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# Measurement of azimuthal asymmetries in neutral current deep inelastic scattering at HERA

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**Abstract**

The distribution of the azimuthal angle of charged and neutral hadrons has been studied in the hadronic centre-of-mass system for neutral current deep inelastic ep scattering with the ZEUS detector at HERA using an integrated luminosity of 45 $pb^{-1}$. Measurements of the dependence of the azimuthal distribution on the pseudorapidity of the final state hadrons are presented. The measurements have been compared with leading-logarithm parton-shower Monte Carlo models and next-to-leading-order QCD calculations.

# 1 Introduction

The investigation of the semi-inclusive process $e{+}p \rightarrow e{+}h{+}X$ in deep inelastic scattering (DIS), where $h$ is an observed hadron, addresses an important prediction of perturbative Quantum Chromodynamics (pQCD) in the description of hadron production. It is of interest to investigate the distribution of the azimuthal angle of the detected hadrons around the virtual photon direction in the hadronic centre-of-mass frame (HCM). The azimuthal angle, $\phi$, is defined as the angle between the hadron production plane and the lepton scattering plane (Fig. 1).

The azimuthal dependence of parton production has the form [1–3]

$$\frac{d\sigma}{d\phi} = \mathcal{A} + \mathcal{B}\cos\phi + \mathcal{C}\cos 2\phi + \mathcal{D}\sin\phi + \mathcal{E}\sin 2\phi.$$

The $\mathcal{B}, \mathcal{C}, \mathcal{D}$ and $\mathcal{E}$ values are extracted from experimental data by calculating statistical moments for experimental distributions of the respective trigonometrical functions of $\phi$:

$$\langle\cos\phi\rangle = \frac{\mathcal{B}}{2\mathcal{A}} \qquad \langle\sin\phi\rangle = \frac{\mathcal{D}}{2\mathcal{A}} \tag{1}$$

$$\langle\cos 2\phi\rangle = \frac{\mathcal{C}}{2\mathcal{A}} \qquad \langle\sin 2\phi\rangle = \frac{\mathcal{E}}{2\mathcal{A}}. \tag{2}$$

In this paper the energy flow method is used to calculate the mean values (1)-(2). For this method the direction of each particle $h$ in the final state is weighted with its transverse energy. The main advantage in studying energy-weighted inclusive quantities lies in the fact that the calorimeter measurements can be used. Thus, both neutral and charged hadrons produced in the reaction are included and the range of the investigated phase space is increased with respect to the previous investigations [4, 5].

Azimuthal asymmetries, (1)-(2) exist only if the the final state hadron has transverse momentum. At the parton level, this transverse momentum can originate from higher order QCD processes such as QCD Compton process or boson-gluon fusion (BGF). These two processes have a different $\eta^{\mathrm{HCM}}$ dependence as shown in Fig. 2. This paper presents a study of $\langle\cos\phi\rangle$ as a function of the pseudorapidity $\eta^{\mathrm{HCM}}$ using the energy flow method.

# 2 Data selection

The experimental results are based on the data collected in 1995-97 with the ZEUS detector at the HERA collider with protons of energy 820 GeV. Electrons of energy

27.5 GeV are longitudinally unpolarized. Neutral current deep inelastic scattering events have been selected from the data corresponding to an integrated luminosity of 45 $pb^{-1}$.

ZEUS is a multipurpose detector described in detail elsewhere [6]. The main component is the uranium-scintillator calorimeter [7] which covers 99% of $4\pi$. The calorimeter is transversely segmented into cells and longitudinally segmented into electromagnetic and hadronic sections; the energy resolution of the calorimeter under test-beam conditions is $\sigma_E/E = 0.18/\sqrt{E}$ for $e^{\pm}, \gamma$ and $\sigma_E/E = 0.35/\sqrt{E}$ for hadrons, with $E$ in GeV.

The calorimeter surrounds the central tracking detector [8] which is a cylindrical drift chamber in a 1.4 T magnetic field covering 83% of $4\pi$; the transverse-momentum resolution for charged tracks traversing all the detector layers is $\sigma_{p_T} = 0.0058 p_T \oplus 0.0065 \oplus 0.0014/p_T$, with $p_T$ in GeV.

