T-ODD ASYMMETRIES IN DEEP INELASTIC SCATTERING WITH UNPOLARISED PROTONS AT HERA*

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Measurements and predictions for T-odd asymmetries deduced from the azimuthal distribution of hadrons relative to the lepton plane are discussed for unpolarised deep inelastic ep scattering. The measurements were performed for neutral current deep inelastic ep scattering at a centre-of-mass energy of 300 GeV for the kinematic range of the exchanged boson virtuality $100 < Q^2 < 8000$ GeV^2, and in the hadronic centre-of-mass system using the energy-flow method.

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1. Introduction

This conference is dedicated to the discovery of parity non-conservation. It is 50 years since the discovery but the nature of parity violation is still a puzzle. Therefore reviews of features observed in different processes is helpful. One of the features is time-reversal-odd effects (T-odd) predicted in lepton–nucleon scattering and in e^+e^- annihilation.

Nearly 35 years ago a few physicists [1] pointed out that parity violating interactions (P-odd) modify hadron production which is essentially governed by quantum chromodynamics (QCD). The total cross-section for hadron production is not affected, however, some observables describing the process can be time-reversal-odd quantities. It means that they change sign under the operation of reversing spins and momenta while keeping the initial

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and final state particles intact[1]. The time reversal invariance leads to a relation between T-odd quantities and the absorptive part of the transition amplitude. T-odd effects cause the hadron production plane to be tilted, leading to the so-called left-right asymmetry.

Some quantitative observation of this prediction has recently been obtained in *ep* semi inclusive deep inelastic scattering (SI DIS) with unpolarised protons at HERA [2]. The observables are related to the angular correlation between the lepton scattering plane and the hadron production plane in the hadronic centre-of-mass (HCM) frame created by the exchanged boson and proton as illustrated in Fig. 1. In the lowest order, T-odd effects

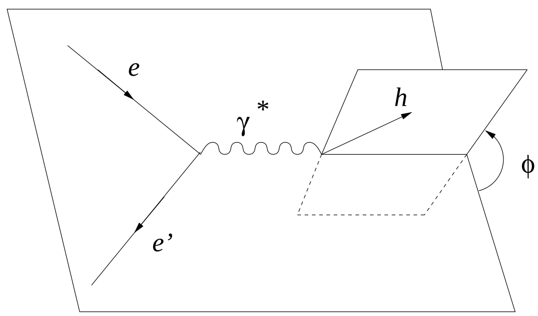

Fig. 1. The definition of the azimuthal angle ϕ in the HCM frame. The incoming electron is denoted by e, the scattered electron by e', the exchanged virtual photon by γ^* and the outgoing hadron by h.

are absent; in the next order T-odd effects appear from the interference between the Born approximation amplitudes and the lowest-order contribution to the absorptive amplitude which may arise *e.g.* from two-photon exchange [1] or loop contributions [3]. In the leading order of perturbative QCD (pQCD), *i.e.* with no loop contributions, the T-odd effects require either parity-violating interactions [3] or spin measurements in form of the polarisation of the target proton [1] or the lepton beam [3, 4]. The lepton polarisation should be longitudinal because for transversally polarised beams T-odd asymmetries vanish as m_e/Q due to the small mass m_e of the incoming lepton [4]. Since interactions via neutral current (NC) by Z^0 exchange and via charged current (CC) by W exchange violate parity the T-odd effects should be seen for both. However, for neutral current processes they are expected to be smaller as parity-odd (P-odd) contributions do vanish for the purely electromagnetic current.

[1] Since it is not a true time-reversal operation, a non-zero value of a T-odd quantity does not signal CPT violation and an observation of the discussed T-odd effect respects CPT invariance.

2. Theoretical background for *T*-odd

One of the T-odd quantities in ep scattering is related to the azimuthal angle ϕ defined in Fig. 1 and calculated in the HCM frame or any other equivalent frame:

$$\langle \sin\phi \rangle = \left\langle \frac{(\vec{k} \times \vec{k'}) \cdot \vec{p'}_{\mathrm{T}}}{|\vec{k} \times \vec{k'}| \cdot |\vec{p'}_{\mathrm{T}}|} \right\rangle ,$$

where $\vec{k}, \vec{k'}$ are the three-vectors of the incoming and outgoing leptons, and $\vec{p'}_{\mathrm{T}}$ is the hadron transverse momentum about direction of the incoming proton (Fig. 1). The expression is not only T-odd but also P-odd.

This quantity was measured in SI DIS in the HCM frame with the ZEUS detector [2]. 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 defined for hadrons leading to the differential cross-section of the form [3, 5–8]:

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

The azimuthal asymmetries, specified by the parameters $\mathcal{B}$, $\mathcal{C}$, $\mathcal{D}$ and $\mathcal{E}$, can be either extracted by fitting the azimuthal distribution (1) or for 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:

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

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

Polarisation of the exchanged virtual boson leads to the ϕ dependence in the Eq. (1). The coefficients $\mathcal{B}$ and $\mathcal{D}$ originate from the interference between the transversely and longitudinally polarised components, *e.g.* [9]; they are expected to have a similar kinematical dependence. 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 $\mathcal{E}$ are the T-odd quantities whereas the coefficient $\mathcal{B}$ and $\mathcal{C}$ are T-even.

