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

ZEUS Collaboration

Abstract

The distribution of the azimuthal angle of charged and neutral hadrons relative to the lepton plane has been studied for neutral current deep inelastic *ep* scattering. The measurements were made in the hadronic centre-of-mass system using an integrated luminosity of 45 pb^{-1} taken with the ZEUS detector at HERA. The analysis exploits the energy-flow method which allows the measurement to be made in a larger range of pseudorapidity compared to previous results. The dependence of the moments of the azimuthal distributions on the pseudorapidity and minimum transverse energy of the final-state hadrons are presented. Although the predictions from next-to-leading-order QCD describe the data better than the Monte Carlo models incorporating leading-logarithm parton showers, they still fail to describe the magnitude of the asymmetries. This suggests that higher-order calculations may be necessary to describe these data.

1 Introduction

The description of the hadronic final state in deep inelastic scattering (DIS) is influenced by perturbative Quantum Chromodynamics (pQCD) in several ways and can be calculated through exact matrix elements or leading-logarithm parton showers. Measurements of the azimuthal distribution of hadrons in the semi-inclusive process $e + p \to e + h + X$ in DIS address predictions of pQCD. The azimuthal angle, ϕ, is defined in the hadronic centre-of-mass (HCM) frame as the angle between the hadron-production plane and the lepton-scattering plane as illustrated in Fig. 1.

Asymmetries in ϕ result from the final-state hadron having transverse momentum with respect to the colliding virtual photon and the incoming proton. In pQCD, higher-order QCD processes such as QCD Compton (QCDC) ($\gamma^* q \to qg$) and boson-gluon fusion (BGF) ($\gamma^* g \to q\bar{q}$) are the main sources of these hadrons. These two processes have different ϕ behaviours [1] as well as a different pseudorapidity, η, dependence, defined here with respect to the incoming proton direction in the HCM frame. Figure 2(a) shows that hadrons from BGF and QCDC dominate over quark-parton-model (QPM) ($\gamma^* q \to q$) events in the region $-4 < \eta^{\mathrm{HCM}} < 0$. In addition, gluons and quarks from the QCDC process have different pseudorapidity dependencies, as illustrated in Fig. 2(b).

The azimuthal dependence for semi-inclusive neutral current (NC) DIS can be written [2–5] as:

$$\frac{d\sigma^{ep\to ehX}}{d\phi} = \mathcal{A} + \mathcal{B}\cos\phi + \mathcal{C}\cos 2\phi + \mathcal{D}\sin\phi + \mathcal{E}\sin 2\phi. \tag{1}$$

The azimuthal asymmetries, specified by the parameters $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$ and $\mathcal{E}$, are extracted from the data by calculating the statistical moments of the experimental distributions:

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

Equation (1) results from the polarisation of the exchanged virtual photon. The coefficient $\mathcal{B}$ originates from the interference between the transversely and longitudinally polarised components; the coefficient $\mathcal{C}$ is due to the interference of amplitudes corresponding to the $+1$ and -1 helicity parts of the transversely polarised exchanged boson. The coefficients $\mathcal{D}$ and $\mathcal{E}$ arise from parity-violating weak interactions, longitudinal polarisation of the initial lepton beam, or from higher-order QCD corrections [3]. They vanish for purely electromagnetic interactions with unpolarised beams.

It has been proposed [4] to analyse the asymmetry as a function of the transverse momentum cutoff, $p_T^{\rm cut}$, of a detected hadron. Such a cut is efficient in removing QPM events. Consequently, at higher $p_T^{\rm cut}$ values a better agreement should be obtained with the perturbative QCD predictions. A model using a resummation formalism [6] to predict azimuthal asymmetries has also been proposed. This model predicts that logarithmic corrections due to soft parton emission could be large. A recent paper [7] showed that a part of the asymmetries previously measured by the ZEUS collaboration [8,9] may come from terms that are not included in the perturbative gluon radiation but are related to the intrinsic transverse motion of quarks. Predictions of these models are addressed in this paper.

For NC DIS with an unpolarised lepton beam, the $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ values have been measured by the ZEUS collaboration [8,9] to be at the few percent level. The first publication [8] measured the azimuthal distribution for charged hadrons whereas the second [9] was performed for jets of high transverse energy. The present analysis uses the energy-flow method, which permits both neutral and charged hadrons to be included in the measurements. This analysis is performed using a similar data sample but in an extended kinematic range compared to previous publications. The polar angle range of the measurements is increased with respect to the previous studies [8,9]. The energy-flow method enhances the contribution of leading hadrons since the direction of each particle in the final state is weighted with its transverse energy [10,11]. Additionally, the values $\langle\sin\phi\rangle$ and $\langle\sin 2\phi\rangle$ are determined, although they are expected [3,5] to be much smaller than $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$.