Particles in the final state were reconstructed by combining information from tracking and calorimeter in the ZEUS detector. The selection criteria were based on the earlier ZEUS investigations [4, 5]. The main cuts were:

- the event had an identified scattered positron with energy $E_{e'} > 10$ GeV;
- in order to define the phase space of the measurement, the event was required to have $100 < Q^2 < 8000$ GeV$^2$, $0.2 < y < 0.8$ and $0.01 < x < 0.1$. The quantities $x, y, Q^2$ were $x$-Bjorken, the fraction $y$ of the incoming electron energy transferred to the exchanged boson and the exchanged boson virtuality $Q^2$. The double angle method was used [9];
- the reconstructed hadrons (charged and neutral particles) were required to have their transverse momenta $\mathrm{p_T^{LAB}} > 150$ MeV. These cuts excluded hadrons contained within the beam pipe or failing to traverse sufficient layers of the tracker to ensure good reconstruction.

## 3 Correction procedure

Monte Carlo events were used to correct the data for detector inefficiences. For this purpose, the generated events were passed through the ZEUS detector- and trigger simulation programs based on GEANT 3.13 [10]. Neutral current (NC) events with electroweak radiative corrections came from the LEPTO 6.5.1 code interfaced to HERACLES 4.6.1 [11, 12] via the DJANGOH 1.1 code [13, 14]. High order QCD processes were simulated using the MEPS option of LEPTO.
A second sample of NC DIS Monte Carlo events was generated with ARIADNE 4.08 [15]

where the QCD cascade came from the colour-dipole model. In all cases, the events have been generated using the CTEQ4D next-to-leading order parton density parametrization [16] of the proton. The final state parton system was hadronised using the LUND string model as implemented in JETSET 7.4.10 [17].

The correction factor for $\phi$ was defined as the ratio of energy flow of hadrons, $E(\phi_{had}^{MC})$, to energy flow detected, $E(\phi_{det}^{MC})$:

$$F^{MC}(\phi) = \frac{E(\phi_{had}^{MC})}{E(\phi_{det}^{MC})}.$$

Here, $E(\phi) = \sum_i E_{Ti}^{\mathrm{HCM}}$ is summed over the emitted or reconstructed hadrons; the reconstructed hadrons are energy flow objects [18] which combine calorimetric and tracking information. The corrected integrated energy flow $E(\phi)$ was determined separately bin-by-bin for each region in the $\eta$-$\phi$ plane as

$$E(\phi^{DATA}) = F^{MC}(\phi) \cdot E(\phi_{det}^{DATA}).$$

For this approach to be valid, the uncorrected energy flow $E(\phi)$ in the data had to be well described by the MC simulations at the detector level. This condition was satisfied by the LEPTO and ARIADNE simulations in the $\eta^{\mathrm{HCM}}$ and $E_T^{\mathrm{HCM}}$ regions under investigation. The samples of events of LEPTO were used for the final corrections; the corrections from the ARIADNE generator were included in the systematic uncertainties. The same method was used to calculate corrections for $\cos\phi^{\mathrm{HCM}}$.

Systematic uncertainties were determined by varying the event selection cuts within their reconstruction resolution and the total systematic uncertainty was the sum in quadrature of the individual systematics. The dominant contributions originated from the use of the measured hadrons to reconstruct the $x, y, Q^2$ values (the Jacquet-Blondel method [19]) and from the loss of hadrons in the beam pipe.

# 4 Fixed-order QCD predictions

The leading-order (LO) calculations of azimuthal asymmetries were based on two generators: the LEPTO 6.5.1 program [20] and the ARIADNE 4.12 code [15] interfaced to the LEPTO code. The LEPTO MEPS option was used, i.e. the partonic processes were simulated using LO matrix elements with inclusion of initial and final-state parton showers. In ARIADNE the QCD cascade was simulated using the colour-dipole model [21–24]. Both Monte Carlo (MC) programs used the Lund string model for the hadronisation [17].

The CTEQ4D [16, 25] proton parton density functions were used for the LO predictions presented here.