Chay, Ellis and Stirling [6, 7] proposed to analyse the asymmetry as a function of the transverse momentum cutoff, $p_{\mathrm{T}}^{\mathrm{cut}}$, of a detected hadron. Such a cut is efficient in removing the simple scattering $\gamma q \to q$ events and at higher $p_{\mathrm{T}}^{\mathrm{cut}}$ values a better agreement should be obtained with pQCD. Using a similar approach Ahmed and Gehrmann evaluated the $\mathcal{B}, \mathcal{C}, \mathcal{D}$ and

$\mathcal{E}$ quantities for NC and CC at the HERA energies [8]. Considering the longitudinally polarised lepton beams they found that for electrons the $\mathcal{D}$ term is larger than for positrons and has the opposite sign. In addition, the $\mathcal{D}$ and $\mathcal{E}$ terms are at least an order of magnitude smaller than the $\mathcal{B}$ and $\mathcal{C}$ terms since the dominant contribution is of order $\alpha_{\rm s}^2$ whereas the leading order contributions to $\mathcal{B}$ and $\mathcal{C}$ are of order $\alpha_{\rm s}$.

An idea [10, 11] similar to the introduction of the $p_{\rm T}^{\rm cut}$ cutoff is in usage of the energy flow method [12–14]. By weighting the direction of an emitted particle or parton in the final state with its transverse energy the method enhances the contribution from leading hadrons and decreases the contribution from $\gamma q \to q$ events and from hadronisation effects. It eliminates the dependence of the results on jet algorithms and gives smaller theoretical uncertainties due to soft and collinear singularities in pQCD. From the experimental point of view the energy flow method permits the use of calorimeter measurements when charged and neutral particles are detected equally well and avoiding the problem of overlapping particles. It permits an increase of the phase space region under investigation and decreases experimental losses of soft particles. In addition, it was proposed to investigate the asymmetries as a function of pseudorapidity, η. Together with the energy flow method this eliminates some experimental problems typical for the calorimetry technique and it permits to separate the current region from the target region. The current region, in analogy to e^+e^- annihilation is dominated by pion production. In this region the kinematical factor $M_{\rm proton}/M_{\rm hadron}$ in the $\mathcal{B}$ and $\mathcal{D}$ term has the largest possible value [15, 16]. This method has been used by the ZEUS Collaboration to obtain the measurements of T-odd asymmetries with unpolarised protons mentioned before [2] .

3. Experimental aspects

The first attempt to estimate the T-odd effects in the $e^+e^- \to Z^0 \to$ hadrons yielded a result consistent with zero [17]. Investigations at HERA energies have been performed by ZEUS for 820 GeV protons and unpolarised positrons of 27.5 GeV [2, 18, 19]. The positrons were transversely polarised due to the Sokolov–Ternov [20] effect, but had no longitudinal polarisation. The kinematical region is defined by the exchanged boson virtuality, $100 < Q^2 < 8000$ GeV^2, the Bjorken variable, $0.01 < x < 0.1$, and inelasticity, $0.2 < y < 0.8$.

For NC DIS the $\langle\cos\phi\rangle$ and $\langle\cos 2\phi\rangle$ values have been measured to be at the few percent level [2,18,19]. The recent ZEUS analysis [2] which permitted to estimate the T-odd asymmetries uses the energy-flow method for NC DIS events considering hadrons with $p_{\rm T}^{\rm LAB} > 0.15$ GeV. The measurements of $\langle\cos\phi\rangle$, $\langle\cos 2\phi\rangle$, $\langle\sin\phi\rangle$ and $\langle\sin 2\phi\rangle$ are shown in Fig. 2 as a function of

