EFFECTS OF $E^{\pm}$ POLARIZATION ON FINAL STATES AT HERA

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At HERA II, longitudinally polarized electrons and positrons collide with unpolarized protons at centre-of-mass-energies of 318 GeV and at high luminosities. This offers unique opportunities for testing the Standard Model and probing new physics areas. A brief overview is given of the possibilities offered by the use of beam charge and polarization dependent final states at HERA, in particular as regards electroweak structure functions, generalized parton distributions and Λ-baryon production.

1. Polarization and Luminosity

The need for luminosity greater than the design value as well as for longitudinally polarized beams at HERA has been anticipated by a series of physics workshops [1]. After tapping the potential of the HERA I phase, in 2000/2001 a major upgrade [2] was performed to the two interaction regions (H1 and ZEUS) to improve focussing at the interaction points and to thus obtain higher luminosity values. Each interaction region was rebuilt and complemented by a pair of spin rotators, allowing the transverse polarization generated via synchrotron radiation in HERA-e to be converted to longitudinal polarization. With one spin rotator pair, which has been working since 1995 at the HERA-e fixed target experiment HERMES, typical polarization values of up to 60% were achieved. In March 2003, successful operation with three spin rotator sets was achieved and the longitudinal polarization of the positrons reached values of up to 54% in colliding mode [2]. The HERA-e polarimeter continuously measure both the transverse and the longitudinal beam polarization. These devices are being upgraded to allow polarization measurements of a relative systematic uncertainty of 1% with negligible statistical errors [3], as is required for precision measurements. Absolute luminosities of $2.7{\cdot}10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ have been reached, suggesting that luminosities of about $5{\cdot}10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are achievable at full beam currents and design specific luminosity. This should allow the collection of about 200 pb^{-1} of data per year [2].

This talk discusses briefly the effects on the final states of scattering polarized $e^{\pm}$ off unpolarized protons at HERA. A collider programme of nucleon and photon spin physics and on electron-ion collisions may be realized after the present HERA II phase [4].

2. Beam Polarization Effects in Electroweak Interactions

High luminosities and high polarization values allow inclusive deep inelastic scattering (DIS) measurements to be extended to large photon virtualities Q^2 where the event rates are small. Basic quantities of interest are the proton structure functions which are effective descriptions of the non-perturbative part of the inclusive ep-scattering process. Utilizing the lepton charge and helicity dependence of the DIS charged current (CC) and neutral current (NC) cross sections, more precise and new information on the proton dynamics can be obtained, or alternately, using the knowledge of proton structure functions, electroweak parameters can be tested.

An impressive, 'textbook' test of the electroweak theory can be per-

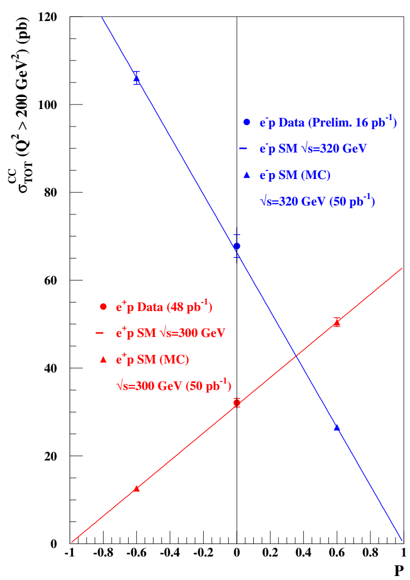

Figure 1. Measured unpolarized (HERA I data) and simulated polarized $e^{\pm}p$ CC cross sections as a function of lepton polarization assuming an integrated luminosity of 50 pb^{-1} for each of the polarized data sets. Figure taken from [5].

formed by measuring of the polarized $e^{\pm}p$ CC cross sections as shown in Fig. 1 [5]. The expected linear dependence of the CC cross section on the beam polarization, i.e. the handedness of the lepton, is a direct consequence of the Standard Model, in which the massive W^+ and W^--particles, the carriers of the weak force, only act on left-handed particles and right-handed antiparticles. Any deviation from a straight line would point to physics beyond the Standard Model. Presently, the H1 and ZEUS experiments are taking data with right-handed positrons and a first analysis of the CC cross section can be expected soon. However, to get the complete picture depicted in Fig. 1, four beam charge and helicity combinations have to be measured with high polarization values and integrated luminosities of about 50 pb^{-1} per sample.