This paper presents measurements of $\langle\cos\phi\rangle$, $\langle\cos 2\phi\rangle$, $\langle\sin\phi\rangle$ and $\langle\sin 2\phi\rangle$ as a function of the pseudorapidity, $\eta^{\rm HCM}$, and minimum transverse energy, $E_{T,\rm min}^{\rm HCM}$ (instead of $p_T^{\rm cut}$ [4]), of the final-state hadrons. The results are compared to theoretical expectations.

2 Data sample

The experimental results are based on the data collected in 1995-97 with the ZEUS detector at HERA. Protons of 820 GeV collided with 27.5 GeV unpolarised[1] positrons. Neutral current DIS events were selected from data corresponding to an integrated luminosity of 45 pb^{-1}. A detailed description of the ZEUS detector can be found elsewhere [13]. A brief outline of the components that are most relevant for this analysis is given below.

The high-resolution uranium–scintillator calorimeter (CAL) [14] consists of three parts: the forward (FCAL), the barrel (BCAL) and the rear (RCAL) calorimeters. Each part

[1] The positrons were transversely polarised due to the Sokolov-Ternov [12] effect, but had no longitudinal polarisation.

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, with E in GeV.

Charged particles are tracked in the central tracking detector (CTD) [15], 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, organised in 9 superlayers covering the polar-angle[2] 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 selection criteria were based on an earlier ZEUS investigation [8]. The main requirements on the event were:

- an identified scattered positron with energy $E'_e > 10$ GeV. Energy deposits in the CAL, within an $\eta - \phi$ cone of radius 1 and consistent with being a photon, were removed from the calculation of the positron energy;
- $100 < Q^2 < 8000$ GeV^2, $0.2 < y < 0.8$ and $0.01 < x < 0.1$. The quantities x, y and Q^2 are respectively x-Bjorken, the inelasticity, and the negative square of the exchanged boson virtuality. The double-angle method was used to reconstruct these variables and so determine the direction of the exchanged boson [16]. The mean values of x, y and Q^2 were respectively 0.0222, 0.351 and 700 GeV^2. The final sample consisted of 16 472 events.

Charged and neutral final-state particles were reconstructed using a combination of track and calorimeter information that optimises the resolution of the reconstructed kinematic variables [17]. The selected tracks and calorimeter clusters are referred to as energy flow objects (EFOs). The EFOs were required to satisfy the following:

- transverse momentum in the laboratory frame $p_T > 0.15$ GeV;
- polar angle $\theta > 8^\circ$.

These cuts ensured the analysis was performed in a region of high acceptance and high detector efficiency. An average of about 18 EFOs per event were reconstructed, yielding a total of 293 000 objects, each of which provided a value of the azimuthal angle, ϕ, used for further analysis.

[2] 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 centre of HERA. The coordinate origin is at the nominal interaction point.

3 Method

The energy-flow method was proposed [18, 19] to ensure that the inclusive variables such as those measured here are infra-red and collinear safe due to the direction of each particle being weighted by its transverse energy.

In this analysis, the moments of trigonometric functions of the azimuthal angle are calculated as follows. For a function, $F(n\phi^{\mathrm{HCM}})$, where $F(n\phi^{\mathrm{HCM}})$ can be $\sin(n\phi^{\mathrm{HCM}})$ or $\cos(n\phi^{\mathrm{HCM}})$ and $n = 1$ or 2, the mean value was determined using the formula:

$$\langle F\left(n\phi^{\mathrm{HCM}}\right)\rangle = \frac{\sum_i E_{T,i}^{\mathrm{HCM}} F\left(n\phi_i^{\mathrm{HCM}}\right)}{\sum_i E_{T,i}^{\mathrm{HCM}}}, \tag{2}$$

where E_T^{HCM} is the transverse energy and ϕ the azimuthal angle for each EFO, i. The value is calculated in bins of η^{HCM}, semi-inclusively, and for different minimum cuts on the transverse energy of the EFO, $E_{T,\min}^{\mathrm{HCM}}$. Equation (2) is also used for the determination of the moments in theoretical calculations in which the sum is either over final-state hadrons or partons. The mean values are not expected to be sensitive to uncertainties in parton distribution functions, fragmentation functions, and calorimeter energy scale, since such effects contribute to both the numerator and the denominator.

4 Correction procedure

Monte Carlo (MC) events were used to correct the data for detector acceptances. The generated events were passed through the ZEUS detector- and trigger-simulation programs based on GEANT 3.13 [20].

