Submitted to the
International Conference on High Energy Physics
16-22 August 2004, Beijing, China

Abstract: 6-0229 **QCD soft interactions**

Observation of large rapidity gap events in charged current deep inelastic scattering at HERA

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Abstract

The observation of large rapidity gap events in charged current deep inelastic scattering using e^+p data collected with the ZEUS detector is reported. The data corresponds to an integrated luminosity of 60.9 pb^{-1}, These events are compared with theoretical models of diffractive scattering in the electroweak regime.

1 Introduction

Diffractive processes are a significant component of the total neutral current (NC) deep inelastic scattering (DIS) cross section measured at HERA. Diffractive exchange leads to formation of a large rapidity gap (LRG) in the hadronic final state, located between fragmentation regions of colliding particles.

Along with the diffractive NC processes, the charged current (CC) induced diffraction may also be of interest. LRG events in CC DIS, $e^+p \to \nu W^+ p \to \nu X$, have already been observed at HERA [1]. One event selected from 1994 e^+p data in the ZEUS CC DIS sample was found with a large rapidity gap. One possible interpretation of such an event is a diffractive exchange between the virtual W^+ boson and the proton.

The aim of this paper is to study diffraction in the electroweak regime by searching for events with a LRG in the CC DIS data taken in 1999 and 2000. Comparison with NC diffractive DIS allows to the testing of factorisation in diffractive DIS at HERA.

2 Experimental setup

A detailed description of the ZEUS detector can be found elsewhere [2]. A brief outline of the components that are most relevant for this analysis is given below.

Charged particles are tracked in the central tracking detector (CTD) [3], which operates in a magnetic field of 1.43 T provided by a thin superconducting coil. The CTD consists of 72 cylindrical drift chamber layers, organized in 9 superlayers covering the polar-angle[1] region $15^\circ < \theta < 164^\circ$. The transverse-momentum resolution for full-length tracks is $\sigma(p_T)/p_T = 0.0058 p_T \oplus 0.0065 \oplus 0.0014/p_T$, with p_T in GeV.

The high-resolution uranium–scintillator calorimeter (CAL) [4] consists of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part is subdivided transversely into towers and longitudinally into one electromagnetic section (EMC) and either one (in RCAL) or two (in BCAL and FCAL) hadronic sections (HAC). The smallest subdivision of the calorimeter is called a cell. The CAL energy resolutions, as measured under test-beam conditions, are $\sigma(E)/E = 0.18/\sqrt{E}$ for electrons and $\sigma(E)/E = 0.35/\sqrt{E}$ for hadrons (E in GeV).

[1] The ZEUS coordinate system is a right-handed Cartesian system, with the Z axis pointing in the proton beam direction, referred to as the "forward direction", and the X axis pointing left towards the center of HERA. The coordinate origin is at the nominal interaction point. The pseudorapidity is defined as $\eta = -\ln\left(\tan\frac{\theta}{2}\right)$, where the polar angle, θ, is measured with respect to the proton beam direction.

In 1998-2000, the forward plug calorimeter (FPC) [5] was installed in the beam hole of the FCAL, with a small hole of radius 3.15 cm in the centre to accommodate the beam pipe. The FPC increased the forward calorimeter coverage by about 1 unit of pseudo-rapidity to $\eta < 5$. The FPC was tested at CERN with electron and hadron beam. The energy resolution was $\sigma(E)/E = 0.41/\sqrt{E} \otimes 0.062$ and $\sigma(E)/E = 0.65/\sqrt{E} \otimes 0.06$ for electrons and pions, respectively, with E in GeV.

3 Data sample

The data sample corresponds to an integrated luminosity of 60.9 ± 1.5 pb^{-1}, collected during the running periods in 1999 and 2000 when HERA collided 27.5 GeV positrons with 920 GeV protons, yielding a centre-of-mass energy ($\sqrt{s}$) of 318 GeV.

