Azimuthal asymmetries in deep inelastic $e^+p \to e^+X$ scattering at HERA

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Abstract. A Monte Carlo study of the azimuthal angular distribution around the virtual boson-proton beam axis at HERA is presented. In the presence of typical acceptance and selection criteria in the laboratory frame the azimuthal distribution is investigated for different kinematical variables. The best measureable dependence of $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ is found to be for rapidity $\mathscr{Y}$ or pseudorapidity η using the energy flow method.

Keywords: Deep inelastic scattering, azimuthal asymmetry, boson polarisation, HERA
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INTRODUCTION

The high-luminosity data on deep inelastic scattering collected at HERA allow the investigation of hadronic final state features going beyond hadron multiplicities or jet structures. One of the possible observables is related to the angular correlation between the lepton scattering plane and the hadron production plane in the hadronic centre-of-mass (HCM) created by the exchanged boson and proton.

This paper presents an investigation of azimuthal asymmetries by counting the emitted hadrons and with energy flow to optimize observables and the kinematical region for precise measurements. The experimental data are presented elsewhere [1]. The Z-axis directed along the incoming proton direction defines the transverse and longitudinal quantities of the emitted hadrons. Around this axis the azimuthal angle ϕ is measured from the lepton scattering plane to the hadron/parton production plane (Fig. 1a).

The semi-inclusive cross section for neutral current can be decomposed according to the dependence on ϕ e.g. [2]:

$$\frac{d^5\sigma^{ep\to ehX}}{dx dQ^2 dp_\perp^2 \dots d\phi} = \mathscr{A} + \mathscr{B}\cos\phi + \mathscr{C}\cos 2\phi \tag{1}$$

The terms with $\mathscr{B}$ and $\mathscr{C}$ quantities exist only if the final hadron or parton carries some transverse momentum. In the zeroth order QCD process the incoming quark is backscattered along the Z-axis. The parton shower development and hadronisation cause the appearance of hadrons with some transverse energy E_T^{HCM}, which on average, is rather small ($E_T^{\mathrm{HCM}} < 0.5$ GeV). The first order QCD processes such as QCD Comptons $(\gamma^* q \to qg)$ and boson-gluon fusion $(\gamma^* g \to q\,\overline{q})$ are the main source of hadrons with large transverse momenta. Hadronisation which is essentially symmetric around the parton direction smears the primary events shape.

The $\mathscr{B}$ and $\mathscr{C}$ values can be extracted within any kinematical cuts by calculating statistical moments for the obtained distributions of the respective trigonometrical functions of ϕ. Some simple relations exist for the averaged asymmetries:

$$\langle\cos\phi\rangle = \frac{\mathscr{B}}{2\mathscr{A}} \qquad \langle\cos 2\phi\rangle = \frac{\mathscr{C}}{2\mathscr{A}} \tag{2}$$

EXPERIMENTAL ASPECTS

The investigations are done for 820 GeV protons and 27.5 GeV positrons. The kinematical region is the same as used in the high-Q^2 ZEUS analysis [3, 4] namely the exchanged boson fourvector is $100 < Q^2 < 8000$ GeV^2, the Bjorken variable $0.01 < x < 0.1$ and inelasitcity $0.2 < y < 0.8$. The main feature of the experimental data included in the MC generation are losses of the hadrons in the beam pipe ($\mathrm{P_T^{LAB}} < 150$ MeV).

In the HERA experiments calorimeters are the dominant suppliers of information on emitted hadrons covering 99% of 4π. They do not measure individual hadrons but are designed to measure clusters of energy for jet algorithms. The detection efficiencies of charged and neutral particles are similar. Tracking detectors cover a narrow region of phase space, i.e. $|\eta^{\mathrm{LAB}}| < 1.75$ for the ZEUS detectors which limits investigations based on charged hadrons [3].

The idea of energy flow method was introduced by theorists [5, 6] to avoid soft and collinear singularities in perturbative QCD. By weighting the directions of the emitted hadrons or partons with their energies any hadrons/partons emitted together are treated as being equivalent to one object carrying the sum of the energies. Experimentally two hadrons emitted nearby in the HCM frames are also detected as one object on the detector level.