The next-to-leading (NLO) predictions were investigated using the dipole factorization formulae [26] implemented in the DISENT program [26,27]. The calculations made use of a generalised version of the subtraction method [28] and were performed in the massless $\overline{\mathrm{MS}}$ renormalisation and factorisation schemes. This model did not contain $Z^0$ exchange and hadronization. The following settings were used as defaults for DISENT: the number of flavours was set to five, factorisation scale was set to $\mu_F = Q$, renormalisation scale to $\mu_R = Q$ and the parton distribution function CTEQ3M [29] was used which was the DISENT default value. Thus the theoretical uncertainty on the renormalisation and factorisation scales were obtained by using $\mu_{F(R)} = Q/2$ and $2Q$ instead of the central values $\mu = Q$. The uncertainties included calculations done for the proton distribution functions CTEQ4M [16] and CTEQ5M [30]. Samples of events from LEPTO 6.5.1 and ARIADNE 4.12 were used to correct the NLO QCD calculations for $Z^0$-exchange effects, hadronisation and detection.

# 5 Results

In Fig. 2 the fraction of hadrons coming from boson-gluon fusion (BGF) and QCD Compton (QCDC) process is shown as a function of pseudorapidity $\eta^{\mathrm{HCM}}$ as predicted by LEPTO. In the region $-4 < \eta^{\mathrm{HCM}} < 0$ hadrons from BGF and QCD dominate over hadrons from the zeroth order DIS process.

The measured azimuthal asymmetries in terms of the mean values of $\cos\phi^{\mathrm{HCM}}$ are presented in Fig. 3 as a function of pseudorapidity $\eta^{\mathrm{HCM}}$. They are compared with the LO predictions obtained from LEPTO and ARIADNE. The data for $\langle\cos\phi^{\mathrm{HCM}}\rangle$ are not well described by the LO predictions. For $-5 < \eta^{\mathrm{HCM}} < -2.5$ the asymmetry is more negative than expected for both models whereas for $-1 < \eta^{\mathrm{HCM}} < 0$ the asymmetry is positive contrary to the negative values expected from the LO predictions. The obtained NLO predictions are also shown in Fig. 3. The theoretical uncertainties due to renormalisation and factorisation scales are indicated together with those due to the parton distribution functions. The dominant uncertainties come from the changes in renormalisation scales while the other contributions are negligible. The NLO predictions give better agreement with experimental values than the LO predictions.

The region $-5 < \eta^{\mathrm{HCM}} < -2.5$ is a part of the current region in DIS defined in the Breit frame as $\eta^{\mathrm{Breit}} \approx \eta^{\mathrm{HCM}} + 2 < 0$; the main contribution to the azimuthal asymmetry comes from the QCD Compton process $\gamma + q \rightarrow g + q$ and arises from hadrons coming from quark fragmentation (Fig. 2). This is the region investigated in the first ZEUS analysis of azimuthal asymmetries [4] using charged hadrons. The high-precision measurements from this analysis confirm that the value of $\langle \cos \phi^{\mathrm{HCM}} \rangle$ is more negative than expected from the LO predictions.

The region $-2.5 < \eta^{\mathrm{HCM}} < -1$ is that with an increasing contribution from boson-gluon fusion (Fig. 2); it is strongly affected by losses of hadrons in the beam pipe as well as by the QED radiation from electrons. The ZEUS analysis of azimuthal asymmetries deduced from jets [5] is based on hadrons from this region of phase space; in this analysis the $\langle \cos \phi^{\mathrm{HCM}} \rangle$ value is consistent with zero. The results presented here confirm a small value for $\langle \cos \phi^{\mathrm{HCM}} \rangle$ when averaged over the $\eta^{\mathrm{HCM}}$ range.

The third region $-1 < \eta^{\mathrm{HCM}} < 0$ is populated equally by hadrons from QCD Compton processes and from boson-gluon fusions (Fig. 2). For these hadrons azimuthal asymmetries are investigated for the first time. Contrary to LO predictions the $\langle \cos \phi^{\mathrm{HCM}} \rangle$ values are positive.

## Conclusions

The azimuthal asymmetries in deep inelastic scattering have been measured in the hadronic centre-of-mass frame for the HERA energies for a selected sample of neutral current events with $100 < Q^2 < 8000$ GeV$^2$ and $0.01 < x < 0.1$. An energy-flow analysis method is used which permits the use of both neutral and charged hadrons.