The reconstruction of kinematic variables and selection cuts used to select CC DIS events were described in detail in a previous publication [6]. The Bjorken scaling variables x_{Bj} and y, as well as Q^2, were reconstructed using the Jacquet-Blondel method [7]. This analysis uses a subsample [2] of CC DIS events selected in the inclusive CC measurement [6]. The main selection cuts are described below:

- a primary vertex position, determined from CTD tracks fitted to the vertex, was required in the range $|Z_{VTX}| < 50$ cm;
- missing transverse momentum, arising from the energetic final-state neutrino which escapes detection, calculated from CAL energy deposits was required to be greater than 12 GeV;
- at least one "good" track was required, where "good" track is associated with the event vertex and has transverse momentum in excess of 0.2 GeV and a polar angle in the range $15°$ to $164°$;
- the requirements $Q^2 > 200\,\text{GeV}^2$ and $y < 0.9$ were also imposed.

A total of about 1100 data events satisfied the above criteria.

4 Monte Carlo simulation

Monte Carlo (MC) simulations were used to determine the selection efficiency, to estimate *ep* background rates and to extract cross sections.

[2] Only events selected based on the CTD vertex were used [6].

Non-diffractive CC events were produced with the DJANGOH 1.1 [8] generator interfaced to colour-dipole model of ARIADNE 4.10 [9] for fragmentation. As a systematic check, the MEPS model of LEPTO 6.5 [10] was used. Both programs use the Lund string model of JETSET 7.4 [11–13] for hadronisation.

Diffractive CC events were modeled with the RAPGAP 2.08/06 [14] generator, in which a colour singlet exchange occurs between the virtual W^+ boson and the proton. As an alternative, the MEPS model of LEPTO including soft colour interactions (SCI), which give rise to large rapidity gap events without introducing the concept of diffractive exchange, was used.

Photoproduction background was estimated using events simulated with HERWIG 5.9 [15]. The background from di-lepton production was estimated using the GRAPE [16] generator, and the background from W production was generated with the EPVEC [17] program.

5 Large rapidity gap events

To establish the presence of events with a LRG, the distribution of η_{max}, defined as the pseudo-rapidity of energy deposition in the CAL above 400 MeV closest to the proton direction, is shown in the upper plot in Fig. 1. An excess of events with a LRG over non-diffractive (ARIADNE) MC expectation is observed in the region of $\eta_{max} < 3$.

The following criteria were applied to select LRG events:

- $E_{FPC} < 1.0\,\mathrm{GeV}$. This cut suppresses the contribution from non-diffractive interactions, as shown on the bottom plot in Fig. 1;
- $\eta_{max} < 2.9$. This cut reduces the remaining non-diffractive background and ensures a gap of at least two units of rapidity between the hadronic system measured in the detector and the rest of the hadronic final state.
- $x_{I\!P} < 0.05$, where $x_{I\!P} = \frac{q\cdot(P-P')}{q\cdot P}$ is the fraction of proton four-momentum carried by the exchanged colour singlet (pomeron). The variables q, P and P' denote the virtual W^+ boson, the initial and final proton four-momenta respectively. This cut rejects non-diffractive events.

An example of LRG CC DIS event is shown in Fig. 2.

The upper plots in Fig. 3 show the distributions of $\log Q^2$, x_{Bj} and $\log M_X^2$ for CC DIS events for data and the sum of non-diffractive (ARIADNE) and diffractive (RAPGAP) MC simulations, where M_X is the mass of the hadronic system X measured in the CAL. The same distributions are also shown for subsamples fulfilling the LRG selection criteria. The MC simulations correctly describe both the inclusive CC sample and the LRG subsample.