The energy flow method permits the use of charged and neutral hadrons as well as the enhancement of hard hadrons/partons with weights thus avoiding dependence on jet algorithms discussed elsewhere [7]. The method diminishes the contributions from QCD Compton and boson-gluon fusions emitted along the Z-axis where some theoretical uncertainties exist [8]. The method is sensitive to energy scale uncertainties but the investigation of mean values (2) leads to cancellation.

Here an individual hadron/parton transverse energy E_T^{HCM} is used as a weight.

MONTE CARLO MODELS

The azimuthal distributions are generated using the LEPTO 6.5.1 program [9] which includes photon and Z exchanges and the QCD processes described by the first order QCD matrix elements (ME). If needed, parton shower (MEPS) in the leading logarithm approximation is switched on. As an alternative, the QCD cascade is modelled with the ARIADNE 4.12 program [10] modified in 1997 to include BGF. In both cases, fragmentation into hadrons is performed according to the JETSET 7.410 code [11] based on the Lund string model. The next-to-leading order (NLO) prediction is obtained with DISENT using the dipole factorization formulae [12].

PREDICTIONS

Using the LO predictions of LEPTO and ARIADNE azimuthal asymmetries are investigated as a function of pseudorapidity η^{HCM} of the emitted hadrons/partons for the $-5 < \eta^{\mathrm{HCM}} < 0$ region because, (see Fig. 1b) the zeroth order QCD process (QPM) contribution is eliminated ($\eta^{\mathrm{HCM}} > -5$) as well as target fragments ($\eta^{\mathrm{HCM}} < 0$). The relative contribution from boson-gluon fusion (BGF) with respect to QCD Compton (QCDC) also changes with rapidity (Fig. 1b) and in addition quarks from QCDC populate mainly $\eta^{\mathrm{HCM}} < -2.8$ whereas gluons populate $\eta^{\mathrm{HCM}} > -2.8$ (Fig. 1c).

a) b) c)

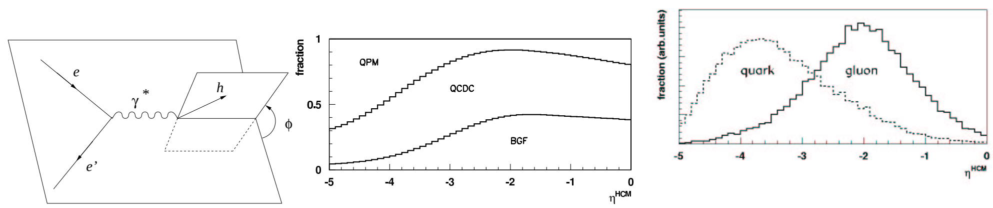

FIGURE 1. a) The definition of the azimuthal angle ϕ; b) the fraction of boson-gluon fusion (BGF), QCD Compton (QCDC) and the zeroth order QCD process (QPM) as a function of pseudorapidity η^{HCM} in the hadronic centre-of-mass frame for the energy flow method; c) for the QCD Compton process the guark and gluon contributions as a function of pseudorapidity η^{HCM}. These predictions are taken from LEPTO 6.5.1.

Two methods are used: the first method is based on energy flow; the second method — on multiplicity. Figure 2 (left side) presents asymmetries in form of $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ obtained from LO predictions of LEPTO and ARIADNE on the hadron level but without detector losses. No significant difference is found between predictions from the different MC models and methods. However asymmetries from energy flow are slightly larger than the ones from multiplicity.

