Submitted to the
XXII International Symposium on Lepton-Photon Interactions at High Energy
June 30-July 5, 2005, Uppsala, Sweden

Abstract: 274 **Session: QCD/HS**

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

ZEUS Collaboration

19. May 2005

Abstract

The azimuthal angle distributions, in the hadronic centre-of-mass system, of charged and neutral hadrons were measured from the observed energy flows. The neutral current, deep inelastic data sample was collected by the ZEUS detector at HERA and corresponds to an integrated luminosity of 45 pb^{-1}. The dependence of the moments of the azimuthal distributions on the pseudorapidity and minimum transverse energy of the hadrons are 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, tests an important prediction of the perturbative Quantum Chromodynamics (pQCD) description of hadron production. Specifically, pQCD specifies the azimuthal distribution of the hadrons. The azimuthal angle, ϕ, is defined in the hadron centre-of-mass frame (HCM) as the angle between the hadron production plane and the lepton scattering plane illustrated in Fig. 1.

The semi-inclusive scattering cross section, can be written, [1–3], as

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

where the azimuthal asymmetries, denoted by parameters $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$ and $\mathcal{E}$, can be evaluated experimentally. They are extracted from experimental data by calculating statistical moments for experimental distributions of the respective trigonometrical functions of ϕ:

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

$$\langle\cos 2\phi\rangle = \frac{\mathcal{C}}{2\mathcal{A}} \qquad \langle\sin 2\phi\rangle = \frac{\mathcal{E}}{2\mathcal{A}} \tag{3}$$

In the energy flow method used here, 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 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 η^{HCM} dependence as shown in Fig. 2. This paper presents a study 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 η^{HCM} using the energy flow method.

2 Data sample

The experimental results are based on 45 pb^{-1} data collected in 1995-97 with the ZEUS detector at HERA. In this period 820 GeV protons collided with 27.5 GeV, longitudinally unpolarised, positrons.

ZEUS is a multipurpose detector described in detail elsewhere [6]. The main component is the uranium-scintillator calorimeter [7] which covers 99% of 4π. 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 (CTD) [8] which is a cylindrical drift chamber in a 1.4 T magnetic field covering 83% of 4π; 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.

The selection of neutral current (NC) events was based on an earlier ZEUS investigation [4]. 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 and Q^2 are x-Bjorken, the inelasticity, y, and the exchanged boson virtuality, Q^2. The double angle (DA) method was used to reconstruct these variables and the direction of the exchanged boson [9];
- the reconstructed hadrons, both charged and neutral, were required to have 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 CTD to ensure good reconstruction.

3 Correction procedure

Monte Carlo (MC) events were used to correct the data for detector acceptances. For this purpose, the generated events were passed through the ZEUS detector- and trigger simulation programs based on GEANT 3.13 [10]. Neutral current events with electroweak radiative corrections were simulated with the LEPTO 6.5.1 program interfaced to HERACLES 4.6.1 [11,12] via the DJANGOH 1.1 program [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 4.10 [15] where the QCD cascade is simulated with the colour-dipole model. The final state parton system was hadronised using the LUND string model as implemented in JETSET 7.4.10 [16].

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

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

Here, $E(\cos\phi) = \sum_i E^{\rm HCM}_{{\rm T}i}$ is summed over the emitted or reconstructed hadrons; the reconstructed hadrons are energy flow objects [17] which combine calorimetric and tracking information. The corrected integrated energy flow $E(\cos\phi)$ was determined separately bin-by-bin for each region in the η-$\cos\phi$ plane as

$$E(\cos\phi^{\rm DATA}) = F(\cos\phi)\cdot E(\cos\phi^{DATA}_{\rm det}).$$

For this approach to be valid, the uncorrected energy flow $E(\cos\phi)$ in the data had to be well described by the MC simulations at the detector level. This condition was satisfied by both the LEPTO and ARIADNE simulations in the $\eta^{\rm HCM}$ and $E^{\rm HCM}_{\rm T}$ regions under investigation. The samples of events of LEPTO were used for the final corrections; the corrections from the ARIADNE generator were included as a systematic uncertainty. The same method was used to calculate corrections for $\cos 2\phi^{\rm HCM}$, $\sin\phi^{\rm HCM}$ and $\sin 2\phi^{\rm HCM}$.

Systematic uncertainties were determined by varying the event selection cuts within their reconstruction resolution and the total systematic uncertainty was taken to be the sum in quadrature of the individual systematics.

4 Fixed-order QCD predictions

The leading-order (LO) calculations of azimuthal asymmetries were based on two generators: the LEPTO 6.5.1 program [18] 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 leading log. In ARIADNE, the QCD cascade was simulated using the colour-dipole model [19–22]. Both Monte Carlo programs used the Lund string model for the hadronisation [16]. The CTEQ4D [23, 24] proton parton density functions were used for the LO predictions presented here.

The next-to-leading-order (NLO) predictions were calculated using the dipole factorisation formulae [25] implemented in the DISENT program [25, 26]. The calculations used a generalised version of the subtraction method [27] and were performed in the massless $\overline{\rm MS}$ renormalisation and factorisation schemes. This model contains neither Z^0 exchange nor hadronisation. The following settings were used as defaults for DISENT: the number of flavours was set to five, the factorisation scale was set to $\mu_F = Q$, the renormalisation scale to $\mu_R = Q$ and the parton distribution function CTEQ3M [28] was used which was the DISENT default value. 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 [23] and CTEQ5M [29]. 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 and to estimate the systematic uncertainties.

