RECENT RESULTS FROM THE ZEUS EXPERIMENT AT HERA

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ABSTRACT

Results from analyses of the data taken with the ZEUS detector in 1992 and 1993 are presented. The topics are selected from photoproduction, deep inelastic scattering in neutral and charged current reactions, and large rapidity gap events.

1 The ZEUS Detector

ZEUS is a magnetic detector[1] at the electron-proton storage ring HERA. Figure 1 shows a vertical cross section through the detector in the plane which contains the HERA beamline. Protons of 820 GeV collide with electrons of 26.7 GeV in the center of the detector. The interaction point is surrounded by the tracking detector system which consists of a small drift chamber, the vertex detector,[2] a large cylindrical drift chamber,[3] and planar drift chambers and transition radiation detectors at both ends of the large cylindrical drift chamber. The tracking detector system is placed inside a superconducting solenoid which produces a magnetic field of 1.43 T. The high resolution uranium-scintillator calorimeter,[4] which encloses the tracking detector system, consists of three parts: the forward* calorimeter (FCAL), the barrel calorimeter (BCAL), and the rear calorimeter (RCAL). The high resolution calorimeter covers the complete solid angle of 4π except for holes of 20 cm $\times$ 20 cm cross section in the FCAL and RCAL to accommodate the HERA beampipe. The inner ZEUS detector is surrounded by an iron flux return yoke. The yoke is instrumented with proportional tube chambers and acts as a backing calorimeter to detect energy leaking out of the high resolution calorimeter. The iron yoke is sandwiched between limited streamer tube chambers to identify and to measure muons. In the forward direction, muon detection is reinforced by additional toroidal magnets, and a system of drift chambers and limited streamer tube chambers. The luminosity monitor[5] consists of two small lead-scintillator calorimeters in the HERA tunnel which measure the rate of the Bethe-Heitler process $e + p \rightarrow e' + p + \gamma$ by detecting the scattered electron and the radiated photon. The leading proton spectrometer consists of six stations with silicon strip detectors very close to the proton beam in the HERA tunnel to measure protons scattered under very small angles.

*The direction of the incident protons is called forward. The ZEUS coordinate system is chosen such that the z axis points forward, the y axis upwards, and the x axis towards the center of the HERA ring.

2 Photoproduction Results from ZEUS

When a 26.7 GeV electron collides with an 820 GeV proton in HERA, the most likely process is that it emits a virtual photon and gets scattered under an angle Θ_e. The photon then interacts with the proton, see Fig. 2.

The virtuality of the emitted photon is given by the square of the difference of the four vectors of the incoming electron (k) and the outgoing electron (k'):

$$Q^2 = -q^2 = -(k - k')^2.$$

We are dealing with a photoproduction reaction if $Q^2 \approx 0$. The energy transfer from the electron to the proton in the rest system of the proton is given by:

$$\nu = \frac{2E_p}{m_p}\left(E_e - E'_e cos\frac{\Theta_e}{2}\right),$$

where E_p and m_p are the energy and the mass of the interacting proton, and E'_e is the energy of the scattered electron. Alternatively, the Lorentz invariant variable

$$y = \frac{\nu}{\nu_{max}} \approx \frac{E_e - E'_e}{E_e}$$

is used. Another quantity which characterizes the process is the hadronic center of mass energy W which is given by:

$$W^2 = (q + p)^2 \cong 4\ E_\gamma E_p.$$

The electron-proton collider HERA is equivalent to a fixed target photoproduction experiment with photon energies up to 48 TeV.

Experimentally, one distinguishes two classes of photoproduction events:

- In tagged photoproduction events, the scattered electron is detected in the electron calorimeter of the luminosity monitor. This restricts the Q^2 of the events to $10^{-7} < Q^2 < 2 \times 10^{-2}$ GeV^2.
- In untagged photoproduction events, the scattered electron is not detected. It is detectable in the ZEUS calorimeter for $Q^2 > 4$ GeV^2. For untagged photoproduction events, the median value of Q^2 is ≈ 0.001 GeV^2.

In both cases, the average Q^2 values are very small, and it is justified to speak of photoproduction reactions.

2.1 The Many Faces of the Photon

It is well-known that in reactions which involve only low transverse momenta, the photon behaves like a hadron. At low energies, this feature is sufficiently well-described by the vector meson dominance model (VDM).[6] The photon fluctuates into a vector meson state (ρ, ω, ϕ) which then interacts with the proton. These interactions are elastic vector meson scattering, single and double diffractive scattering, and nondiffractive scattering, see Fig. 3. In nondiffractive scattering, the final state may also contain high transverse momentum particles.