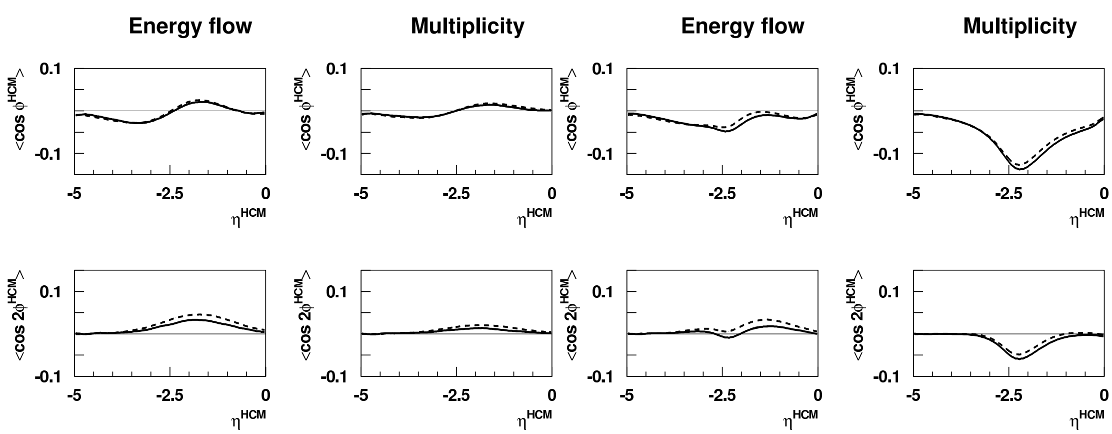

FIGURE 2. Predictions for azimuthal asymmetries in form of $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ for the energy flow method and for the multiplicity method generated with the LEPTO 6.5.1 code (solid line) and the ARIADNE 4.12 (dashed line) code. All emitted hadrons are detected (left side) and with the detection effects included (right side) i.e. losses of hadrons in the HERA beampipe ($\mathrm{P_T^{LAB}} < 150$ GeV).

Detection of hadrons modify the conclusion. With the present colliding beams the reconstruction excludes hadrons with the low transverse momenta in the laboratory frame

$P_T^{LAB} < 150$ MeV. Loss of hadrons modifies slightly asymmetries from the energy flow in the region of pseudorapidity, $-2.5 < \eta^{HCM} < -1$ but the ones from the multiplicity method are completely different (Fig. 2, right side).