Neutral current events with electroweak radiative corrections were simulated with the LEPTO 6.5.1 [21] program interfaced to HERACLES 4.6.1 [22, 23] via the DJANGOH 1.1 program [24, 25]. High-order QCD processes were simulated using the MEPS option of LEPTO. A second sample of MC events was generated with ARIADNE 4.12 [26], where the QCD cascade is simulated with the colour-dipole model. In all cases, the events were generated using the CTEQ4D parton density parametrisation [27] of the proton. The final-state partonic system was hadronised using the Lund string model as implemented in JETSET 7.4 [28].

For a given bin in η^{HCM}, the correction factor was determined in many bins, j, of the trigonometric function, $F(n\phi^{\mathrm{HCM}})$. For a given bin in η^{HCM} and $F(n\phi^{\mathrm{HCM}})$, two correction factors were derived from MC as the ratio of values determined using hadrons and EFOs:

$$C_j = \frac{\left[\sum_i E_{T,i}^{\rm HCM} F\left(n\phi_i^{\rm HCM}\right)\right]_{{\rm had},j}^{\rm MC}}{\left[\sum_i E_{T,i}^{\rm HCM} F\left(n\phi_i^{\rm HCM}\right)\right]_{{\rm EFO},j}^{\rm MC}}, \qquad D_j = \frac{\left[\sum_i E_{T,i}^{\rm HCM}\right]_{{\rm had},j}^{\rm MC}}{\left[\sum_i E_{T,i}^{\rm HCM}\right]_{{\rm EFO},j}^{\rm MC}},$$

where C_j corrects the trigonometric function weighted with E_T and D_j corrects the sum of E_T in the bin, j. The corrected data for a bin in $\eta^{\rm HCM}$ is then given by:

$$\langle F\left(n\phi^{\rm HCM}\right)\rangle = \frac{\sum_j \left(\sum_i E_{T,i}^{\rm HCM} F\left(n\phi_i^{\rm HCM}\right)\right)_{{\rm EFO},j} \cdot C_j}{\sum_j \left(\sum_i E_{T,i}^{\rm HCM}\right)_{{\rm EFO},j} \cdot D_j}.$$

The correction factors are about 10% and arise mainly from undetected hadrons.

For this approach to be valid, the uncorrected energy flow in the data must be well described by the MC simulations at the detector level. This condition was satisfied [29] by both the LEPTO and ARIADNE simulations in the $\eta^{\rm HCM}$ and $E_T^{\rm HCM}$ regions under investigation. The samples of LEPTO events were used for the final corrections.

Systematic uncertainties of the azimuthal asymmetry were determined by varying the event selection cuts within their reconstruction resolution and the total systematic uncertainty was taken as the sum in quadrature of the individual systematics. The dominant contributions originated from the following sources (maximal deviations for $\langle\cos\phi\rangle$ are shown in parentheses):

- the use of an the ARIADNE MC model to correct the data (0.017);
- varying the cut on the p_T of the final-state objects from 0.15 GeV to 0.2 GeV to estimate the effect due to low-p_T tracks (0.013);
- the inclusion of energy deposits consistent with being a photon for the calculation of the hadronic angle, used in the double-angle method [16], and therefore the transformation to the HCM frame (0.009).

The effect of the variation of other selection cuts was negligible.

5 QCD calculations

The data were compared to the MC programs, LEPTO and ARIADNE, described in the previous section, and to a next-to-leading-order (NLO) prediction. In these two MC programs, the azimuthal-angular distribution is implemented according to the first-order QCD matrix elements for QCDC and BGF. The parton-shower and soft-matrix-element events are flat in azimuth. The NLO predictions were calculated using the dipole factorisation formulae [30] implemented in the DISENT program [30,31]. The calculations used a generalised version of the subtraction method [32] and were performed in the massless $\overline{\mathrm{MS}}$ renormalisation and factorisation schemes. The azimuthal-angle distribution is calculated to NLO by the DISENT program through the use of the photon leptonic current in the amplitudes for the QCDC, BGF and $\mathcal{O}(\alpha_s^2)$ processes. This program contains neither Z^0 exchange nor hadronisation effects. The following settings were used as defaults for DISENT: the number of flavours was set to five, the factorisation and renormalisation scales were set to $\mu_{F,R} = Q$, and the parton distribution function was set to CTEQ3M [33]. Samples of events from LEPTO 6.5.1 were used to correct the NLO QCD calculations for Z^0-exchange effects, hadronisation and undetected particles due to the requirements on p_T and θ of the produced hadrons.

The uncertainty in the DISENT predictions was estimated by changing the following:

- the renormalisation and factorisation scales were individually changed to $\mu_{F,R} = Q/2$ and $2Q$;
- the parton distribution functions CTEQ4M [27], CTEQ5M [34], were used;
- the correction for Z^0-exchange effects, hadronisation and undetected particles was repeated with the ARIADNE 4.12 MC.