The bottom plots in Fig. 3 show the distribution of diffractive variables $\log(x_{I\!P})$ and β for LRG CC DIS events after statistical subtraction of non-diffractive background, where β is the fraction of pomeron momentum carried by the struck parton. It is equivalent to the Bjorken x_{Bj}, but relative to the pomeron momentum. The agreement with the result of diffractive (RAPGAP) MC simulation is satisfactory. The LRG events populate the region of relatively large $x_{I\!P}$ and β.

Fig. 4 shows the distributions of $\log Q^2$, x_{Bj}, number of "good" tracks, $\log M_X^2$ and η_{max} for CC DIS events together with the results of the MEPS with SCI included MC simulation. The same distributions are also shown for subsamples fulfilling the LRG selection criteria. The rate of LRG events expected by this MC model is compatible with the data. The distribution of track multiplicity in inclusive sample however, is not described by this model, in contrast to the ARIADNE generator. The MEPS version without SCI describes the track multiplicity distribution better, but the rate of LRG events is reduced (not shown).

The numbers of selected CC events with LRG for 60.9 pb^{-1} of integrated luminosity were:

- 9 in the data;
- 5.6 ± 0.7 in the diffractive CC (RAPGAP) MC simulation;
- 2.1 ± 0.4 in the non-diffractive CC (ARIADNE) MC simulation. This number also includes a small contribution from di-lepton (GRAPE) background simulation;
- $3.9^{+1.0}_{-0.7}$ in the CC MEPS MC simulation including SCI.

The sum of RAPGAP and ARIADNE expectations and the expectation from MEPS including SCI describe the rate of LRG events. The MEPS with SCI does not describe the distribution of track multiplicity in inclusive sample.

6 Results

Assuming that the excess of a LRG events over the non-diffractive expectation modeled by ARIADNE generator is due to the diffractive exchange, the diffractive CC cross section, $\sigma^{diff}(e^+p \to \nu X p)$, was measured in the kinematic region $Q^2 > 200\,\text{GeV}^2$ and $x_{I\!P} < 0.05$. The cross section was determined by $(N - N_{bkg})/(A\mathcal{L})$, where N is the number of LRG events observed in the data, N_{bkg} is the number of non-diffractive background as expected from ARIADNE simulation, A is the acceptance given by diffractive (RAPGAP) MC simulation and $\mathcal{L}$ is the integrated luminosity. In addition the ratio of $\sigma^{diff}(e^+p \to \nu X p)$ to the total CC cross section $\sigma^{tot}(e^+p \to \nu X)$ was calculated, where $\sigma^{tot}(e^+p \to \nu X)$ was measured in the kinematic region given by $Q^2 > 200\,\text{GeV}^2$ and $x_{Bj} < 0.05$.

The overall systematic uncertainty in the cross section and ratio of cross sections was obtained by summing in quadrature the uncertainties listed below:

- uncertainty related to the diffractive proton dissociation. The contribution of proton dissociative events is suppressed by the cut on E_{FPC} and was estimated to be less than 20%. This background was not subtracted but instead included in the systematic uncertainty and corresponds to an uncertainty on both diffractive cross section and cross sections ratio of -20%;
- selection of large rapidity gap events. Systematic checks were performed by varying the cuts on η_{max} by ± 0.1 and by increasing the cut on E_{FPC} to 1.5 GeV. This resulted in changes of $\pm 17\%$ in both diffractive cross section and in ratio of cross sections;
- parton-shower scheme [6]. The MEPS without SCI was used instead of ARIADNE model for simulation of non-diffractive events. This modification to the analysis lead to changes in the diffractive cross section of less than $\pm 5\%$ and less than $\pm 10\%$ in the ratio of cross sections;
- uncertainty of the calorimeter energy scale [6]. This uncertainty was estimated to be less than $\pm 7\%$ in the cross section and assumed to cancel in the ratio of cross sections;
- uncertainty in the non-diffractive background subtraction. This uncertainty was found to be ± 0.4 event. The effect on both diffractive cross section and cross sections ratio was $\pm 5\%$;