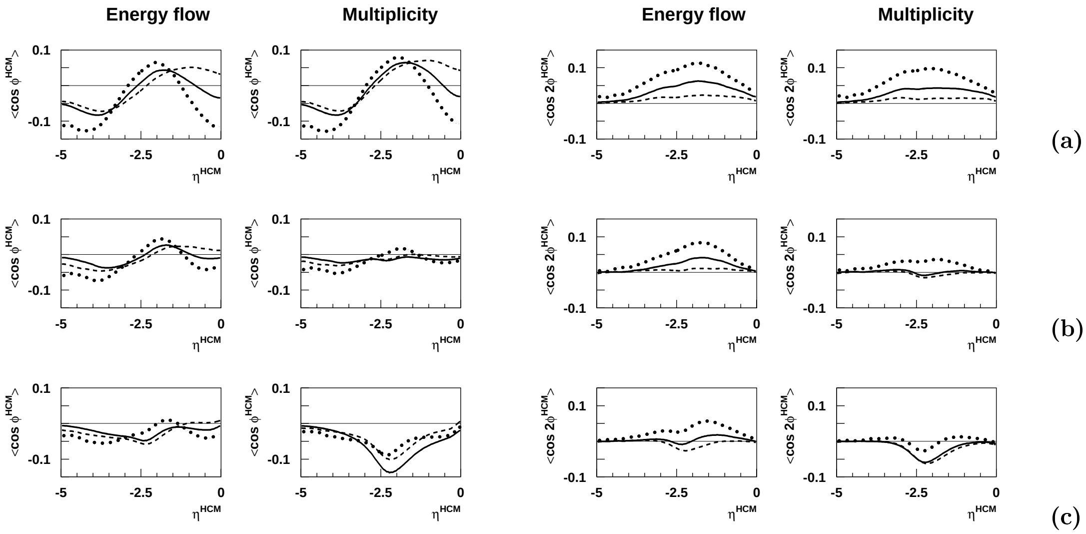

FIGURE 3. Predictions for azimuthal asymmetries for $\langle \cos\phi \rangle$ and $\langle \cos 2\phi \rangle$ generated by the LEPTO 6.5.1 code as a function of pseudorapidity η^{HCM} in the hadronic centre-of-mass system for the energy flow method (left side) and for the multiplicity method (right side). The results are presented for all emitted partons together (solid line) and separately for main processes: for QCD Compton (dashed line) and for boson-gluon fusion (BGF) (dotted line): (a) for hard processes only, i.e. for the matrix element option (ME) without hadronisation; (b) with parton shower included, i.e. for the MEPS option without hadronisation; (c) with hadronisation included, i.e. for the MEPS option with hadronisation. The detection effects in form of losses in the HERA beam pipe ($P_T^{LAB} < 150$ GeV) are included but are insignificant without hadronisation. Line at $\langle \cos\phi \rangle = 0$ is to guide an eye.

Using LEPTO the step-by-step contributions to azimuthal asymmetries are investigated including detector effects: for hard scattering of partons described by the QCD matrix elements (ME) followed by parton showers (PS) and hadronisation (JETSET). This is shown for all partons from QPM + QCDC + BGF together, and separately for QCDC and BGF. Figure 3a is equivalent to the jet study; the results are expected to be nearly the same for both methods. One can see that the asymmetry is large for hard processes and larger for the multiplicity method; therefore the multiplicity method is better for jets but experimentally can be used in the narrower region of phase space [4]. Although losses of particles affect predictions on the parton level the main effect is visible for the multiplicity method after hadronisation where many low P_T^{LAB} hadrons are lost.

Figure 4 shows the LO and NLO predictions of DISENT and the LO predictions with the LEPTO and ARIADNE codes. Some differences come from a lack of correlation in generation of the hadronic part of the LEPTO/ARIADNE events with amount of the longitudinal structure function F_L; helicity conservation for the longitudinally polarized exchanged boson excludes QPM but allows for QCDC. In the region $-5 < \eta^{HCM} < -2.5$ the main contribution to the azimuthal asymmetry comes from the QCD Compton process and arises from hadrons coming from quark fragmentation (Fig. 1c). The region $-2.5(-3) < \eta^{HCM} < -1$ is that with an increasing contribution from boson-gluon fusion (Fig. 1b); this region is strongly affected by detection losses. The third region $-1 < \eta^{\mathrm{HCM}} < 0$ is populated equally by hadrons from QCD Compton process and from boson-gluon fusions (Fig. 1b); the $\langle \cos\phi^{\mathrm{HCM}} \rangle$ values are sensitive to NLO corrections; they are positive whereas the LO predictions give the negative values (Fig. 4).

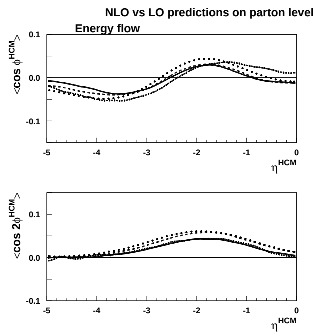

FIGURE 4. The LO predictions for azimuthal asymmetries generated with the LEPTO 6.5.1, ARIADNE 4.12 and DISENT codes (solid, dashed and dotted line respectively) on the parton level. The NLO predictions of DISENT is also imposed (dashed-dotted line). No detection effects included.

SUMMARY AND CONCLUSIONS

Azimuthal asymmetries are proposed to be analyzed as a function of hadron rapidity in the HCM frame using the energy flow method. This novel approach provides precise measurements and small systematical uncertainties in the wider interval of phase space [1]. It permits the investigation of the contribution of boson-gluon fussion with respect to the QCD Compton process as well as contribution from quarks produced in the QCD Compton process with respect to the gluon. Calculation of mean values minimizes the experimental uncertainties by cancellation of some systematical effects like the calorimeter energy scale, uncertainties of the parton density functions and partially of the fragmentation functions to some extent. The latter means that hadron spectra and consequently their detection depend on the feature of fragmentation function. Detection inefficiency modifies the values of asymmetries.

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