The above uncertainties were at most 0.004 in both $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$. They were added in quadrature and are displayed in the figures as shaded bands around the central prediction. The sensitivity to different gluon distributions was checked by using the MRST99 [35] parton distributions functions with an increased or decreased gluon density; the differences were negligible.

6 Results

Azimuthal asymmetries have been measured in NC DIS events with the requirements: $100 < Q^2 < 8000$ GeV^2, $0.2 < y < 0.8$ and $0.01 < x < 0.1$ for hadrons with $p_T > 0.15$ GeV and $\theta > 8°$. The mean values of $\cos\phi^{\mathrm{HCM}}$, $\cos 2\phi^{\mathrm{HCM}}$, $\sin\phi^{\mathrm{HCM}}$ and $\sin 2\phi^{\mathrm{HCM}}$ are shown in Fig. 3 as a function of η^{HCM}. The data are compared with predictions from MC models and from NLO QCD as described in the previous section.

Figure 3 shows that the value of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ is negative for $\eta^{\mathrm{HCM}} < -2$ but becomes positive for larger η^{HCM}. This is in disagreement with both MC predictions, which are less negative for $\eta^{\mathrm{HCM}} < -2$ and remain negative for larger η^{HCM}. The measured $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ values are consistent with zero for $\eta^{\mathrm{HCM}} < -2$ but are positive for higher values of η^{HCM}. This is consistent with the expectations from both LEPTO and ARIADNE.

The NLO QCD predictions, corrected for hadronisation, agree better with the experimental values for $\langle\cos\phi^{\mathrm{HCM}}\rangle$ than do the MC predictions. The predictions from NLO

QCD are more negative for $\eta^{\rm HCM} < -2$ than those from the MC generators and also have positive values for larger $\eta^{\rm HCM}$. However, the NLO calculation still fails to describe the magnitude of the asymmetry in the data. The comparison with NLO QCD was also made at higher p_T, greater than 1 GeV (not shown). The Monte Carlo was used to correct the NLO for this cut; although the final correction for $\langle \cos\phi^{\rm HCM}\rangle$ is small, the correction for hadron removal was large. However, the comparison with the data was qualitatively the same as when the more inclusive cut was used. The disagreement between data and NLO suggests that higher-order calculations may be necessary to predict this distribution fully. Inclusion of higher orders through a resummation of large logarithmic terms is expected [6] to give an improved description compared to that of LO for $-5 < \eta < -3$. However, the description is not qualitatively better than for the other predictions. For $\langle \cos 2\phi^{\rm HCM}\rangle$, the NLO and MC predictions are similar and describe the data reasonably well.

Figure 3 shows that the values of $\langle \sin\phi^{\rm HCM}\rangle$ and $\langle \sin 2\phi^{\rm HCM}\rangle$ are small and consistent with zero. The mean values are expected to be at least an order of magnitude smaller than the $\langle \cos\phi^{\rm HCM}\rangle$ term [5]. None of the theoretical models include predictions for $\langle \sin\phi^{\rm HCM}\rangle$ or $\langle \sin 2\phi^{\rm HCM}\rangle$.

To investigate the effect of the minimum transverse energy cut, $E_{T,{\rm min}}^{\rm HCM}$, on the asymmetries, the event sample was subdivided into three regions of $\eta^{\rm HCM}$: $-5 < \eta^{\rm HCM} < -2.5$, $-2.5 < \eta^{\rm HCM} < -1$ and $-1 < \eta^{\rm HCM} < 0$. For $E_{T,{\rm min}}^{\rm HCM} = 1\,{\rm GeV}$, the acceptance is approximately 100%. Below this value, some hadrons are removed by the $p_T > 0.15\,{\rm GeV}$ requirement mainly in the region $-2.5 < \eta^{\rm HCM} < -1$. The data are shown in Fig. 4 compared to the predictions from Lepto and Ariadne MCs. As stated previously, NLO QCD predictions for higher $E_{T,{\rm min}}^{\rm HCM}$ have large corrections for hadron removal.

The first region $-5 < \eta^{\rm HCM} < -2.5$ is part of the current region in DIS defined in the Breit frame as $\eta^{\rm Breit} \approx \eta^{\rm HCM} + 2 < 0$; in this region the main contribution to the azimuthal asymmetry comes from QCDC and arises from hadrons from quark fragmentation (Fig. 2). This region was investigated in the first ZEUS analysis of azimuthal asymmetries [8] using charged hadrons. The data from the current analysis, shown in Fig. 4, confirm, with higher experimental precision and to higher $E_{T,{\rm min}}^{\rm HCM}$, that the value of $\langle \cos\phi^{\rm HCM}\rangle$ is more negative than expected from MC predictions. The $\langle \cos 2\phi^{\rm HCM}\rangle$ values are small and consistent with zero and also in agreement with both Lepto and Ariadne.