Competitive searches for new physics can be performed by investigating parity violation in NC DIS, where the cross section depends on both beam polarization and charge, see e.g. [6] for a systematic consideration of cross sections and their combinations. The interference of neutral electromagnetic (γ) and weak (Z) currents leads to additional vector and axial-vector contributions to the $e^{\pm}p$ cross section. These are parameterized in terms of two new structure functions, G_2 and xG_3 (not to be confused with the well known polarized structure functions). Both contain the quark couplings to the Z-boson. Since the strength of the γZ interference itself is about $10^{-4}\cdot GeV^2/Q^2$, high Q^2 values are preferable if these structure functions are to be measured. Measuring the asymmetries introduced by electroweak effects has the advantage that common systematic uncertainties, like acceptances and global inefficiencies, cancel.

Varying the beam polarization for a fixed lepton charge delivers a parity-violating asymmetry ($\propto G_2/F_2$), studied first at SLAC in 1978 in a high statistics ed-scattering experiment at a Q^2 of 1.6 GeV^2 [7]. Measured at large x_{Bj}, the parity-violating asymmetry is dominated by the ratio of d to u-valence quarks. Simulated HERA data covering the range of Q^2 from 1000 until 30000 GeV^2 unveil the feasibility of a G_2 measurement at $x_{Bj} > 0.01$ using the excellent knowledge of the electromagnetic structure function F_2 already obtained from the HERA I data. High polarization values, of about 50%, and high luminosity values of about 200 pb^{-1} per sample are needed [8]. Variation of both lepton polarization and charge, first performed in μC-scattering in 1982 at CERN [9], allow the determination of a beam conjugation asymmetry which is predominantly sensitive to the interference structure function xG_3. At HERA this delivers new information on the behavior of valence quark distributions in the sea quark range, $x_{Bj} > 0.01$.

High polarization values of at least 50% and integrated luminosities of about 150 pb^{-1} per sample can significantly improve the tests of electroweak parameters, for example the determination of the aforementioned vector and axial-vector couplings of the Z-boson to the light quarks [10]. The best sensitivity to the mass of the W-boson and the value of $\sin^2\theta_{\mathrm{W}}$ can be achieved using the polarization dependent neutral to charged current cross section ratio for electrons; slightly less precise results are obtained using positrons [11].

3. DVCS Cross Section and Asymmetries

With the advent of HERA, a new class of large rapidity gap events was discovered in DIS [12] at small $x_{\mathrm{Bj}} < 0.01$. These diffractive events were not expected in the quark-parton model (QPM). An intuitive picture of these events was offered by the color dipole model [13], a nearly forgotten picture at this time. With increased luminosity, in 1999 another class of diffractive events was discovered at HERA [14,15,16] in which there is a large rapidity gap between the recoiling proton and a real photon in the final state, see Fig. 2a. These deeply virtual, or off-forward, Compton scattering (DVCS) events at small momentum transfer t to the proton can also be described by the color dipole model; see [16,17] for comparisons with recent ZEUS and H1 data. Furthermore, the observation of DVCS triggered the further development and use of another theoretical concept for diffractive and exclusive processes, generalized parton distribution (GPD) functions. GPDs were revived in 1996 when the spin physics community realized the unique potential they have for unravelling the spin structure of the nucleon [18]. Only recently, the exciting potential of GPDs in the study of three dimensional hadron structure has been recognized [19]. In the case that the initial and final state differ only in their transverse momenta, GPDs encode simultane-

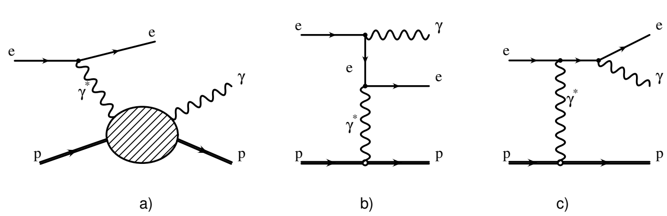

Figure 2. a) DVCS graph, b) BH with photon from initial state lepton and c) with photon from final state lepton. Figure taken from [15].

ously information on the longitudinal momentum, determined by $x_{\rm Bj}$, and transverse position of partons in the infinite momentum frame, described by an impact parameter $\rm b \sim 1/\sqrt{-t}$. Nowadays, GPD based model calculations deliver fair descriptions of the measured, t-integrated DVCS cross section and its kinematic dependence [16,17], and are theoretically rather well understood, see [20] for a review. More, and more precise, measurements are required to pin down the various theoretical model uncertainties.

The diffractive electroproduction of a real photon, depicted in Fig. 2a, interferes with the Bethe-Heitler (BH) process shown in Figs. 2b,c. Both deliver the same final states, but these can be distinguished experimentally by the different weights they have in different kinematic regions. Furthermore, the BH process is a pure QED process with a calculable cross section. This kind of background is well controlled and can be subtracted allowing DVCS cross section measurements [15,16]. Moreover, with the advent of HERA II, the complex and rich angular structure of the DVCS cross section can be employed to access more observables which may help to unfold GPDs.