5 Results

The measured azimuthal asymmetries in terms of the mean values of $\cos\phi^{\rm HCM}$, $\cos 2\phi^{\rm HCM}$, $\sin\phi^{\rm HCM}$ and $\sin 2\phi^{\rm HCM}$ are presented in Figs. 3 and 4 as a function of pseudorapidity $\eta^{\rm HCM}$ for hadrons with transverse momenta $\rm p_T^{LAB} > 150$ MeV. Also shown are the LO and NLO predictions.

Figure 3 shows that the mean value of $\langle\cos\phi^{\rm HCM}\rangle$ is negative for $\eta^{\rm HCM} < -2$ but becomes positive for larger $\eta^{\rm HCM}$. This is in disagreement with the LO predictions that are negative throughout the measured $\eta^{\rm HCM}$ range.

The measured $\langle\cos 2\phi^{\rm HCM}\rangle$ values are consistent with zero for for $\eta^{\rm HCM} < -2$ but are positive for higher values of $\eta^{\rm HCM}$. This is consistent with the LO expectations from both LEPTO and ARIADNE.

The NLO predictions are also shown. The theoretical uncertainties (shaded band), due to renormalisation and factorisation scales, are indicated together with those due to the structure functions. The ARIADNE correction for Z^0-exchange effects, hadronisation and detection are included in the systematic uncertainties. The NLO predictions give better agreement with the experimental values for $\langle\cos\phi^{\rm HCM}\rangle$ than do the LO predictions. For $\langle\cos 2\phi^{\rm HCM}\rangle$ the NLO and LO predictions are similar.

Figure 4 shows that that the mean values of $\langle\sin\phi^{\rm HCM}\rangle$ and $\langle\sin 2\phi^{\rm HCM}\rangle$ are small and consistent with zero. They are expected to be at least an order of magnitude smaller than the $\langle\cos\phi^{\rm HCM}\rangle$ terms [3].

The asymmetry can be analysed [2, 4] as a function of the detected hadron's transverse momentum cutoff, $p_{T\ \rm cut}$ or the minimum transverse energy $\rm E_T^{HCM}(min)$. This allows the removal of the zeroth order QCD processes and a selection of leading hadrons produced directly from the scattered partons. Consequently, at higher $E_T^{HCM}(\mathrm{min})$ values a better agreement should be obtained with the pQCD prediction. For this study the sample has been subdivided into three regions of η^{HCM}: $-5 < \eta^{HCM} < -2.5$, $-2.5 < \eta^{HCM} < -1$ and $-1 < \eta^{HCM} < 0$.

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

The region $-2.5 < \eta^{HCM} < -1$ is that with an increasing contribution from boson-gluon fusion (Fig. 2). The ZEUS analysis of azimuthal asymmetries deduced from jets [5] was based on hadrons from this region of phase space. The results presented here in Fig. 6 confirm a small value of $\langle \cos\phi^{HCM} \rangle$ and positive values for $\langle \cos 2\phi^{HCM} \rangle$ for all $E_T^{HCM}(\mathrm{min})$. The LO predictions of LEPTO and ARIADNE are in good agreement with data.

The third region $-1 < \eta^{HCM} < 0$ is populated equally by hadrons from QCD Compton and from boson-gluon fusion processes (Fig. 2). For these hadrons azimuthal asymmetries are investigated for the first time. The results are presented in Figure 7. The $\langle \cos\phi^{HCM} \rangle$ values are positive, contrary to LO predictions, whereas the $\langle \cos 2\phi^{HCM} \rangle$ values are positive and in agreement with LO predictions.

6 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 η^{HCM}. The $\langle \cos\phi^{HCM} \rangle$ values are not well described by the LO predictions. The $\langle \cos 2\phi^{HCM} \rangle$ values are only significant in the region $\eta^{HCM} > -2.5$ when high minimum transverse momentum is selected for hadrons; this agrees with LO predictions.

References

[1] A. Méndez, Nucl. Phys. **B 145**, 199 (1978).

[2] J. Chay, S.D.Ellis, W.J.Stirling, Phys. Lett. **B 269**, 175 (1991).

[3] M. Ahmed, T. Gehrmann, Phys. Lett. **B 465**, 297 (1999).

[4] ZEUS Coll., J. Breitweg et al., Phys. Lett. **B 481**, 199 (2000).

[5] ZEUS Coll., S. Chekanov et al., Phys. Lett. **B 551**, 3 (2003).

[6] ZEUS Coll., U. Holm (ed.), *The ZEUS Detector*. Status Report (unpublished), DESY (1993), available on `http://www-zeus.desy.de/bluebook/bluebook.html`.

[7] M. Derrick et al., Nucl. Inst. Meth. **A 309**, 77 (1991);
A. Andresen et al., Nucl. Inst. Meth. **A 309**, 101 (1991);
A. Caldwell et al., Nucl. Inst. Meth. **A 321**, 356 (1992);
A. Bernstein et al., Nucl. Inst. Meth. **A 336**, 23 (1993).