The region $-2.5 < \eta^{\rm HCM} < -1$ is still dominated by QCDC events but the contribution from BGF events increases. The ZEUS analysis of azimuthal asymmetries measured using jets [9] was based on hadrons from this region of phase space. In that analysis, a large positive value of $\langle \cos 2\phi^{\rm HCM}\rangle$ was measured, whereas the $\langle \cos\phi^{\rm HCM}\rangle$ value was consistent with zero. The $\langle \cos 2\phi^{\rm HCM}\rangle$ values agreed with the NLO QCD prediction and were inconsistent with the LO prediction. The results presented here in Fig. 4 confirm, with higher experimental precision, a small value of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ and positive values for $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ for all $E_{T,\mathrm{min}}^{\mathrm{HCM}}$. The MC predictions of Lepto and Ariadne are in good agreement with the data.

The third region, $-1 < \eta^{\mathrm{HCM}} < 0$, is populated roughly equally by hadrons from QCDC and from BGF processes. This measurement extends the kinematic region over those presented previously. The results are presented in Fig. 4. The $\langle\cos\phi^{\mathrm{HCM}}\rangle$ values are positive, contrary to MC predictions, whereas the $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ values are positive and in agreement with MC predictions. These trends persist up to the highest $E_{T,\mathrm{min}}^{\mathrm{HCM}}$ values measured.

7 Summary and conclusions

The azimuthal asymmetries in deep inelastic scattering have been measured in the hadronic centre-of-mass frame at HERA for a selected sample of neutral current events with $100 < Q^2 < 8000$ GeV^2, $0.2 < y < 0.8$ and $0.01 < x < 0.1$. An energy-flow analysis method was used, which permitted the use of both neutral and charged hadrons and extends the phase space over previous measurements.

Azimuthal asymmetries are investigated as a function of hadron pseudorapidity, η^{HCM}. The value of $\langle\cos\phi^{\mathrm{HCM}}\rangle$ is negative for $\eta^{\mathrm{HCM}} < -2$ but becomes positive for larger η^{HCM}. The distribution is not well described by the MC predictions of Ariadne and Lepto. Although the predictions from NLO QCD describe the data better than the MCs, they still fail to describe the magnitude of the asymmetries. This suggests that higher-order calculations may be necessary to describe these data. However, the predicted values of $\langle\cos 2\phi^{\mathrm{HCM}}\rangle$ in both MC models and in NLO QCD agree with the data.