The diffractive CC cross section measured in the kinematic region given by $Q^2 > 200\,\mathrm{GeV}^2$ and $x_{I\!P} < 0.05$ was

$$\sigma^{diff}(e^+p \to \nu X p) = 0.49 \pm 0.20(\mathrm{stat.}) \pm 0.13(\mathrm{syst.})\ \ \mathrm{pb}$$

The ratio of this cross section to that of total CC cross section calculated in the corresponding kinematic region $Q^2 > 200\,\mathrm{GeV}^2$ and $x_{Bj} < 0.05$ was

$$\sigma^{diff}(e^+p \to \nu X p)/\sigma^{tot}(e^+p \to \nu X) = 2.9 \pm 1.2(\mathrm{stat.}) \pm 0.8(\mathrm{syst.})\ \%$$

The ratio of diffractive to total CC cross section is similar to that measured in NC DIS process [18].

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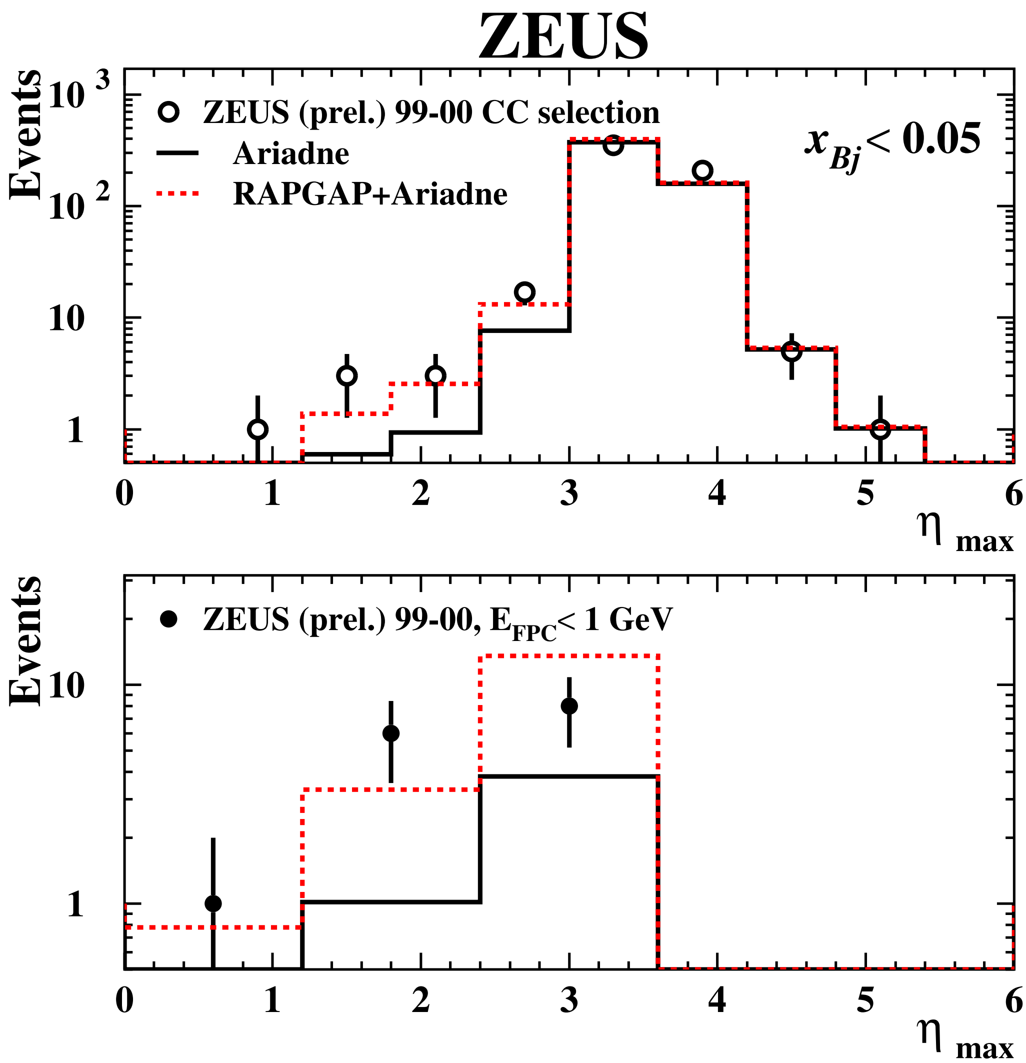