[8] N. Harnew et al., Nucl. Inst. Meth. **A 279**, 290 (1989);
B. Foster et al., Nucl. Phys. Proc. Suppl. **B 32**, 181 (1993);
B. Foster et al., Nucl. Inst. Meth. **A 338**, 254 (1994).

[9] S. Bentvelsen, J. Engelen and P. Kooijman, *Proc. Workshop on Physics at HERA*, W. Buchmüller and G. Ingelman (eds.), Vol. 1, p. 23. Hamburg, Germany, DESY (1992).

[10] R. Brun et al., GEANT3, Technical Report CERN-DD/EE/84-1, CERN, 1987.

[11] A. Kwiatkowski, H. Spiesberger and H.-J. Möhring, Comp. Phys. Comm. **69**, 155 (1992). Also in *Proc. Workshop Physics at HERA*, 1991, DESY, Hamburg.

[12] H. Spiesberger, *An Event Generator for ep Interactions at HERA Including Radiative Processes (Version 4.6)*, 1996, available on `http://www.desy.de/~hspiesb/heracles.html`.

[13] H. Spiesberger, HERACLES *and* DJANGOH*: Event Generation for ep Interactions at HERA Including Radiative Processes*, 1998, available on `http://www.desy.de/~hspiesb/djangoh.html`.

[14] K. Charchula, G.A. Schuler and H. Spiesberger, Comp. Phys. Comm. **81**, 381 (1994).

[15] L. Lönnblad, Comp. Phys. Comm. **71**, 15 (1992).

[16] T. Sjöstrand and M. Bengtsson, Comp. Phys. Comm. **43**, 367 (1987).

[17] ZEUS Coll., J. Breitweg et al., Eur. Phys. J. **C 6**, 43 (1999).

[18] G. Ingelman, A. Edin and J. Rathsman, Comp. Phys. Comm. **101**, 108 (1997).

[19] Y.Azimov et al., Phys. Lett. **B 165**, 147 (1985).

[20] G.Gustafson, Phys. Lett. **B 175**, 453 (1986).

[21] G.Gustafson, U.Pettersson, Nucl. Phys. **B 306**, 746 (1988).

[22] B.Andersson et al., Z. Phys. **C 43**, 625 (1989).

[23] H.L.Lai et al., Phys. Rev. **D 55**, 1280 (1997).

[24] H.L. Lai et al., Phys. Rev. **D 51**, 4763 (1995).

[25] S.Catani, M.H.Seymour, Nucl. Phys. **B 485**, 401 (1997).

[26] S.Catani, M.H.Seymour, Nucl. Phys. **B 510**, 503 (1998).

[27] R.K.Ellis, D.A.Ross, A.E.Terrano, Nucl. Phys. **B 178**, 421 (1981).

[28] J. Botts et al., Phys. Lett. **B 304**, 159 (1995).

[29] CTEQ Coll., H.L. Lai et al., Eur. Phys. J. **C 12**, 375 (2000).

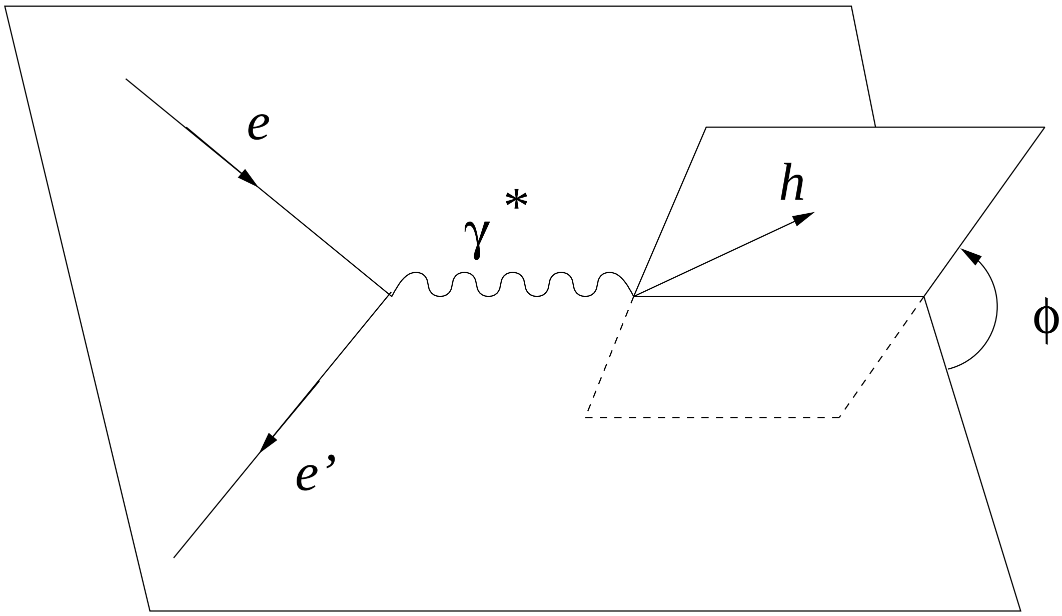

Figure 1: *The definition of the azimuthal angle ϕ either in the hadronic centre-of-mass frame (HCM) or the Breit frame. The incoming electron is denoted by e, the scattered electron by e', the exchanged virtual photon by $\gamma^\star$ and the outgoing hadron or parton by h.*