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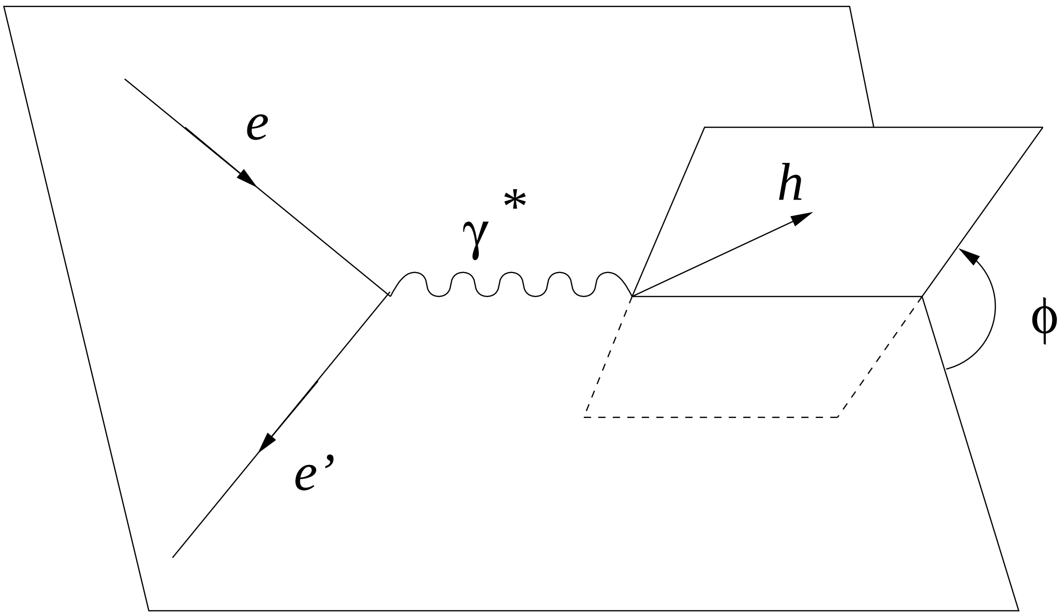
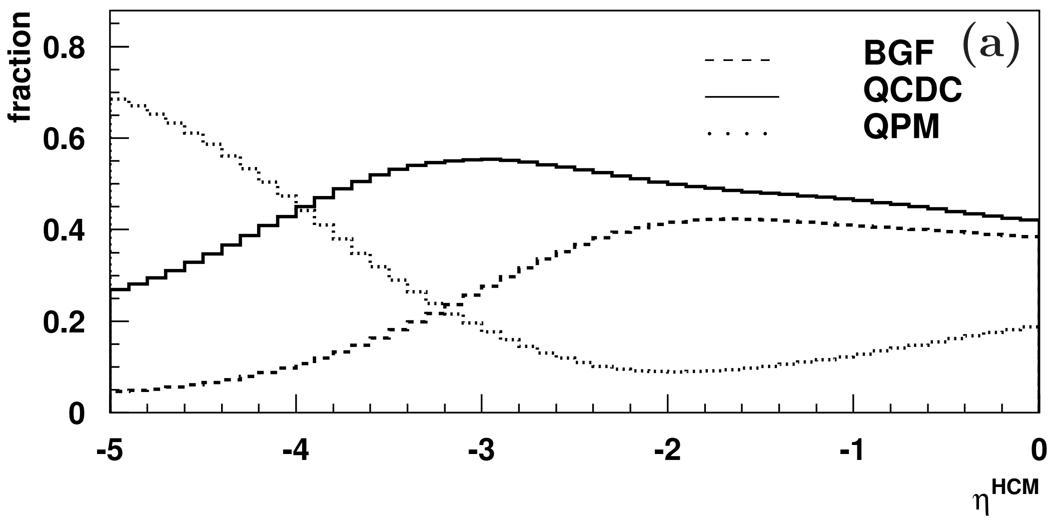


Figure 1: *The definition of the azimuthal angle ϕ either in the HCM or the Breit frame. The incoming electron is denoted by e, the scattered electron by e', the exchanged virtual photon by $\gamma^\star$ and the outgoing hadron or parton by h.*



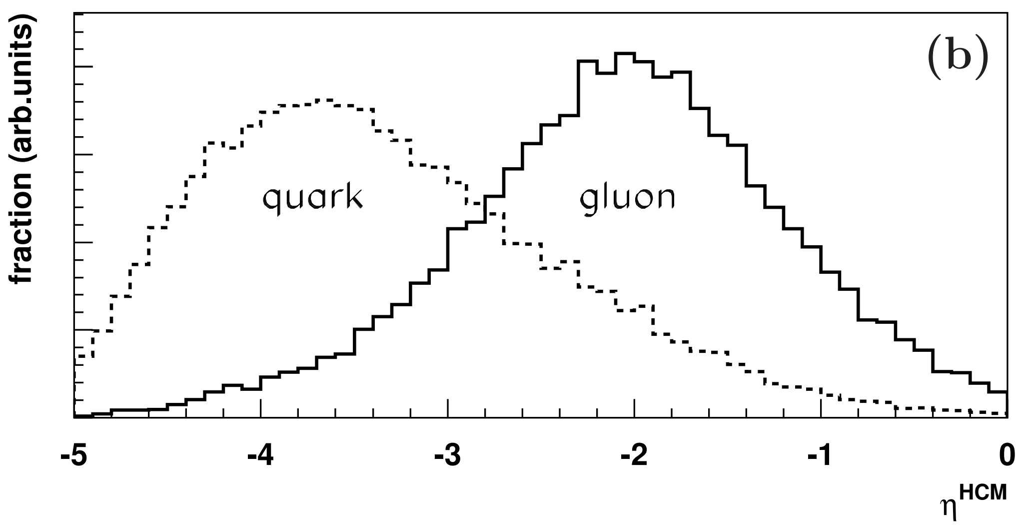


Figure 2: *(a) The fraction of BGF (dashed line), QCDC (full line) and QPM (dotted line) processes as a function of pseudorapidity, η^{HCM}, in the HCM frame for the energy-flow method. (b) For the QCD Compton process, the quark and gluon contributions as a function of η^{HCM}. These predictions are taken from* LEPTO *6.5.1 and are shown for the kinematic region $100 < Q^2 < 8000\,GeV^2$, $0.2 < y < 0.8$ and $0.01 < x < 0.1$ for hadrons with $p_T > 0.15\,GeV$ and $\theta > 8°$.*