Photoproduction reactions involving high transverse momenta are supposed to be described by perturbative Quantum Chromodynamics (QCD). In lowest order QCD, there are two ways for the photon to interact with constituents of the proton:

- As shown in Fig. 4(a), the photon couples directly to the electric charge of a quark inside the proton. The whole momentum of the photon is transferred to the scattered quark.
- The photon fluctuates into a hadronic state and only a fraction of this state interacts with the proton. An example is shown in Fig. 4(b). In this case, part of the initial momentum of the photon is carried away by the photon remnant. One calls this a resolved photon interaction.

The distinction between direct and resolved processes is not so strict in higher orders of QCD.

2.2 The Total Photoproduction Cross Section

In the ZEUS experiment, the total photoproduction cross section was measured using a sample of tagged photoproduction events at an average photon-proton center-of-mass energy of $< W_{\gamma p} > = 180$ GeV (Ref. 7). We identified the major contributions to the total cross section by fitting Monte Carlo models of the various subprocesses to the measured energy distributions in the calorimeter parts (FCAL, BCAL, and RCAL). The same models were used to calculate the detector acceptances for the subprocesses. In this way, the total cross section as well as the fractional ones for the subprocesses were determined. Primarily, a cross section for the ep reaction is calculated. It is related to the γp cross section by

$$\sigma_{ep} = F_{e\gamma} \cdot \sigma_{\gamma p},$$

where $F_{e\gamma}$ is a known flux factor for the radiation of photons from the incoming electron. The result is:

$$\sigma_{tot}(\gamma p) = (143 \pm 4 \pm 17)\ \mu b.$$

The contributions of subprocesses are: $(12.7 \pm 1.5 \pm 4.7)\%$ elastic vector meson scattering, $(23.3 \pm 2.7 \pm 4.3)\%$ for single- and double-diffractive processes, and $(64.0 \pm 0.9 \pm 3.6)\%$ for nondiffractive reactions. Figure 5 shows the total photoproduction cross section, measured by ZEUS, together with the measurement of H1 (Ref. 8) at HERA and measurements at lower $W_{\gamma p}$ values.[9] Also shown are extrapolations of cross-section parametrizations by Donnachie and Landshoff (DL),[10] and by Abramowicz, Levin, Levy, and Maor (ALLM),[11] which are both based on Regge Theory, as well as a QCD-inspired prediction (minijets).[12] The Regge-based extrapolations are in agreement with the ZEUS and H1 measurements. The "minijet" prediction shows a faster rise with $W_{\gamma p}$ but is also compatible with the data.

2.3 Vector Meson Production

Elastic vector meson production has been observed at ZEUS in various channels in untagged photoproduction events. In Figs. 6(a)-(d), the signals for ρ, ω, ϕ, and J/Ψ production are shown.

The analyses are still in progress. Preliminary cross sections are:[13] for ρ production,

$$\sigma(\gamma p \to \rho^0 p) = (12.5 \pm 0.7 \pm 2.8)\ \mu b \quad \text{for } p_t^2 < 0.5 \text{ GeV}^2,\ < W_{\gamma p} > = \ 70 \text{ GeV},$$

where p_t is the transverse momentum of the ρ^0.

For J/Ψ production,

$$\begin{aligned}
\sigma(\gamma p \to J/\Psi + p \to e^+e^- + p) &= (62 \pm 13 \pm 13)\ nb \text{ at } 40 < W_{\gamma p} < \ 75 \text{ GeV} \\
\sigma(\gamma p \to J/\Psi + p \to e^+e^- + p) &= (70 \pm 16 \pm 13)\ nb \text{ at } 75 < W_{\gamma p} < 140 \text{ GeV}
\end{aligned}$$

$$\sigma(\gamma p \to J/\Psi + p \to \mu^+\mu^- + p) = (48 \pm 12 \pm 14)\ nb \text{ at } 40 < W_{\gamma p} < 90 \text{ GeV}$$
$$\sigma(\gamma p \to J/\Psi + p \to \mu^+\mu^- + p) = (84 \pm 21 \pm 24)\ nb \text{ at } 90 < W_{\gamma p} < 140 \text{ GeV}.$$

In the case of "elastic" J/Ψ cross sections, an as-yet-undetermined contribution from proton dissociation is present in the data. All cross sections are corrected for the branching ratios of the J/Ψ decay channels. In Fig. 7, the ZEUS results are compared to measurements at lower energies.[14] While $\sigma(\gamma p \to \rho^0 p)$ is consistent with a slow rise for $W > 10$ GeV, the $\sigma(\gamma p \to J/\Psi + p)$ shows a significant rise.