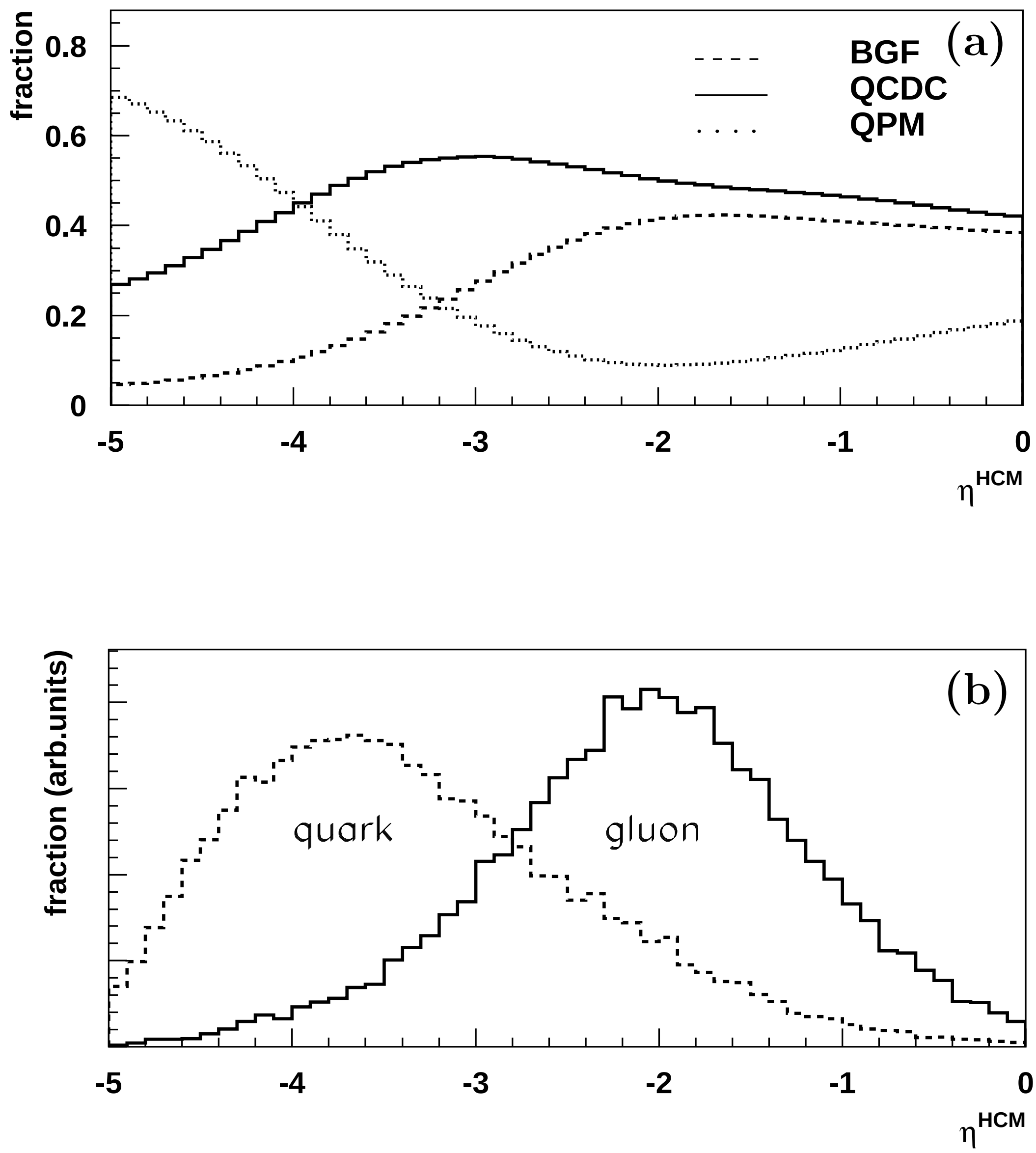

Figure 2: *(a) The fraction of boson-gluon fusion (BGF) (dashed line), QCD Compton (QCDC) (full line) and the zeroth order QCD process (dotted line) as a function of pseudorapidity* η^{HCM} *in the hadronic centre-of-mass frame for the energy flow method. (b) For the QCD Compton process the guark and gluon contributions as a function of pseudorapidity* η^{HCM}*. These predictions are taken from LEPTO 6.5.1.*