Figure 1: *The distribution of η_{max} is shown in the upper plot for CC DIS events in the kinematic range $Q^2 > 200\ GeV^2$, $y < 0.9$ and $x_{Bj} < 0.05$. The circles are the data points, the solid histogram is the result of the non-diffractive (ARIADNE) MC simulation and the dashed histogram is that of the sum of non-diffractive and diffractive (RAPGAP) MC sample. The bottom plot shows the same distributions with an additional requirement of $E_{FPC} < 1\ GeV$.*

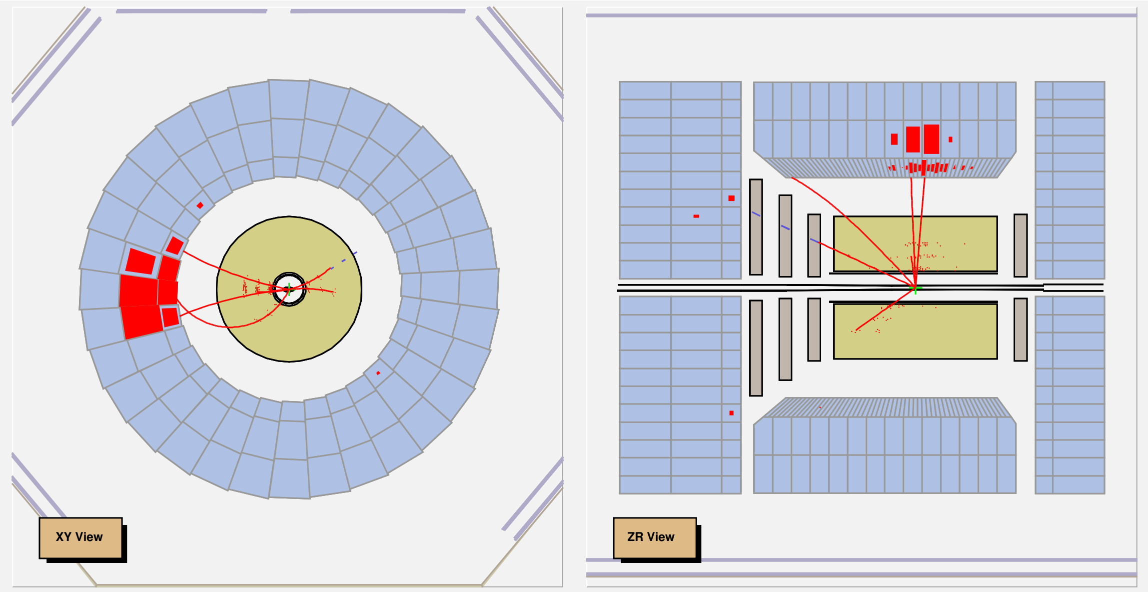

Figure 2: *Example of LRG CC DIS event, as seen in the ZEUS detector. In the right panel, the positrons come from the left, the protons from the right. One observes large missing momentum, arising from the final-state neutrino which escapes detection and no activity in the CAL region closest to the outgoing proton direction (LRG). There is also no activity in the FPC, which is installed in the beam hole of the left part of CAL, not shown on the plot.*

