy below 60 MeV (110 MeV) were excluded. Also those cells associated with the scattered electron were removed when performing the jet search. Clusters were formed around cells with transverse energy greater than 300 MeV.

### 6.3.1 Jet studies in the $ep$ system

A cluster was called a jet if its transverse energy $E_T^{jet}$ in the laboratory with respect to the beam axis was larger than 4 GeV. An example of a 1-jet event is shown in Fig. 3a. Of the 1973 DIS events with $\eta_{max} < 1.5$ we found 294 events of the 1-jet type and 6 events of the 2-jet category. Jet rates for data and Monte Carlo simulations are given in Table 1a. Both the hard POMPYT and NZ models predict jet rates that are somewhat higher than the data. The total hadronic transverse energy distribution is shown in Fig. 4a for all events with $\eta_{max} < 1.5$ and for those with $\geq 1$ jet (hashed) and 2 jets (cross-hashed) in the final state . For $E_T \geq 10$ GeV practically all events are of the 1-jet type. In Fig. 4b, the distribution of the azimuthal angular difference $\Delta\phi_{e-jet}$ between the scattered electron and the jet is displayed. It shows that the scattered electron and the jet are preferentially back-to-back in azimuth. Fig. 4c shows the transverse jet energy for events with $\eta_{max} < 1.5$ containing at least one jet. Both the hard POMPYT and NZ models give reasonable accounts of the data.

Even if the cross section for jet production in $\gamma^*$pomeron interactions were large, we would not expect to see sizeable 2-jet production in the HERA system because of the requirement that $E_T^{jet} > 4$ GeV and the rather small centre-of-mass energy of the $\gamma^*$pomeron system. The average momentum of the pomeron for our event sample with $\eta_{max} < 1.5$ is small, $< \xi > \cdot E_p = 2.63$ GeV. If the minimum $E_T^{jet}$ requirement is lowered from 4 to 2 GeV the 1- and 2-jet rates increase as shown in Table 1a. A minimum jet energy of 2 GeV can be used because the $\eta_{max}$ cut removes the proton remnant in the FCAL. Also as we describe below in section 6.4, the jet profiles in rapidity and azimuth show that there is little hadronic activity outside the jets.

### 6.3.2 Jet studies in the $\gamma^* p$ system

The question whether the observed jets are a mere kinematic artifact of the necessity to balance the transverse momentum of the scattered electron is investigated in the $\gamma^* p$ system. To boost to the $\gamma^* p$ system the 4-momentum of the virtual photon is first reconstructed using DA variables. From Monte Carlo studies the uncertainty in the total hadronic transverse energy, $E_T^*$, generated by the Lorentz transformation is of the order of 650 MeV rms. In Fig. 4d we show the $E_T^*$ distribution for large rapidity gap events, and observe transverse energies as large as 15 GeV.

In this study the minimum transverse jet energy required, with respect to the $\gamma^*$ axis, was 2 GeV. With this definition 117 events were found of the 1-jet type, 69 of the 2-jet type and 7 of the 3-jet type. Jet rates in the $\gamma^* p$ system for data and Monte Carlo event samples are given in Table 1b. The events with $\geq 1$, $\geq 2$ and 3 jets are shown in Fig. 4d as hashed, cross-hashed and solid histograms respectively. Jet production is the dominant mechanism for $E_T^*$ values larger than 7 GeV. The NZ model gives jet rates in better agreement with the data than the hard POMPYT model, though both models reproduce the overall features of the data in the $\gamma^* p$ frame shown in Figs. 4e and 4f below.

In Fig. 4e the difference in azimuth for the 2-jet events ($\Delta\phi_{jet-jet}$) is displayed, showing that the jets are preferentially back-to-back. In Fig. 3b we show an example of a 2-jet event, which satisfies the 2-jet criteria in both the *ep* and $\gamma^* p$ frames. In Fig. 4f we show, for events with $\geq 1$ jet, the jet transverse energy distribution (with respect to the $\gamma^*$ direction) where jets with transverse energies, $E_T^{*jet}$, as large as 7 GeV are observed. The same holds for the sub-sample of 2-jet events. A momentum transfer squared $t$ between the virtual photon and the incident proton could contribute to the jet transverse energy in the $\gamma^* p$ frame. However the analysis of the jet transverse energy in the X system shows good agreement with that in the $\gamma^* p$ system demonstrating that a non-zero $t$ value is not the cause of the hard $E_T^{*jet}$ spectrum. Taking these observations together we have evidence for hard scattering processes in both the $\gamma^* p$ system and the X system, producing large rapidity gap events ($\eta_{max} < 1.5$) in *ep* scattering.