Azimuthal asymmetries are investigated as a function of hadron pseudorapidity $\eta^{\mathrm{HCM}}$. The $\langle \cos \phi^{\mathrm{HCM}} \rangle$ values are not described by LO predictions. The measurements provide clear evidence that higher order QCD calculations are required to describe the data.

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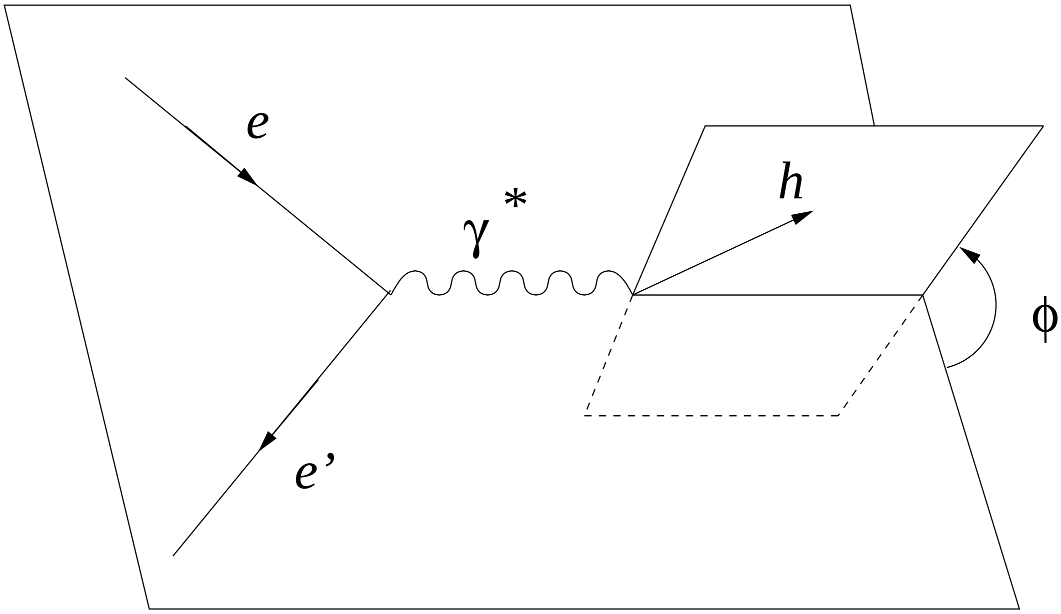


**Figure 1:** *The definition of the azimuthal angle $\phi$ either in the hadronic centre-of-mass system (HCM) or the Breit system. The incoming electron is denoted by e, the scattered electron by $e'$, the exchanged virtual photon by $\gamma^\star$ and the outgoing hadron or parton by $h$.*