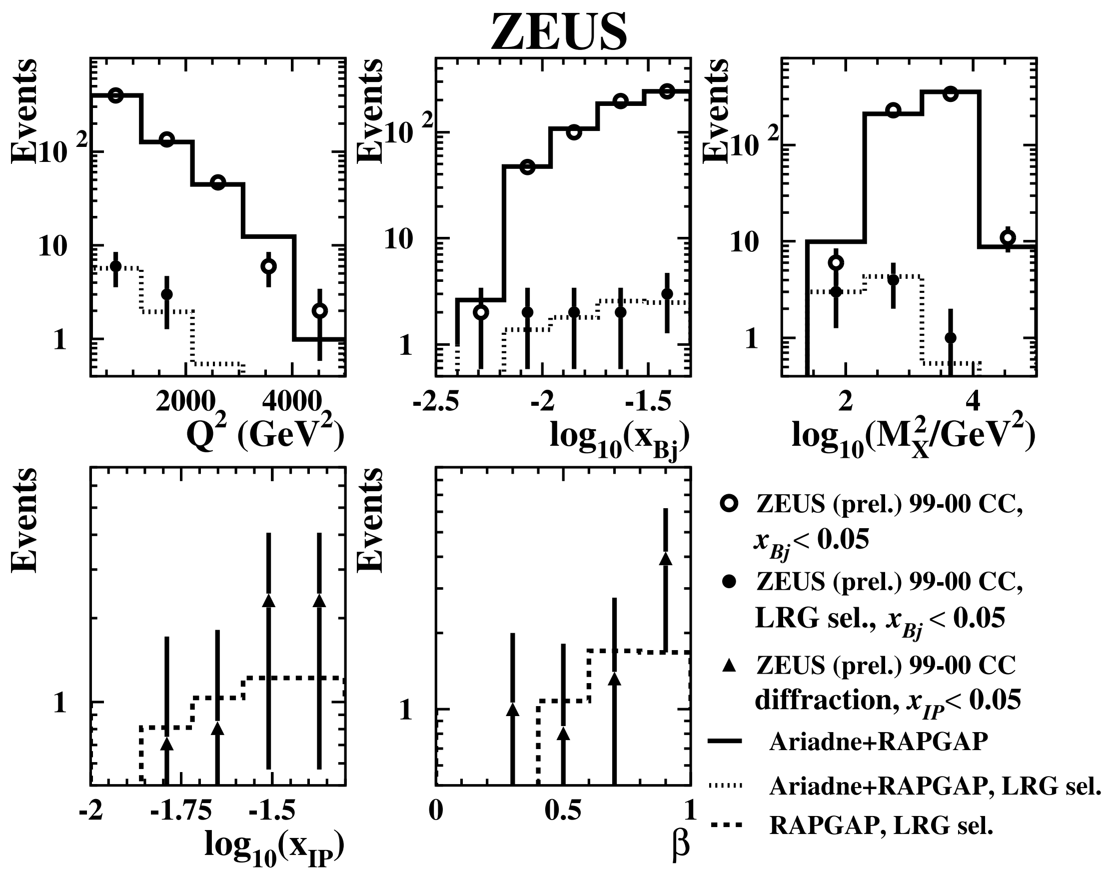

Figure 3: *The upper plots show the distributions of* $\log Q^2$, x_{Bj} *and* $\log M_X^2$ *for CC DIS events in the kinematic range of* $Q^2 > 200\ GeV^2$, $y < 0.9$ *and* $x_{Bj} < 0.05$. *The circles are the data points and the solid histograms are the sum of results of non-diffractive (ARIADNE) and diffractive (RAPGAP) MC simulations. The lower data points and MC histograms on each plot correspond to the subsamples fulfilling the LRG selection criteria (see text). The bottom plots shows the* $\log x_{I\!P}$ *and* β *distributions of the CC DIS events fulfilling the LRG selection criteria. The triangles are the data points after statistical subtraction of non-diffractive (ARIADNE) contribution. The dashed histogram is the result of diffractive (RAPGAP) MC simulation.*