## 6.4 Energy flow around the jet axis

The transverse energy flow around the jet axis in the *ep* system was studied for 1-jet events with and without a rapidity gap as a function of $\Delta\phi$ and $\Delta\eta$ with respect to the jet axis. $\Delta\phi$ and $\Delta\eta$ are defined as the differences $\phi_{cell} - \phi_{jet\ axis}$ and $\eta_{cell} - \eta_{jet\ axis}$ respectively. The 1-jet DIS sample with $\eta_{max} > 1.5$ was restricted to the kinematic region $10^{-4} \leq x \leq 10^{-2}$ and $10 \leq Q^2 \leq 100$ GeV$^2$, where most of the events with $\eta_{max} < 1.5$ lie. To avoid any bias from the $\eta_{max}$ cut the jets for both samples were restricted to the region $\eta_{jet} < 0$. The transverse energy weighted flows around the jet axis with respect to $\Delta\eta$ and $\Delta\phi$ are shown in Figs. 3c and d respectively. In the case of the $\Delta\eta$ plot only transverse energy deposits in the hemisphere defined by the jet axis are included. Positive $\Delta\eta$ values are closer to the forward (proton beam) direction. For the $\Delta\phi$ plot transverse energy deposits with $\eta > 1.5$ were excluded. The following conclusions can be drawn. The jets are strongly collimated and the energy flow in the central core of the jet is very similar for events with a large rapidity gap and for standard DIS events ($\eta_{max} > 1.5$). However, while standard DIS events have a significant amount of transverse energy flow between the jet and the proton direction, there is practically no such energy flow seen for large rapidity gap events in the $\Delta\eta$ distribution. These results confirm our earlier conclusion [1] that, for large rapidity events, there is no colour flow between the jet and the proton direction. Both the hard POMPYT and NZ models give good descriptions of the jet profiles for events with $\eta_{max} < 1.5$.

## 7 Summary and conclusions

We have investigated the production of events with a large rapidity gap at HERA energies in the DIS regime for $Q^2 \geq 10$ GeV$^2$ with a twentyfold increase in statistics compared to our previous analysis [1]. Focussing on the region $W \geq 140$ GeV we find that the events with a large rapidity gap, defined by $\eta_{max} < 1.5$, account for $7 - 8\%$ of all DIS events, without acceptance corrections. The ratio $r$ of events with $\eta_{max} < 1.5$ to all DIS events is constant with $W$ suggesting a diffractive production mechanism. Since the total DIS sample shows a leading twist behaviour and the ratio $r$ is found to be approximately constant with $Q^2$, the large rapidity gap events are also consistent with leading twist. The analysis of the hadronic system in the $ep$ frame shows that for total transverse energies $E_T \geq 10$ GeV basically all events are of the 1-jet type, when the jet is required to have more than 4 GeV transverse energy with respect to the beam direction. The jet is found to be back-to-back with the scattered electron in the transverse plane. The analysis of the hadronic system in the $\gamma^* p$ centre-of-mass frame shows that for transverse jet energies greater than 2 GeV with respect to the virtual photon direction, small but significant two-jet production is observed with transverse jet energies up to 7 GeV. The two jets are produced preferentially back-to-back in azimuth. This demonstrates the presence of a hard scattering process in the virtual photon proton interaction in large rapidity gap events. The hard POMPYT and NZ models give fair descriptions of the shapes of the distributions studied in the large rapidity gap event sample. The $Q^2$ independence of $r$ together with the observation of high $E_T$ jets in the $\gamma^* p$ system and the noted absence of colour flow indicate that a natural interpretation is the interaction of the virtual photon with partons in a colourless object inside the proton.