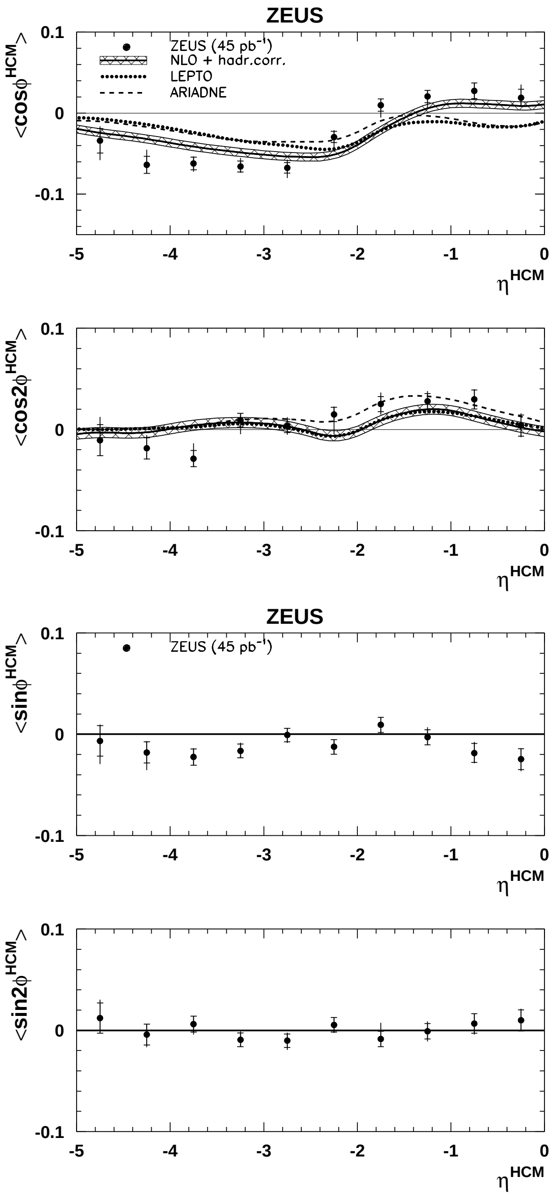

Fig. 2. The values of $\langle\cos\phi^{\rm HCM}\rangle$, $\langle\cos 2\phi^{\rm HCM}\rangle$, $\langle\sin\phi^{\rm HCM}\rangle$ and $\langle\sin 2\phi^{\rm HCM}\rangle$ calculated using the energy-flow method as a function of hadron pseudorapidity, $\eta^{\rm HCM}$. The NLO QCD predictions of DISENT (solid line), with its associated uncertainty (shaded band), corrected for hadronisation and hadron losses (see [2]), the predictions of LEPTO 6.5.1 (dotted line), and the predictions of ARIADNE 4.12 (dashed line) are shown.

the pseudorapidity, $\eta^{\rm HCM}$ and compared to theoretical expectations. NC events were simulated with the LEPTO 6.5.1 [21] using the MEPS option and with ARIADNE 4.12 [22], where the QCD cascade is simulated with the colour-dipole model. The next-to-leading-order (NLO) QCD predictions were calculated using the dipole factorisation formulae implemented in the DISENT program [23, 24].

The mean values of $\cos\phi^{\rm HCM}$ are negative for $\eta^{\rm HCM} < -2$ but become positive for larger $\eta^{\rm HCM}$. This is in disagreement with the predictions. The measured $\langle\cos 2\phi^{\rm HCM}\rangle$ values are perhaps negative for $\eta^{\rm HCM} < -3$, but certainly consistent with zero, and positive for higher values of $\eta^{\rm HCM}$. The positive values are consistent with the expectations from both LEPTO and ARIADNE. The NLO predictions, corrected for hadronisation, agree better with the experimental values for $\langle\cos\phi^{\rm HCM}\rangle$ but still fail to describe their magnitude.

Fig. 2 shows that the values of $\langle\sin\phi^{\rm HCM}\rangle$ and $\langle\sin 2\phi^{\rm HCM}\rangle$ are small. A deviation of $\langle\sin\phi^{\rm HCM}\rangle$ from zero at the level of three standard deviations is observed at $-5 < \eta^{\rm HCM} < -3$ which corresponds to the current region of the Breit frame. In this region hadronisation is dominated by pion production. The values of $\langle\sin 2\phi^{\rm HCM}\rangle$ are consistent with zero. None of the theoretical models include predictions for $\langle\sin\phi^{\rm HCM}\rangle$ or $\langle\sin 2\phi^{\rm HCM}\rangle$.

To understand the origin of the T-odd asymmetries more experimental tests were done using also the longitudinal polarisation of the HERA lepton beams. The rough tests done for NC events and (un)polarised e^+ and e^- beams show neither any new effect nor charge dependence on larger statistics. They confirm negative values of $\langle\cos 2\phi^{\rm HCM}\rangle$ at $\eta^{\rm HCM} < -3.5$ and negative values of $\langle\sin\phi^{\rm HCM}\rangle$ at $\eta^{\rm HCM} < -3$. This is not explained by the existing theoretical predictions.

4. Summary and conclusions

Measurements of the azimuthal angle ϕ of the detected hadron around the virtual photon direction provide information on the hadron production mechanism. Non-zero T-odd term arise from absorptive contributions to the parton level scattering amplitudes. Antisymmetric contributions to the hadronic tensor are increased either by parity violating weak interactions or by the polarisation of the initial lepton beam or by two boson exchange contribution.

Azimuthal asymmetries including T-odd asymmetries have been measured by the ZEUS experiment for deep inelastic scattering with unpolarised beams in the hadronic centre-of-mass frame at HERA for high Q^2 NC events. A deviation of $\langle\sin\phi^{\rm HCM}\rangle$ from zero at the level of three standard deviations is observed. The predictions available for these T-odd asymmetries expect them to be zero or at least an order of magnitude smaller than the $\langle\cos\phi^{\rm HCM}\rangle$ term.

This note is dedicated to the memory of Leszek Łukaszuk, our friend and teacher, who helped us to deepen our understanding of the origin of T-odd effects.

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