2.4 Inclusive Charged Particle $\mathrm{p_t}$ Distribution

Inclusive charged particle distributions have been determined using a sample of tagged photoproduction events. To ensure a precise tracking and good geometrical acceptance, tracks were required to have transverse momenta $p_t > 300$ GeV/c and pseudorapidities[†] $-1.2 < \eta < 1.4$ ($27.7° < \Theta_{track} < 146.5°$). Preliminary results for the inclusive charge particle p_t distributions have been obtained for nondiffractive events and two samples of diffractive events with average masses of the diffractive system of $< \mathrm{M_x} > = 5$ GeV and $< \mathrm{M_x} > = 10$ GeV.[15] For these distributions, the average γp cms energy is $< W_{\gamma p} > = 180$ GeV. The results are shown in Fig. 8. At low p_t, the distributions show an e^{-bp_t} behavior with coefficients $b = 4.87 \pm 0.1 \pm 0.08$ for nondiffractive events, $b = 5.19 \pm 0.05 \pm 0.23$ for $< \mathrm{M_x} > = 10$ GeV, and $b = 5.61 \pm 0.1 \pm 0.14$ for $< \mathrm{M_x} > = 5$ GeV. In the nondiffractive event sample, the distribution shows a clear excess of events at higher transverse momenta. This indicates the presence of hard scattering processes in photoproduction.

2.5 High $\mathrm{p_t}$ Photoproduction

Hard scattering processes with high transverse momenta in the final state manifest themselves by the appearance of jets. A search for jets was performed with the ZEUS detector.[16] Jets were defined by a cone algorithm.[17] The radius of the cone was chosen to be $\mathrm{R} = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 1$ where ϕ is the azimuthal angle. Figure 9(a) shows the inclusive jet cross section for the kinematical regime $\mathrm{E_t^{jet}} >$ 8 GeV, $-1 < \eta^{jet} < 2$, and $0.2 < \mathrm{y} < 0.85$. Figure 9(b) shows the corresponding

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[†]The pseudorapidity is defined as $\eta = -ln(tan\frac{\Theta}{2})$. Note that $\Theta = 0°$ is the proton direction. Positive η values correspond to the forward direction.

η distribution of the found jets. The data are compared to Monte Carlo model calculations using the proton structure function parametrization MRSD[18] and two different photon structure function parametrizations, GRV[19] and LAC1.[20]

As outlined above, the photon interaction may be direct or resolved. Figure 10 visualizes one possibility of a resolved photon interaction. If two jets are detected in such events, one can determine the fraction x_γ of the photon's momentum which took part in the hard scattering process:

$$x_\gamma = \frac{\sum_{jets}(E - p_z)}{\sum_{cal}(E - p_z)},$$

where E and p_z are the energy and the longitudinal momentum measured in a single calorimeter cell. The longitudinal momentum p_z is calculated from the cell energy and the polar angle of the center of the cell with respect to the interaction vertex. A sum runs over all cells associated with the jets or all cells in the calorimeter. The distribution of measured x_γ values[21] is presented in Fig. 11. One recognizes a clear peak at high x_γ values coming from direct photon interactions and a rather flat distribution down to low x_γ values which originates from resolved photon processes. Also shown are Monte Carlo simulations of only direct interactions, only resolved processes, and the sum of the two contributions. These simulations describe fairly well the measured data and confirm the above interpretation of the x_γ distribution. Quantitatively, one finds for the kinematical region $0.2 < y < 0.7$, $\mathrm{E_T^{jets}} > 5\ \mathrm{GeV}^2$, and $\eta^{jets} < 1.6$:

$$\sigma_{res} = (21.1 \pm 5.2 \pm 5.7)\ nb \quad \text{and}$$

$$\sigma_{dir} = (9.4 \pm 2.7 \pm 2.7)\ nb.$$

At photon-proton center-of-mass energies achievable at HERA, the resolved photon interactions dominate in hard scattering processes.