## Acknowledgements

We thank Profs J. Bartels and G. Kramer for valuable discussions. The strong support and encouragement of the DESY Directorate: Prof. B.H.Wiik, Drs H. Krech, J. May, Profs G.A. Voss, and A. Wagner have been invaluable, as well as the support given by Dr. G. Söhngen.

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.

# References

[1] ZEUS Collab., M. Derrick et al., Phys. Lett. B315 (1993) 481.

[2] H1 Collab.: A. De Roeck, invited talk at the Europhysics Conf. on HEP, Marseille 1993 and DESY 94-005: J. B. Dainton, invited talk at the XVI International Symposium on Lepton-Photon Interactions, Cornell 1993 and RAL-94-012.

[3] G. Ingelman and P. Schlein, Phys. Lett. 152 B (1985) 256.

[4] F. E. Low, Phys. Rev. D12 (1975) 163; S Nussinov, Phys. Rev. Lett. 34 (1975) 1286 and Phys. Rev. D14 (1976) 246.

[5] A. Donnachie and P. V. Landshoff, Nucl. Phys. B244 (1984) 322.

[6] UA8 Collab., A. Brandt et al., Phys. Lett. B 297 (1992) 417.

[7] The ZEUS Detector, Status Report 1993 , DESY 1993.

[8] ZEUS Collab., M. Derrick et al., Phys. Lett. B293 (1992) 465.

[9] C. Alvisi et al., Nucl. Instr. and Meth. A305 (1991) 30.

[10] C.B. Brooks et al., Nucl. Instr. Meth. A283 (1989) 477; B Foster et al., Nucl. Instr. Meth. A338 (1994) 254.

[11] A. Andresen et al., Nucl. Inst. and Meth. A309 (1991) 101.

[12] A. Bernstein et al., Nucl. Inst. and Meth. A336 (1993) 23.

[13] A. Caldwell et al., Nucl. Inst. and Meth. A321 (1992) 356.

[14] J. Andruszków et al., DESY 92–066 (1992).

[15] F. Jacquet and A. Blondel in Proc. of the study for an *ep* facility in Europe, DESY 79/48(1979), 391-394, ed. U. Amaldi.

[16] S. Bentvelsen, J Engelen and P Kooijman, Proc. of the Workshop on Physics at HERA, Vol 1, DESY (1992) 23.

[17] ZEUS Collab., M. Derrick et al., Phys. Lett. B316 (1993) 412.

[18] A. Kwiatkowski, H. Spiesberger and H.J. Möhring, Proc. of the Workshop on Physics at HERA, Vol. 3, DESY (1992) 1294.

[19] G. A. Schuler and H. Spiesberger, ibid 1419.

[20] ARIADNE 4.0 Program Manual, L. Lönnblad, DESY-92-046 (1992).

[21] B. Andersson et al., Phys. Rep. 97 (1983) 31.

[22] T. Sjöstrand, Comp. Phys. Comm. 39 (1986) 347 and T. Sjöstrand and M. Bengtsson, Comp. Phys. Comm. 43 (1987) 367.

[23] A. D. Martin, W.J. Stirling and R.G. Roberts, Phys. Lett. B306 (1993) 145.

[24] P. Bruni and G. Ingelman, DESY 93-187, to be published in the proceedings of the Europhysics Conf. on HEP, Marseille 1993.

[25] H.-U. Bengtsson and T. Sjöstrand, Comp. Phys. Comm. 46 (1987) 43 and T. Sjöstrand, CERN-TH.6488/92.

[26] A. Donnachie and P.V. Landshoff, Phys. Lett. 191B (1987) 309; Nucl. Phys. B303 (1988) 634.

[27] N.N. Nikolaev and B.G. Zakharov, Z. Phys. C 53 (1992) 331.

[28] A. Solano, Ph D Thesis, University of Torino 1993, unpublished.

[29] UA1 Collab., G. Arnison et al., Phys. Lett. 123B (1983) 115.