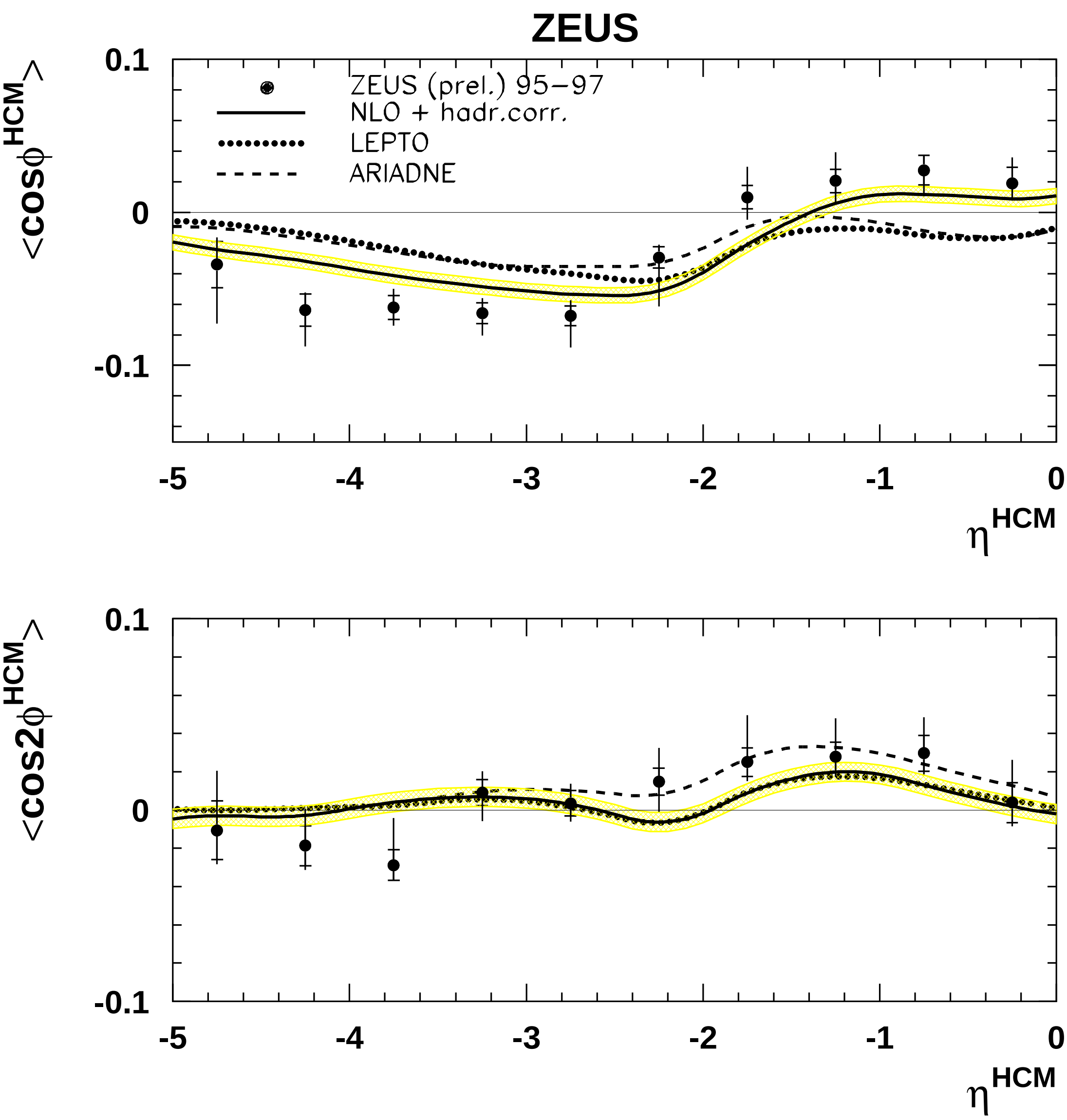

Figure 3: *The values of* $\langle \cos\phi^{\rm HCM} \rangle$ *and* $\langle \cos 2\phi^{\rm HCM} \rangle$ *are shown as a function of hadron pseudorapidity* $\eta^{\rm HCM}$ *obtained using the energy flow method in the hadronic centre-of-mass system in the kinematical region* $0.01 < x < 0.1$ *and* $0.2 < y < 0.8$. *In experiment and in Monte Carlo hadrons are taken with hadron minimum transverse energy* $\mathrm{E_T^{HCM}} > 0.15$ GeV. *The inner error bars are statistical uncertainties, the outer are statistical and systematic uncertainties added in quadrature. The full line represents the NLO predictions of DISENT corrected for hadronisation and hadron losses (see text), the dotted line represents LEPTO 6.5.1 and the dashed line represents the ARIADNE 4.12 predictions.*