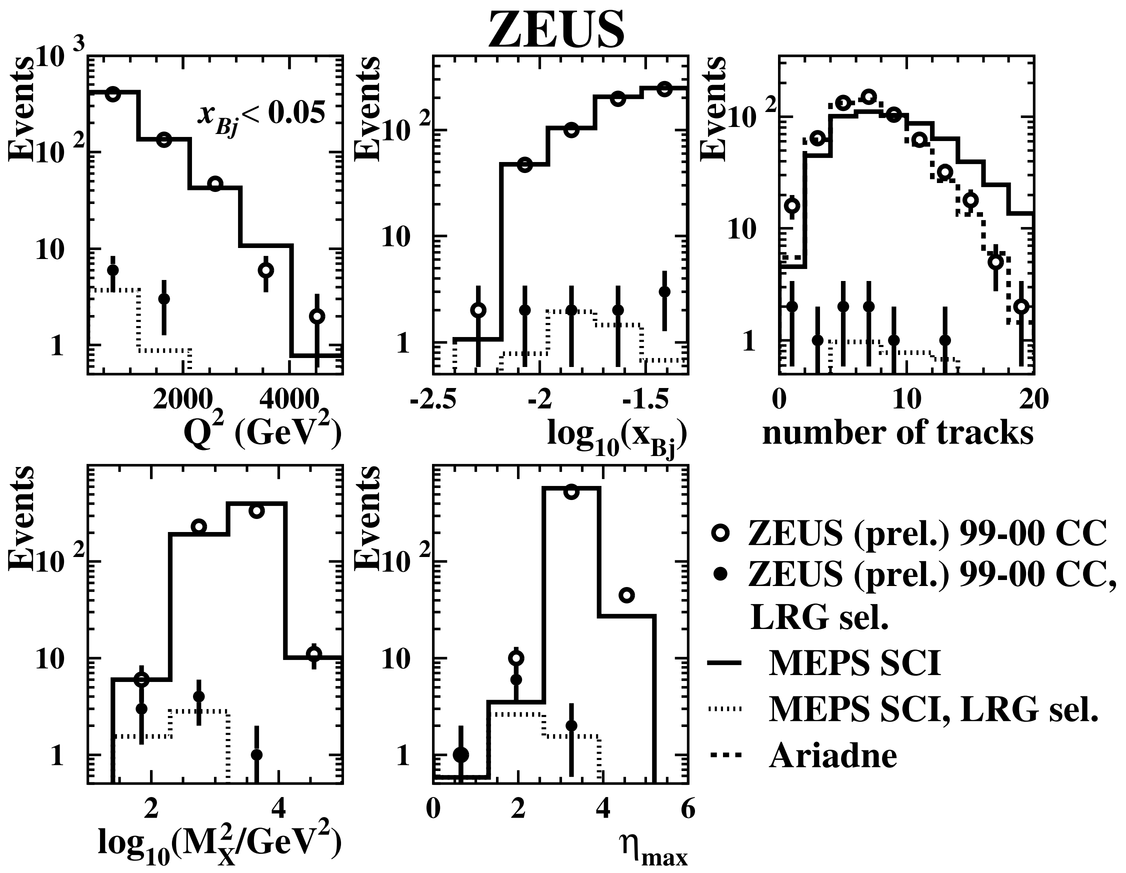

Figure 4: *The distributions of* $\log Q^2$, x_{Bj}, *number of good tracks,* $\log M_X^2$ *and* η_{max} *for CC DIS events in the kinematic range* $Q^2 > 200\ GeV^2$, $y < 0.9$ *and* $x_{Bj} < 0.05$. *The circles are the data points and the solid histograms are the sum of results of MEPS with SCI included MC simulations. The dashed histogram superimposed on the distribution of the number of good tracks is the result of ARIADNE simulation. The lower data points and MC histograms on each plot correspond to the subsamples fulfilling the LRG selection criteria (see text).*