2.6 Study of the Photon Remnant

The measured x_γ distribution proves the existence of both direct and resolved photon processes. Figure 12 demonstrates the presence of the resolved component in a different way for events in which jets have been detected. It shows a scatter plot of the energy measured in the rear calorimeter (E_{RCAL}) versus the pseudorapidity of the most backward-going jet (η_{min}). As long as η_{min} is in the rear direction, i.e., η_{min} is negative, a clear correlation with E_{RCAL} is visible in the way that E_{RCAL} decreases when η_{min} increases. However, if η_{min} gets larger than zero, i.e., the most backward jet is going forward, many events remain with sizable energy deposits in the RCAL. These energy deposits are due to photon remnants. To further study the behavior of the photon remnant, events were selected with a total transverse energy of more than 12 GeV measured in the calorimeter outside a cone of 10° in the forward direction. A cluster algorithm was applied to all events and was forced to find three separate energy clusters in addition to the proton remnant ($3+1$ cluster events).[22] The clusters were ordered according to their measured tranverse energies in the calorimeter. For each cluster, an axis was determined as the direction of the vector sum of the momenta measured in the associated calorimeter cells. The pseudorapidities of the cluster axes were required to be $\eta(3) < -1$ for cluster 3 and $\eta(1,2) < 1.6$ for clusters 1 and 2. In order to guarantee that the event was generated by a hard scattering process, the transverse momenta of clusters 1 and 2 were requested to be $p_t(1,2) > 5$ GeV. These cuts select events in which cluster 3 is predominantly the photon remnant. For each cluster, longitudinal and transverse energies with respect to the cluster axes were calculated as $E_{L,T} = \sum_i E^i_{L,T}$ where the sum runs over the associated calorimeter cells. In Fig. 13, the average longitudinal and transverse energies $< E_L >$ and $< E_T >$ are plotted versus the cluster energies. Here, $< E_L >$ as well as $< E_T >$ rise linearly with the cluster energy for all three clusters in the same way. The rise of $< E_T >$ with the cluster energy is a typical feature of a QCD jet. Therefore, one concludes that the photon remnant behaves like a normal jet produced by colored constituents.

3 Deep Inelastic Scattering

Deep inelastic scattering (DIS) for neutral current events is described in lowest order, which is the naive quark parton model, by the diagram in Fig. 14. The incoming electron is scattered by exchanging either a photon or a Z-boson with one of the quarks inside the proton. The incoming quark, carrying the fraction x of the proton's four momentum p, is scattered out of the proton and gives rise to the observable current jet. The remnants of the proton form a jet which goes mainly into the forward direction.

The kinematics of the reaction is determined by two variables. Commonly used are the negative square of the four momentum transfer Q^2, which is nonzero for DIS events, and the struck quark's momentum fraction x which is given by

$$x = \frac{Q^2}{2q \cdot p} \ .$$

The normalized energy transfer variable y can be expressed in a Lorentz-invariant way

$$y = \frac{q \cdot p}{k \cdot p} \ .$$

These three variables are not independent. They are connected with the center-of-mass energy squared of the ep system $s = (k+p)^2$:

$$xys = Q^2.$$

At HERA, the ep center-of-mass energy is $\sqrt{s} = 296$ GeV. The virtual photon-proton center-of-mass energy is $W = \sqrt{(q+p)^2}$. Figure 15 shows the kinematical regime in the Q^2 vs. x plane covered by the ZEUS measurements. The line $y = 1$ is the kinematical limit. The shape of the scatter plot at low x and low Q^2 is determined by the calorimeter acceptance; the scattered electron starts to escape detection in the calorimeter through the rear beampipe hole. Also shown are the kinematical regimes covered by previous fixed target experiments.

The double differential cross section for the production of DIS neutral current events is given in terms of three structure functions F_2, F_L, and xF_3:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[(1+(1-y)^2)\cdot F_2(x,Q^2) - y^2 \cdot F_L(x,Q^2) + (1-(1-y^2))\cdot xF_3(x,Q^2)].$$

The structure function xF_3 originates from the Z-boson exchange, the parity violating weak neutral current contribution. At Q^2 values presently accessible with sufficient statistics, given the collected luminosity at HERA, this contribution is small and generally neglected. In certain kinematical regions, where it cannot be neglected, the data are corrected such that F_2 gives the cross section for the photon exchange only. The total virtual photon-proton cross section can then be written as:

$$\sigma_{tot}(\gamma^* p) = \sigma_T(x,Q^2) + \sigma_L(x,Q^2) = \frac{4\pi^2\alpha}{Q^2(1-x)} \cdot F_2(x,Q^2).$$

3.1 Measurement of F_2

DIS events are identified by the detection of the scattered electron. ZEUS is a hermetic detector, i.e., particles are detected in the full solid angle 4π, except in the beampipe region. Therefore, the kinematical variables can be calculated from either the scattered electron, the measured hadronic system, or any combination of them. In the ZEUS analysis, two different methods were used:

- Electron method:
  The measured energy $E_e^{'}$ and angle Θ_e of the scattered electron are used (see Fig. 14). This method gives a good resolution for Q^2 and for x in the region of high y.
- Double angle (DA) method:[23]
  $\Theta_e^{'}$ and γ_h are used. The hadronic angle γ_h is given by :

$$cos\gamma_h = \frac{(\Sigma p_x)^2 + (\Sigma p_y)^2 - (\Sigma(E - p_z))^2}{(\Sigma p_x)^2 + (\Sigma p_y)^2 + (\Sigma(E - p_z))^2}.$$

In the naive quark parton model, γ_h is the angle under which the struck quark emerges. The DA method has the advantage of being rather insensitive to the energy scale of the calorimeter measurement. Variables determined in this way are denoted by the subscript DA.