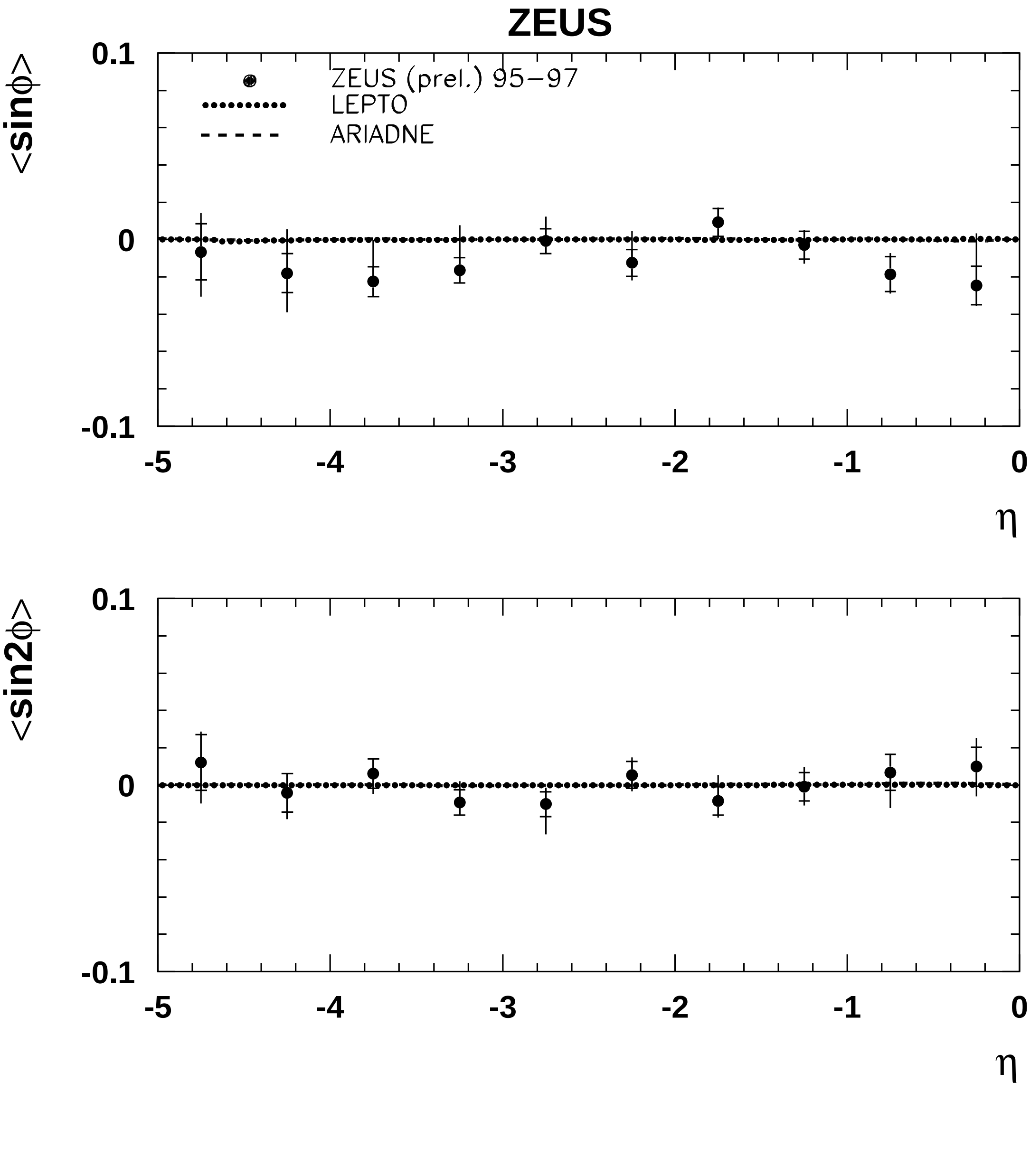

Figure 4: *as figure 3 but as a function of hadron pseudorapidity* $\eta^{\rm HCM}$ *are shown the values of* $\langle\sin\phi^{\rm HCM}\rangle$ *and* $\langle\sin 2\phi^{\rm HCM}\rangle$.