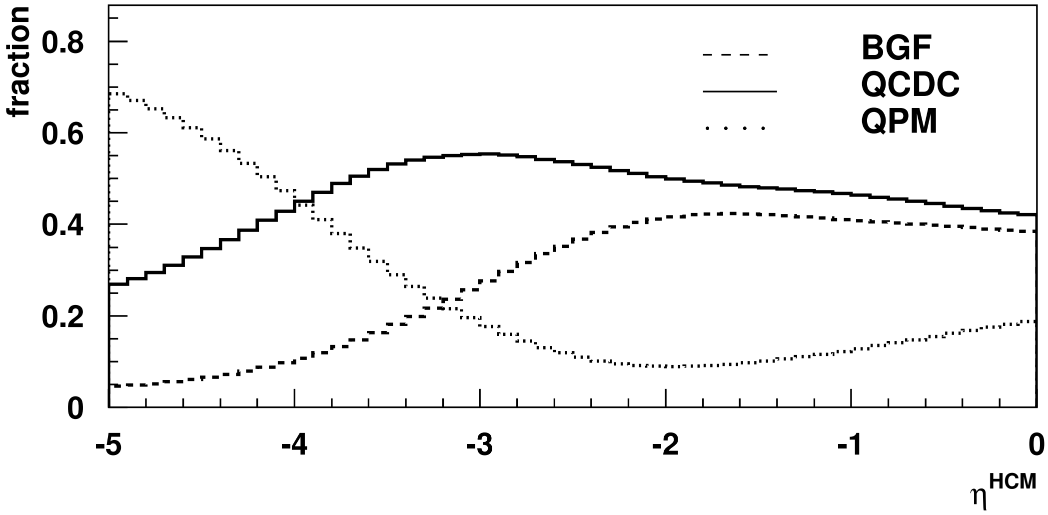


**Figure 2:** *The fraction of boson-gluon fusion (*BGF*), QCD Compton (*QCDC*) processes and the zeroth order QCD process(*QPM*) as a function of pseudorapidity* $\eta^{\mathrm{HCM}}$ *in the hadronic centre-of-mass system for energy flow method as predicted by LEPTO 6.5.1.*

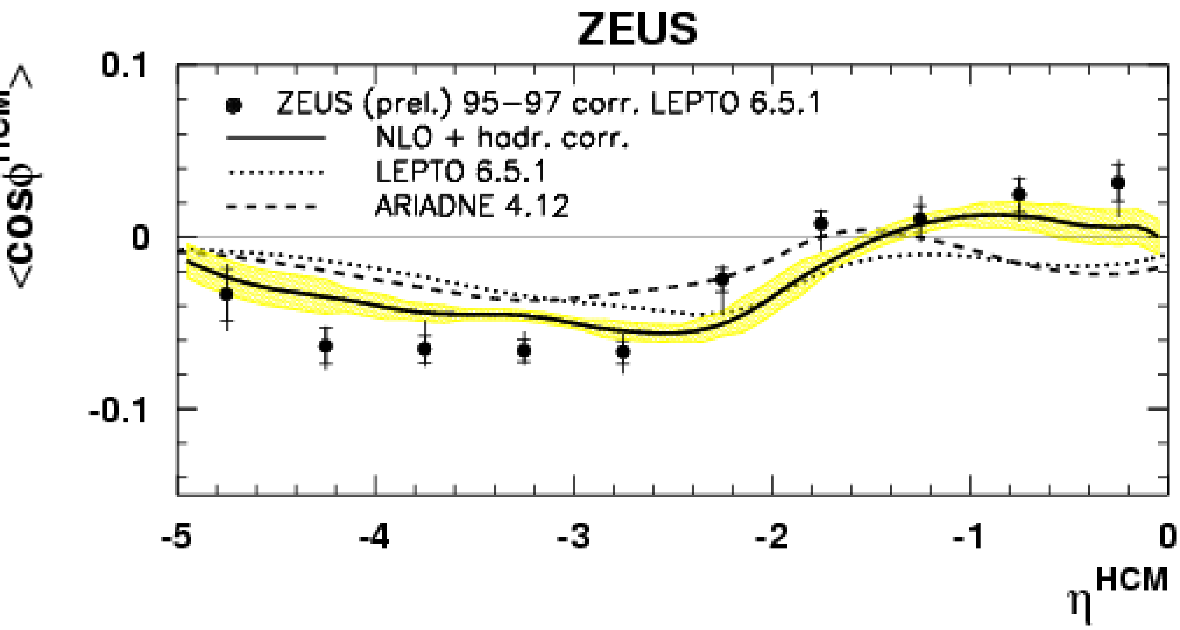


**Figure 3:** *The values of* $\langle \cos\phi^{\rm HCM} \rangle$ *are shown as a function of hadron pseudorapidity* $\eta^{\rm HCM}$ *obtained using the energy flow method in the hadronic centre-of-mass system in the kinematical region* $0.01 < x < 0.1$, $0.2 < y < 0.8$ *and* $100 < Q^2 < 8000$ GeV$^2$. *In experiment and in Monte Carlo hadrons are required to have the transverse momenta* $\mathrm{p_T^{LAB}} > 0.15$ GeV. *The inner error bars are statistical uncertainties, the outer are statistical and systematic uncertainties added in quadrature. The solid line represents the NLO predictions of DISENT corrected for* $Z^0$*-exchange effects, hadronisation and detection using LEPTO, the dotted line represents LEPTO 6.5.1 and the dashed line represents the ARIADNE 4.12 predictions.*