[30] J. Huth et al., FERMILAB-Conf-90-249-E.

| (a) $ep$ | | Data | Hard POMPYT | NZ |
|---|---|---|---|---|
| $E_T^{jet} > 4$ GeV | 1 jet<br>2 jets | 15± 1%<br>0.3± 0.1% | 21.5%<br>0.5% | 23%<br>0.6% |
| $E_T^{jet} > 2$ GeV | 1 jet<br>2 jets | 66± 2%<br>5± 0.5% | 76%<br>2.2% | 69%<br>3.8% |
| (b) $\gamma^* p$ | | Data | Hard POMPYT | NZ |
| $E_T^{*jet} > 2$ GeV | 1 jet<br>2 jets<br>3 jets | 5.9± 0.5%<br>3.5± 0.4%<br>0.4± 0.1% | 2.0%<br>0.5%<br>- | 4.6%<br>2.2%<br>- |

Table 1: (a) Percentage of large rapidity gap events with jets in the $ep$ frame for two values of the minimum transverse jet energies. (b) Percentage of large rapidity gap events for jets in the $\gamma^* p$ frame with a minimum transverse jet energy of 2 GeV.

Figure 1: (a) The distribution of the calorimeter cluster with maximum rapidity, $\eta_{max}$, for the DIS sample. The dotted histogram shows the standard DIS Monte Carlo sample alone, the other histograms show fits to the data using a combination of standard DIS Monte Carlo plus hard POMPYT events (full), or plus soft POMPYT events (dash-dotted) or plus NZ events (dashed). The combined total of Monte Carlo events has been normalised to the data. (b) The correlation between the mass of the hadronic system $M_X$ and $W_{DA}$. (c) The distribution of $M_X$ in large rapidity gap events with comparisons from the hard POMPYT and NZ models, see text for details. (d) The distribution of $W_{DA}$ for events with a large rapidity gap with the same model comparisons. (e) $Q^2_{DA}$ and (f) Bjorken $x_{DA}$ distributions for events with $\eta_{max} < 1.5$ with model comparisons as labelled.

Figure 2: (a) The ratio $r$ of the number of events with $\eta_{max} < 1.5$ to the total number of DIS events as a function of $W_{DA}$. The histogram shows the acceptance of the $\eta_{max}$ cut in arbitrary units. (b), (c) and (d) The ratio $r$ for $W_{DA} > 140$ GeV as a function of $Q^2_{DA}$ for three intervals in Bjorken $x_{DA}$: $3 - 6 \cdot 10^{-4}$, $6 - 12 \cdot 10^{-4}$ and $12 - 24 \cdot 10^{-4}$ respectively.

Figure 3: a) Transverse energy deposition in $\eta - \phi$ space for a large rapidity gap event with one hadronic jet balancing the electron's transverse momentum. (b) A similar display for a large rapidity gap two-jet event. (c), (d) The transverse energy weighted profiles for jets with $\eta_{jet} < 0$ in events with $\eta_{max} < 1.5$ (filled circles) and with $\eta_{max} > 1.5$ (open circles); (c) shows the rapidity profile with a hemisphere cut and (d) the azimuthal profile excluding energy deposits with $\eta > 1.5$, see text. The profiles for jets in events with a large rapidity gap are compared with expectations of the hard POMPYT and NZ models (full and dashed histograms respectively).

Figure 4: (a) The distribution of the total hadronic transverse energy seen in the calorimeter, $E_T$, for DIS events with a large rapidity gap and those with, in addition, $\geq 1$ (hashed) and $\geq 2$ jets (cross-hashed). A jet is required to have at least 4 GeV transverse energy with respect to the beam direction. (b) The difference in azimuthal angle between the scattered electron and the jet. (c) The jet transverse energy in the laboratory for events in the DIS sample with a large rapidity gap. (d) The total hadronic energy transverse to the virtual photon direction, $E^*_T$, for DIS events with a large rapidity gap and those with, in addition, $\geq 1$ (hashed), $\geq 2$ (cross-hashed) or 3 jets (solid) in the final state. Here a jet is required to have at least 2 GeV with respect to the virtual photon direction. (e) The difference in azimuthal angle between the two jets in the $\gamma^* p$ centre-of-mass system (2-jet sample). (f) The distribution of the jet energy transverse to the virtual photon direction for the 1- and 2-jet samples. In figures (b), (c), (e) and (f) the data are shown as black dots with errors and the results from the hard POMPYT and NZ models as full and dashed histograms respectively.