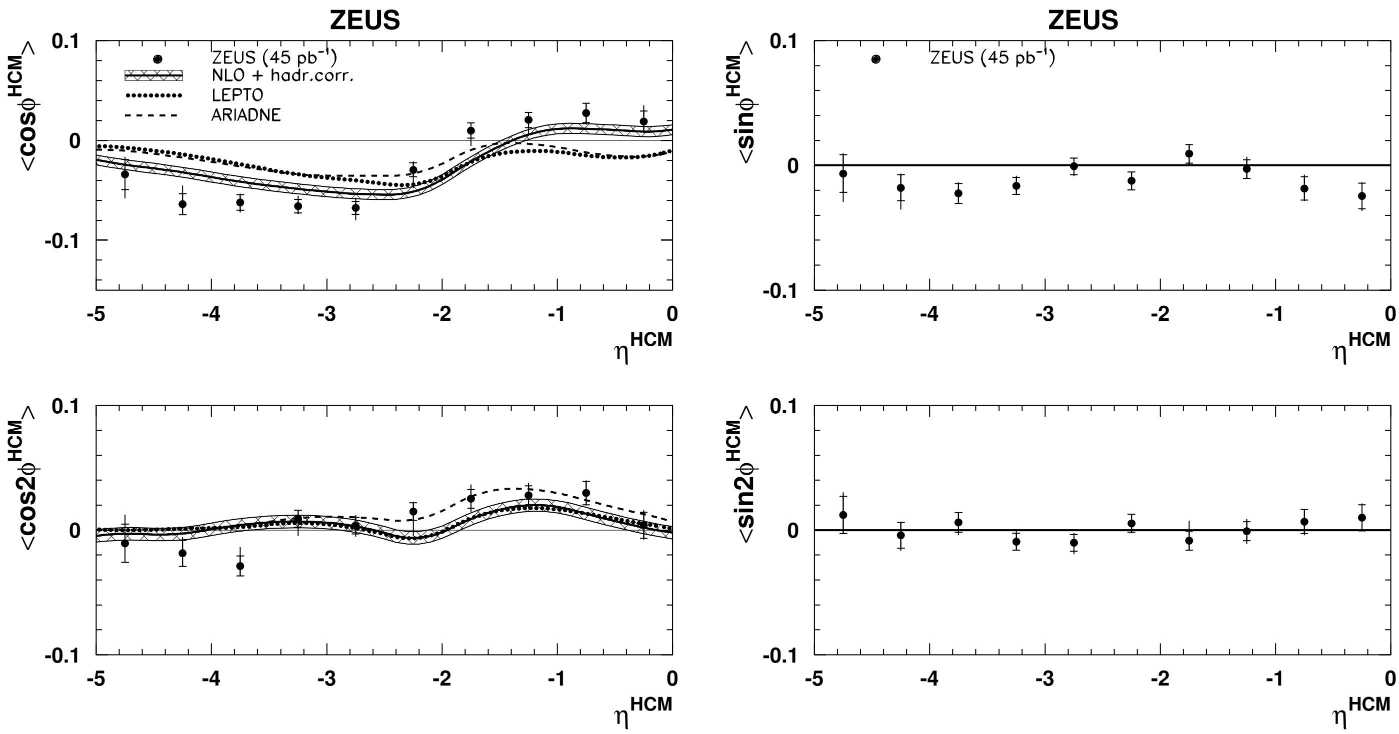


Figure 3: *The values of* $\langle \cos \phi^{\rm HCM} \rangle$, $\langle \cos 2\phi^{\rm HCM} \rangle$, $\langle \sin \phi^{\rm HCM} \rangle$ *and* $\langle \sin 2\phi^{\rm HCM} \rangle$, *calculated using the energy-flow method as in Eq. (2), as a function of hadron pseudorapidity,* $\eta^{\rm HCM}$. *They are obtained in the HCM frame for the kinematic region* $100 < Q^2 < 8000\,GeV^2$, $0.01 < x < 0.1$ *and* $0.2 < y < 0.8$ *for hadrons with* $p_T > 0.15\,GeV$ *and* $\theta > 8°$. *The inner error bars are statistical uncertainties, the outer are statistical and systematic uncertainties added in quadrature. The NLO QCD predictions of* DISENT *(solid line), with its associated uncertainty (shaded band), corrected for hadronisation and hadron losses (see text), the predictions of* LEPTO *6.5.1 (dotted line), and the predictions of* ARIADNE *4.12 (dashed line) are shown.*