Figures 16(a) and 16(b) show the measured F_2 values as functions of x for different Q^2 values.[24] The background from photoproduction events in which electrons or other particles are misidentified as the scattered electrons is of the order of a few percent. In the worst bin, it is 12%. Data were corrected for this background bin-by-bin on a statistical basis.

The prominent feature of the data is the strong rise of F_2 with decreasing x at all measured Q^2 values. This means that the parton density increases at small x.

Perturbative QCD predicts for fixed x the dependence of F_2 on Q^2. The Q^2 dependence of the structure function F_2 is described by the GLAP evolution equation:[25]

$$\frac{dF_2}{dlnQ^2} = \sum_q e_q^2 \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{qq}\left(\frac{x}{y}\right) q(y, Q^2) + P_{qg}\left(\frac{x}{y}\right) g(y, Q^2) \right].$$

The quark and gluon distribution functions $q(y, Q^2)$ and $g(y, Q^2)$ describe the probability to find a quark or gluon with momentum fraction y inside the proton in a reaction at Q^2. P_{qq} and P_{qg} are the splitting functions. $P_{qq}(\frac{x}{y})$ gives the probability to find a quark with momentum fraction x of the proton coming from the splitting (gluon radiation) of a quark with momentum fraction y. P_{qg} gives the probability to find a quark with momentum fraction x from the splitting of a gluon (quark pair production) with momentum fraction y. The splitting functions are calculable in perturbative QCD.

Various authors have parametrized the structure function $F_2(x)$ at some $Q^2 = Q_o^2$ and used the GLAP equation to predict the QCD evolution. The parameters of $F_2(x)$ are then fitted to data used as experimental input at all x and Q^2 values. Several such parametrizations are compared to the ZEUS data in Figs. 16(a) and 16(b). They differ in the assumptions about the x dependence, in particular about the gluon momentum distribution function $xg(x)$ in the proton at Q_o^2. The following parametrizations are plotted:

- MRSD$'_{\mathrm{o}}$:[26] Input data from fixed target experiments are used. The gluon distribution at small x is assumed to behave like $xg(x) \to$ const.
- MRSD$'_{-}$:[18] The same input is used as for MRSD$'_{\mathrm{o}}$ but $xg(x) \to x^{-0.5}$ for small x.
- CTEQ2D:[27] Fixed target data plus the HERA 1992 data have been used as input and a gluon distribution $xg(x) \to x^{-n}$ ($n \approx 0.3$) for small x is assumed.
- GRV-HO:[28] These authors start the Q^2 evolution already from $Q_0^2 = 0.3$ GeV^2 and use valence-type distributions for the quarks, the sea, and the gluons.
- GRV-MCH:[29] This is the same as GRV-HO but the charm quark mass is properly taken into account.

The data are best described by parametrizations with singular gluon distributions at small x, either parametrized or generated dynamically (GRV).

Figure 17 shows the F_2 measurements from ZEUS as functions of Q^2 at different x values. Also shown are data from H1,[30] NMC,[31] and E665.[32] The data are consistent with each other and are well in agreement with the predicted scaling violations, i.e., the variation of F_2 with lnQ^2 at a fixed x. Also plotted are predictions from the MRSD$'_{\mathrm{o}}$ and MRSD$'_{-}$ parametrizations.

Scaling violations occur through gluon radiation from quarks and quark pair production from gluons. At $x < 10^{-2}$, the latter process dominates the scaling violations. This property can be used to extract the gluon density from the slope

$dF_2/dlnQ^2$ of the proton structure function. Two methods have been developed so far:

- The Prytz method:[33] The quark contribution is neglected at small x. In this approximation, the gluon momentum distribution $xg(x)$ is directly related to the scaling violations. The result for the gluon distribution has been calculated in leading order (LO) QCD and next-to-leading order (NLO). The corresponding results are respectively:

$$\begin{aligned} xg(x) &= \frac{dF_2(x/2, Q^2)/dlnQ^2}{(40/27)\alpha_s/4\pi} \\ xg(x) &= \frac{dF_2(x/2, Q^2)/dlnQ^2}{(40/27 + 7.96\alpha_s/4\pi)} - \frac{(20/9)(\alpha_s/4\pi)N(x/2, Q^2)}{40/27 + 7.96\alpha_s/4\pi}. \end{aligned}$$

- The EKL method:[34] These authors solve the full GLAP equation in moment space in NLO and NNLO for the gluon contribution. They make the assumption that the gluon distribution at small x is of the functional form $xg(x) \sim x^{-\omega_o}$. The x dependence of the singlet part of F_2 is assumed to be the same. The value of ω_o is an input parameter and has to be determined from the data.