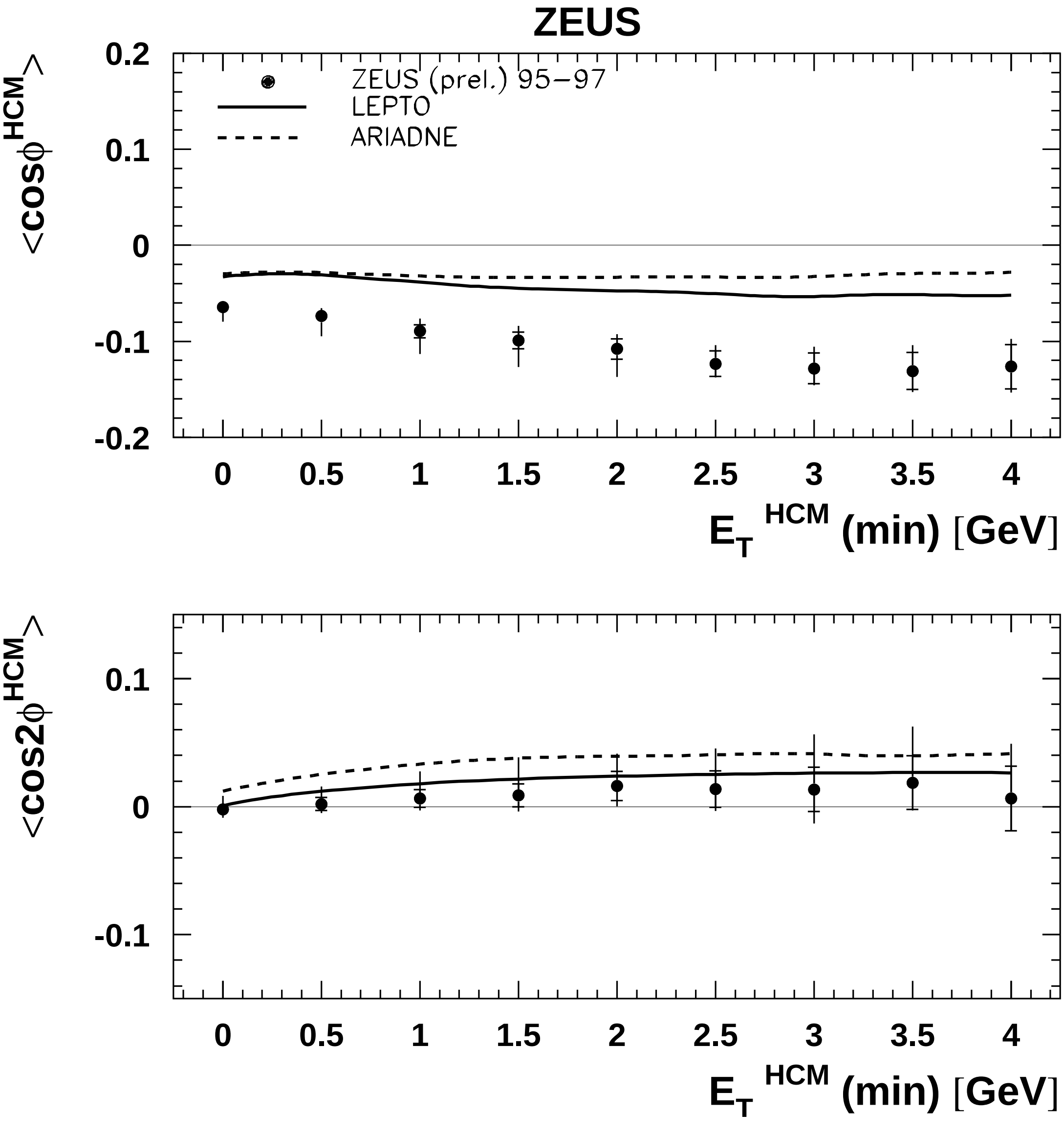

Figure 5: *The values of* $\langle \cos\phi^{\rm HCM}\rangle$ *and* $\langle \cos 2\phi^{\rm HCM}\rangle$ *are shown as a function of hadron minimum transverse energy* $\rm E_T^{HCM}$ (min) *in the hadronic centre-of-mass system for the pseudorapidity interval* $-5 < \eta^{\rm HCM} \leq -2.5$ *in the kinematical region* $0.01 < x < 0.1$ *and* $0.2 < y < 0.8$. *The energy flow method is used with the hadron minimum transverse energy* $\rm E_T^{LAB} > 0.15$ GeV. *The inner error bars are statistical uncertainties, the outer are statistical and systematic uncertainties added in quadrature. The full line represents LEPTO 6.5.1 and the dashed line — the ARIADNE 4.12 predictions.*