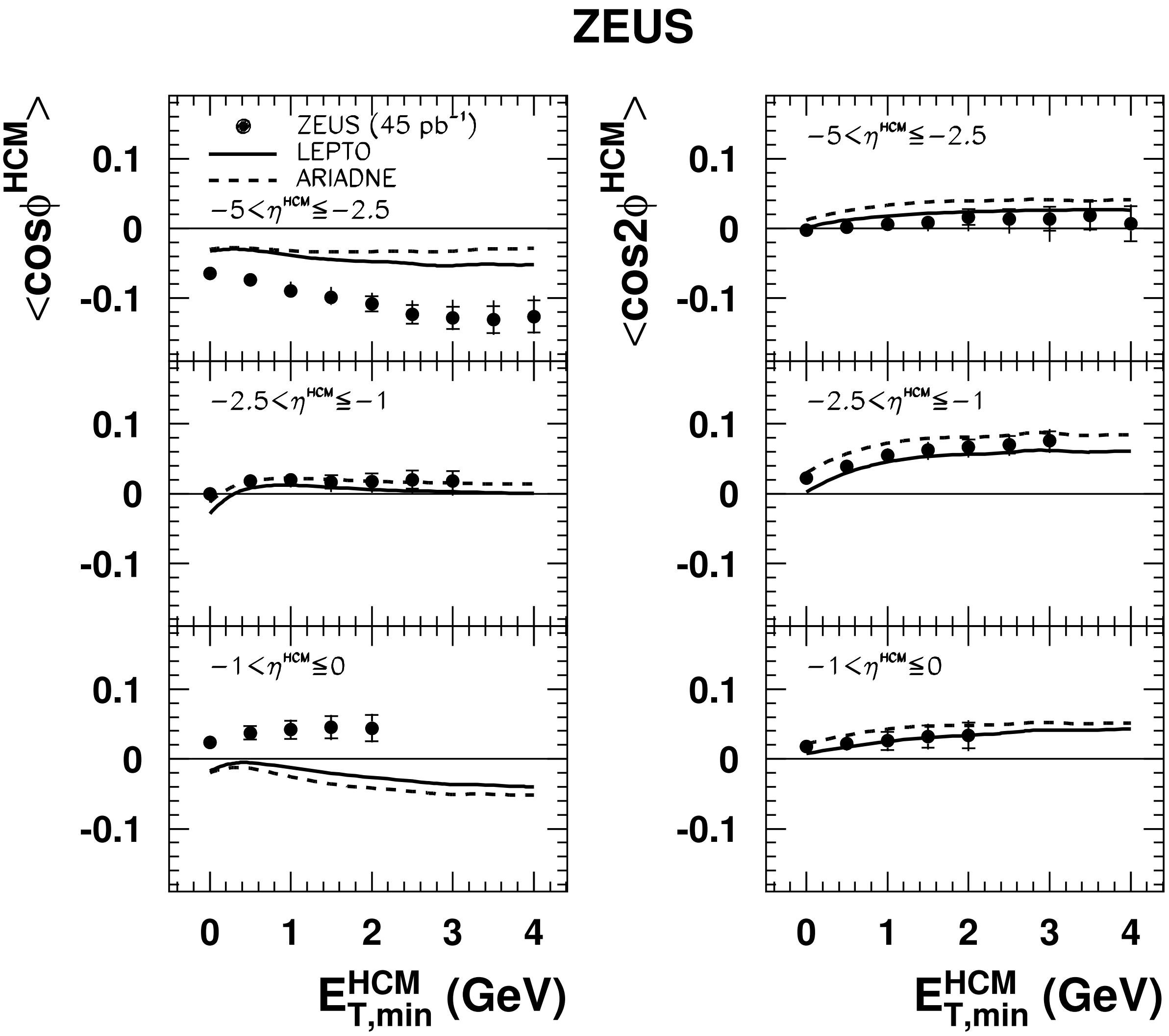


Figure 4: *The values of* $\langle \cos\phi^{\rm HCM}\rangle$ *and* $\langle \cos 2\phi^{\rm HCM}\rangle$*, calculated using the energy-flow method as in Eq. (2), as a function of hadron minimum transverse energy,* $E^{HCM}_{T,min}$*. They are obtained in the HCM frame for the pseudorapidity intervals* $-5 < \eta^{HCM} \leq -2.5$*,* $-2.5 < \eta^{HCM} \leq -1$ *and* $-1 < \eta^{HCM} \leq 0$ *in the kinematic region* $100 < Q^2 < 8000\,GeV^2$*,* $0.01 < x < 0.1$ *and* $0.2 < y < 0.8$ *for hadrons with* $p_T > 0.15\,GeV$ *and* $\theta > 8^\circ$*. The inner error bars are statistical uncertainties, the outer are statistical and systematic uncertainties added in quadrature. The predictions of* LEPTO *6.5.1 (solid line) and of* ARIADNE *4.12 (dashed line) are shown.*