ZEUS used both methods to extract the gluon distribution from their measured F_2 data.[35] The results are shown in Fig. 18.

ZEUS also performed a complete fit of the GLAP equation to the data. The resulting gluon distribution is shown in Fig. 18. The data are compared to extrapolations from the MRSD$'_{\rm o}$ and MRSD$'_-$ parametrizations. The data suggest a strong rise of $xg(x)$ towards low x. Parametrizations with a flat gluon distribution at small x, like MRSD$'_{\rm o}$, are disfavored.

The x dependence of F_2 is not directly predicted by the GLAP equation. For the gluon distribution, an x dependence can be derived which is however a function of Q^2:

$$xg(x) \sim exp[2\xi(Q^2_\circ, Q^2)ln(1/x)]^{\frac{1}{2}}.$$

The function $\xi(Q^2_\circ, Q^2)$ is calculable in perturbative QCD. A different perturbative approach for the QCD evolution of structure functions is the BFKL equation.[36]

This results in:

$$xg(x) \sim x^{-\lambda} \quad ; \quad \lambda = (3\alpha_s/\pi)4ln2 \approx 0.5.$$

From a comparison of the ZEUS data with the structure function parametrizations (e.g., MRSD$'_-$), one sees that the data at low x and $Q^2 > 35$ GeV^2 are compatible with

$$F_2 \approx a + \frac{b}{\sqrt{x}}.$$

Using the relation $W^2 \approx Q^2/x$, one can write

$$F_2 \approx a + b\frac{W}{Q}.$$

Since $\sigma_{tot}(\gamma^* p) = (4\pi\alpha/Q^2)F_2$, this means that the total cross section at a fixed Q^2 is proportional to W. Figure 19 shows the measured total cross sections multiplied by Q^2 as a function of W. The rise of the total cross section with W is in contrast to that of the total cross section for real photoproduction reactions at $Q^2 = 0$. It is also unlike the total $p\overline{p}$ cross section which is described by a term proportional to $W^{0.16}$ (Ref. 10).

3.2 Charged Current Events

The diagram for charged current interactions of lowest order in deep inelastic electron-proton scattering is shown in Fig. 20:

$$e^- + p \rightarrow \nu + X.$$

The exchanged current is the charged vector boson W. The scattered lepton in the final state is a neutrino which leaves the detector unobserved. Therefore, the total transverse momentum p_t of the visible particles in the detector is not balanced, i.e., there is a missing p_t^{miss}. For these events, x and Q^2 must be calculated from the measured hadronic final states.

ZEUS looked for charged current events in a data sample corresponding to an integrated luminosity of 550 nb^{-1} requiring $Q^2 > 400$ GeV^2 and a missing transverse momentum $p_t^{miss} > 12$ GeV/c. In the data sample, 22 charged current events were found.[37] This results in a cross section which is shown in Fig. 21 as a function of Q^2. It is compared to the neutral current cross section and to the prediction of the Standard Model. The dotted curve shows the prediction for $\mathrm{M_W} \rightarrow \infty$.

Because of the high mass of the W boson, the cross section for this process at low Q^2 is much smaller than that for neutral current reactions. It becomes comparable only at $Q^2 \approx \mathrm{M^2_W}$. At HERA, it has been observed for the first time that at Q^2 of about 10^4 GeV^2, the charged current cross section is of the same magnitude as the neutral current one. The agreement of the data with the Standard Model implies the presence of the weak propagator with a finite W mass.

4 Large Rapidity Gap Events

Figure 22(a) shows a standard neutral current DIS event in the ZEUS detector. The scattered electron is detected in the high resolution calorimeter. There is hadronic activity in the central region of the calorimeter as well as close to the proton direction. The underlying process is sketched in Fig. 22(b). The hadronic final state originates from fragmentation of the struck quark, of the proton remnant, and from initial and final state QCD radiation. ZEUS observed a new class of events in deep inelastic scattering,[38] an example of which is shown in Fig. 23(a). The underlying process is sketched in Fig. 23(b). No hadronic activity close to the proton direction is detected. The first particle or energy deposit in the calorimeter is seen under a larger angle, i.e., at small pseudorapidity. Such events show a rapidity gap between the edge of the calorimeter in the forward direction and the closest hadronic activity at $\eta = \eta_{max}$, where η_{max} is the largest pseudorapidity of any cluster with at least 400 MeV energy.