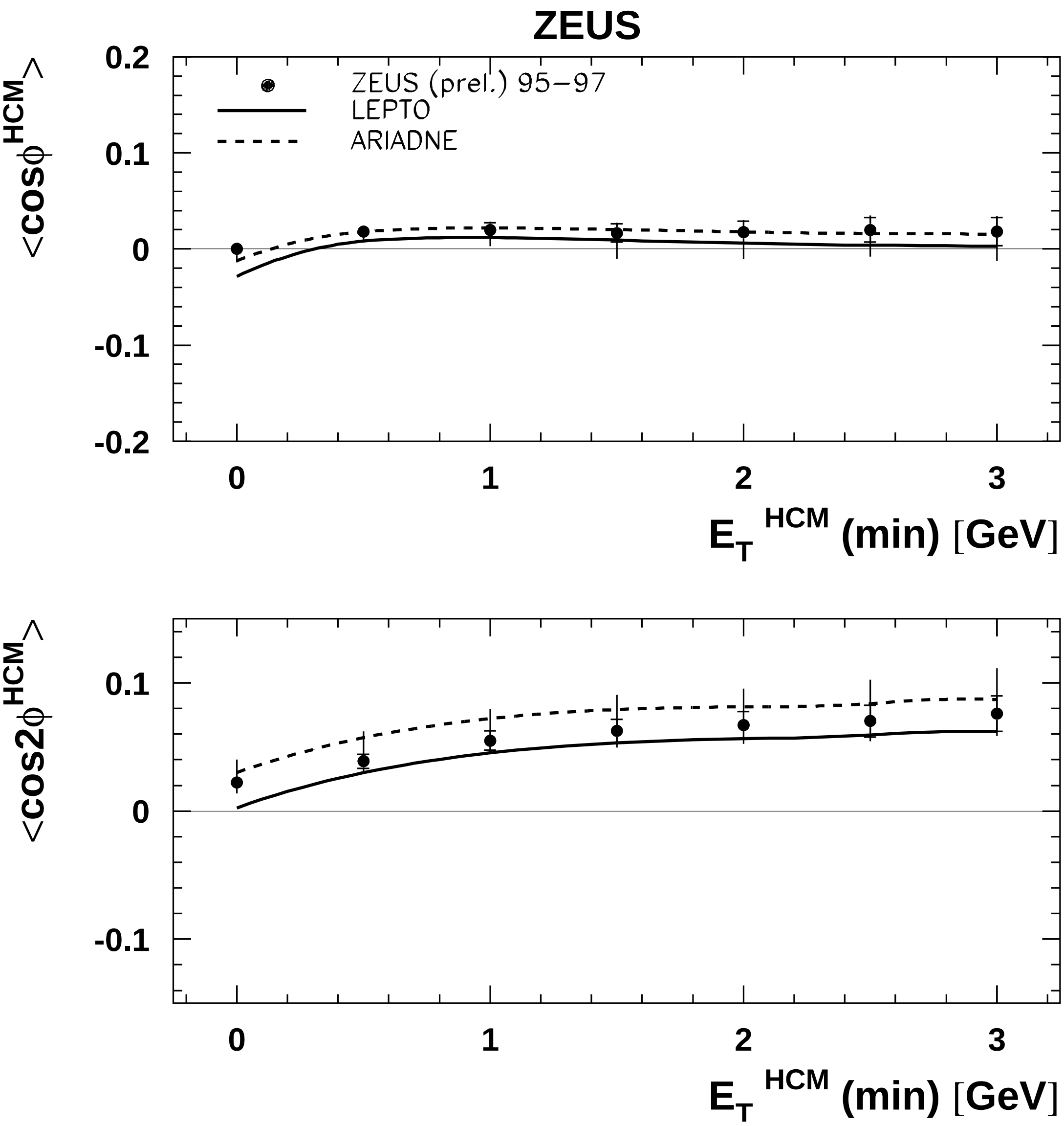

Figure 6: *as in figure 5 but the values of* $\langle \cos\phi^{\rm HCM}\rangle$ *and* $\langle \cos 2\phi^{\rm HCM}\rangle$ *are shown as a function of the hadron minimum transverse energy* $\rm E_T^{HCM}$ (min) *for the pseudorapidity interval* $-2.5 < \eta^{\rm HCM} \leq -1$.

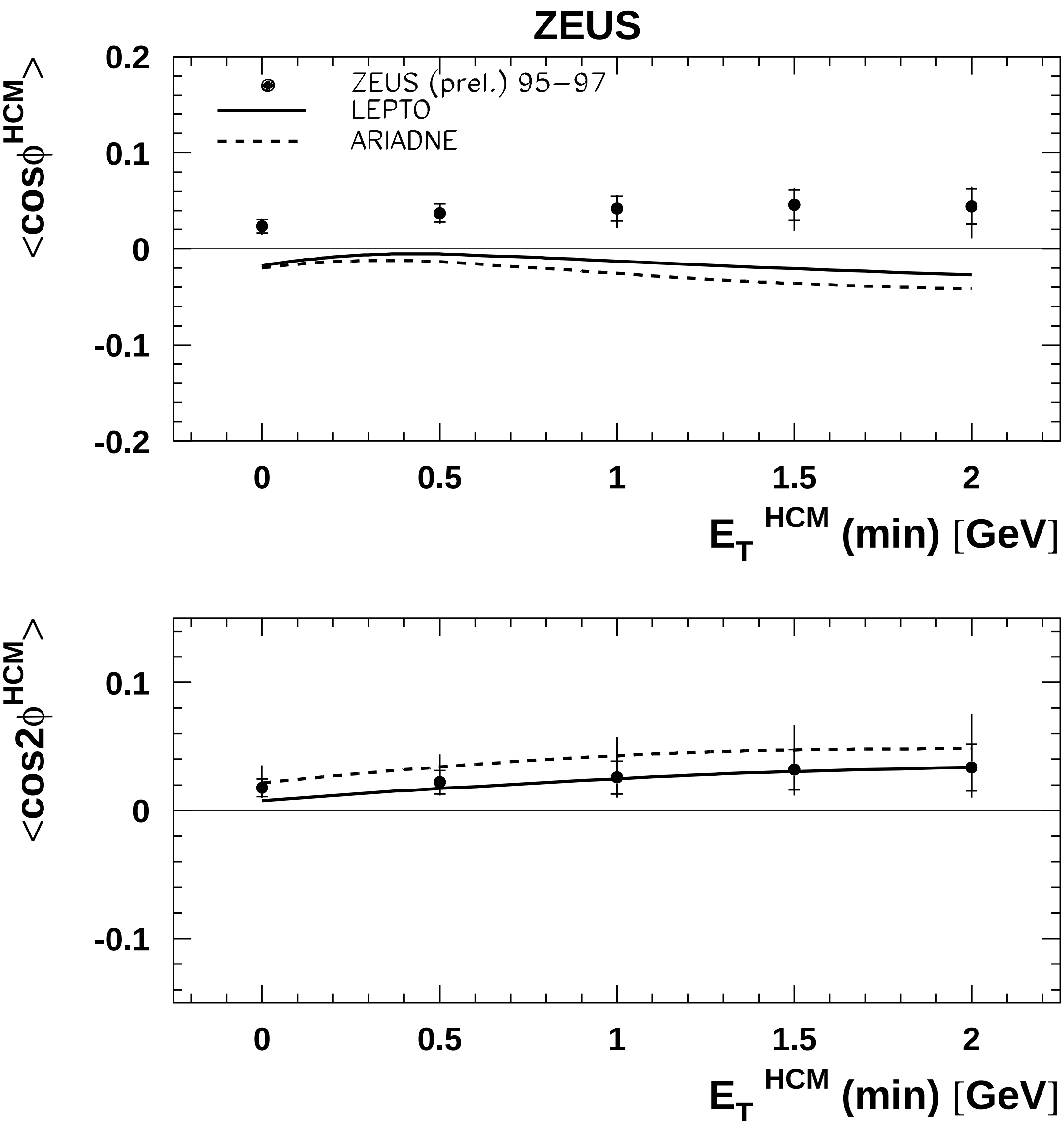

Figure 7: *as in figures 5 and 6 but the values of* $\langle \cos\phi^{\rm HCM}\rangle$ *and* $\langle \cos 2\phi^{\rm HCM}\rangle$ *are shown as a function of hadron minimum transverse energy* $\mathrm{E}_{\mathrm{T}}^{\mathrm{HCM}}$ (min) *for the pseudorapidity interval* $-1 < \eta^{\rm HCM} \leq 0$.