The distribution of η_{max} for all DIS events is presented in Fig. 24. The obvious feature of the data is an excess of events at low η_{max} values that cannot be described by a model which contains only the standard DIS processes. A scatter plot of W vs. η_{max} for all events, as given in Fig. 25(a), demonstrates that there is a distinct class of events with $\eta_{max} < 1.5$. This is confirmed by a scatter plot of the measured hadronic mass $\mathrm{M_x}$ vs. W in Fig. 25(b). Events with $\eta_{max} < 1.5$ are clearly distinct from those with $\eta_{max} > 1.5$. Their hadronic mass distribution is shown in Fig. 26. The invariant masses of the detected final states of large rapidity gap (LRG) events defined by $\eta_{max} < 1.5$, are considerably smaller than those for standard DIS events. In Fig. 27, the ratio of the number of detected LRG events to all DIS events is plotted as a function of W. Also shown is the acceptance of the detector for DIS events. Above $W = 140$ GeV, where the acceptance is almost independent of W, the ratio is about constant. This means that the W

dependence of LRG events is similar to that of standard DIS events, at least at higher W values. Figure 28 show the Q^2 dependence of the ratio of LRG events to all events for three different x intervals. This ratio is essentially flat, meaning that the Q^2 dependence of LRG events is the same as that of standard DIS events. Since deep inelastic scattering is a leading-twist process, one consequently has to conclude that the underlying mechanism which produces LRG events is also a leading-twist process.

In LRG events, the proton did not fragment into a jet of hadrons. It could have dissociated only into a system which is closely confined to the proton direction in order not to be detected. Also, no appreciable amount of initial state QCD radiation could have taken place since it would have resulted in hadrons detectable in the forward calorimeter. The most natural explanation for such events is the emittance of a color-neutral particle from the proton with little transverse momentum which interacts with the exchanged virtual photon to form a hadronic system of mass $\mathrm{M_x}$.

4.1 What Is the Mechanism for the Production of LRG Events?

Large rapidity gaps in events are known to occur in peripheral processes if the center-of-mass energy of the reaction is much larger than the masses of involved particles (systems).

Peripheral processes are described by the Reggeon exchange which gives rise to the following dependence on the center-of-mass energy squared, s, of the cross section:

$$\sigma_R \sim \left(\frac{s}{\mathrm{M}_\circ^2}\right)^{2\alpha_R(0)-2} .$$

Here, $\mathrm{M}_\circ$ is some reference mass and $\alpha_R(0)$ is the intercept of the trajectory of Reggeon R at $t = 0$, where t is the four-momentum transfer squared to the proton or target particle. Note that in the case of DIS LRG events, $s = W^2_{\gamma^* p}$. Table 1 gives the intercepts and the resulting s dependences of cross sections for Regge trajectories.

Table 1

R	$\alpha_R(0)$	σ_R
π	0	$\sim s^{-2}$
ρ	$\frac{1}{2}$	$\sim s^{-1}$
$I\!P$	≈ 1	$\approx$ constant

Here, $I\!P$ is the Pomeron trajectory. The Pomeron was invented as a hypothetical particle to describe diffractive processes. At higher $W_{\gamma^* p}$ values, the contributions from the π and ρ trajectories will have vanished because of their steeply falling contribution to the cross section. Experimentally, one finds that the fraction of LRG events stays approximately constant at high W, as seen in Fig. 27. This suggests that LRG events are produced by diffractive-like processes.

ZEUS has compared the data with two Monte Carlo programs which are available to simulate the production of LRG events. One is the Nikolaev-Zakharov (NZ) model[39] and the other one the POMPYT model.[40] The NZ model describes the Pomeron exchange essentially by the splitting of the virtual photon into a quark-antiquark pair which interacts with a colorless system of two gluons emitted from the proton, as shown in Fig. 29.

The POMPYT program is based on the Ingelmann-Schlein model[41] which was developed to describe diffractive processes in $p\overline{p}$ scattering observed by UA8 (Ref. 42). It assumes a partonic structure of the Pomeron. The virtual photon couples to one of the quarks (antiquarks) inside the Pomeron, as shown in Fig. 30. The histograms in Fig. 25 and Fig. 27 refer to these NZ and POMPYT Monte Carlo simulations. Both models give a reasonable description of the main features of the data.

4.2 Hard Scattering and Jets in LRG Events

If LRG events are due to Pomeron exchange processes and the Pomeron has a partonic structure, then jet production should show up in a certain fraction of these events. In Fig. 31, one possibility for two-jet production by Pomeron exchange is sketched. A parton in the Pomeron undergoes a hard interaction with the virtual photon and produces two jets. ZEUS has looked for the production of jets in LRG events.[43] Figure 32 shows the pattern of energy deposits in the $\eta - \phi$ plane of such an event. The scattered electron and two jets are clearly visible. An analysis of jets in LRG events has been performed in the ep laboratory system and in the $\gamma^* p$ cms system. A jet was accepted if its transverse energy was $\mathrm{E_T} > 4$ GeV in the ep-system and $\mathrm{E_T} > 2$ GeV in the $\gamma^* p$-system. In Fig. 33(a), the measured transverse energy distribution of jets in the ep-system is presented. The transverse energy distribution of all LRG events in the $\gamma^* p$-system is given in Fig. 33(b). The fractions of events with identified one, two, or three jets are indicated also. In the $\gamma^* p$-system, the production of LRG events with transverse energies above 5 GeV is saturated by hard processes leading to jet production. The presence of hard scattering processes support the idea of a partonic structure of the Pomeron as seen in deep inelastic scattering.

4.3 Outlook on Diffractive Scattering at ZEUS

LRG events are defined by the absence of particle production in the very forward direction. They are interpreted as diffractive processes originating from Pomeron exchange. However, the detailed nature of LRG events has not yet been studied; for instance, the scattered proton has not been detected. In 1993, ZEUS has commissioned the leading proton spectrometer (LPS), which is a system of six stations of silicon strip detectors located in the HERA tunnel between 26 m and 96 m behind the interaction point in the proton direction. The stations can detect protons scattered under very small angles and provide a precise momentum measurement, $\Delta p/p < 1\%$. In 1994, the first data have been collected with the LPS in operation. With LPS tagged events, it will be possible to identify reactions of the type $ep \to ep\ X$ where X results from diffractive dissociation of the virtual photon. This will lead to a better understanding of the production mechanism for LRG events.

5 Summary

In this talk, results from the ZEUS experiment were presented on photoproduction, deep inelastic scattering, and large rapidity gap events in deep inelastic scattering.

In photoproduction, the following data were presented and conclusions were drawn:

- The total photoproduction cross section shows a slow rise from $W = 20$ GeV to HERA energies. The energy dependence can be described by models based on Regge theory as well a QCD-inspired models.
- Data were presented for elastic vector meson production. Cross sections were given for ρ° and J/Ψ production.
- Inclusive charged particle transverse momentum distributions show that there is a hard component in γp scattering.
- The existence of direct and resolved photon processes has been demonstrated. Resolved processes dominate photoproduction at HERA.
- In resolved photon processes, the photon remnant has been identified. The photon remnant behaves like quarks or gluons.

For deep inelastic scattering, the following results were found:

- The structure function F_2 has been measured down to x values of $4 \cdot 10^{-4}$ at $Q^2 \geq 8.5$ GeV^2. It shows a strong rise with decreasing x at all values of $Q^2 < 500$ GeV^2. The rise demonstrates an increase of the parton density in the proton as $x \to 0$. It can be described by parametrizations which include a rising gluon distribution with decreasing x.
- The measured F_2 values show the predicted logarithmic scaling violations.
- The gluon momentum distribution of the proton was extracted from the scaling violations of F_2 at $Q^2 = 20$ GeV^2 for x values between $4 \cdot 10^{-4}$ and 10^{-2}. A substantial increase of the gluon momentum distribution is found at small x.
- A measurement of the charged current cross section up to Q^2 above 10^4 GeV^2 was presented. It agrees with the Standard Model predictions. At HERA, for the first time, the weak interaction in deep inelastic scattering at $Q^2 \approx M_W^2$ has been observed to have a strength comparable to that of the electromagnetic interaction.

A special class of events with a large rapidity gap has been detected. The presented results indicate that:

- Large rapidity gap events are a class of events separate from standard DIS events. Their invariant event masses of the detected final states are small compared to standard DIS events. Their W and Q^2 dependences are the same as for standard DIS events. This leads to the conclusion that their production mechanism is diffractive-like and a leading-twist process.

- Hard scattering processes with jet production occur in LRG events. This supports the hypothesis of a partonic structure of the Pomeron as seen in LRG events.
- The Leading Proton Spectrometer at ZEUS will enable a unique identification of diffractive processes.

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