In general, the amplitude-squared of the real photon electroproduction cross section receives contributions from pure DVCS (Fig. 2a), from pure BH (Figs. 2b,c) and from their interference (with a sign governed by the lepton charge): $|\mathcal{T}|^2 \propto |\mathcal{T}_{\rm DVCS}|^2 + |\mathcal{T}_{\rm BH}|^2 + \mathcal{I}$. Each term can be expanded in a Fourier series in the azimuthal angle ϕ between the electron scattering plane and the real photon reaction plane [21]. This can be used to filter out the relevant information about the Compton process. The terms are given by

$$|\mathcal{T}_{\rm BH}|^2 \propto \left[{\rm c}_0^{\rm BH} + \sum_{\rm n=1}^{2} {\rm c}_{\rm n}^{\rm BH} \cos({\rm n}\phi) + {\rm s}_1^{\rm BH} \sin(\phi) \right] \tag{1}$$

$$|\mathcal{T}_{\rm DVCS}|^2 \propto \left[{\rm c}_0^{\rm DVCS} + \sum_{\rm n=1}^{2} \left[{\rm c}_{\rm n}^{\rm DVCS} \cos({\rm n}\phi) + {\rm s}_{\rm n}^{\rm DVCS} \sin({\rm n}\phi) \right] \right] \tag{2}$$

$$\mathcal{I} \propto -{\rm sign(e)} \left[{\rm c}_0^{\mathcal{I}} + \sum_{\rm n=1}^{3} \left[{\rm c}_{\rm n}^{\mathcal{I}} \cos({\rm n}\phi) + {\rm s}_{\rm n}^{\mathcal{I}} \sin({\rm n}\phi) \right] \right] \tag{3}$$

According to the detailed formulae in [22], ϕ dependent contributions in the scattering of polarized leptons with helicity λ off an unpolarized proton can be expected to arise from:

i) pure BH (Eq. 1) in addition to the known kinematical ϕ dependence of the BH propagator giving
   (a) $\cos\phi$ and $\cos 2\phi$ terms (leading twist-2)

(b) no $\sin\phi$ term (appears only for transversely polarized proton)
(c) no beam helicity dependence (appears only for longitudinally or transversely polarized protons)

ii) pure DVCS (Eq. 2) giving

(a) suppressed $\cos\phi$ and $\lambda\sin\phi$ terms (twist-3)
(b) α_S power suppressed $\cos 2\phi$ term (leading twist-2, related to gluon transversity; $\sin 2\phi$ will appear only for longitudinally or transversely polarized protons)

iii) DVCS-BH Interference (Eq. 3) in addition to the known kinematical ϕ dependence of the BH propagator and the dependence on the sign of the lepton charge giving

(a) $\cos\phi$ and $\lambda\sin\phi$ terms (leading twist-2)
(b) suppressed $\cos 2\phi$ and $\lambda\sin 2\phi$ terms (twist-3)
(c) α_S power suppressed $\cos 3\phi$ and $\sin 3\phi$ terms (leading twist-2, related to gluon transversity).

The Fourier coefficients c_n and s_n in Eqs. 2-3 are directly related to the amplitudes of the γ^*p Compton process which can be parameterized by the so-called Compton Form Factors (CFF) [22]. CFFs for their part are convolutions of QCD coefficient functions and GPDs denoted usually by H, $\tilde{\text{H}}$, E, $\tilde{\text{E}}$. CFFs, and hence the GPDs, appear in quadratic combinations in the DVCS cross section, but in linear combinations in the interference term (Eq. 3). Particularly for HERA kinematics, measurements of the dominant interference Fourier coefficients ${c_1}^{\mathcal{I}}$ and ${s_1}^{\mathcal{I}}$ gives access to, respectively, the real and the imaginary part of the CFF $\mathcal{H}$ and thus to the leading twist-2 GPD H, since at small $x_{\rm Bj}$ possible contributions from the GPDs $\tilde{\text{H}}$ and E can be safely neglected [23]. In principle, a complete separation of the four leading twist-2 GPDs would require in addition data taken with transversely and longitudinally polarized protons.

The real photon production observable containing information on the ${s_1}^{\mathcal{I}}$ term is the single beam spin asymmetry (SSA), measured at Q^2 of about 2 GeV^2 by the fixed target experiments CLAS and HERMES for the first time [24]. A measurement of the SSA requires high lepton beam and virtual photon polarizations (high y). A simulation [23] for the HERA-positron beam reveals significant negative asymmetry values, shown in Fig. 3 (left). This asymmetry is positive for an electron beam. Experimentally, the ϕ dependence of the difference between the number of events with positive beam helicity and negative beam helicity has to be formed. Using an un-

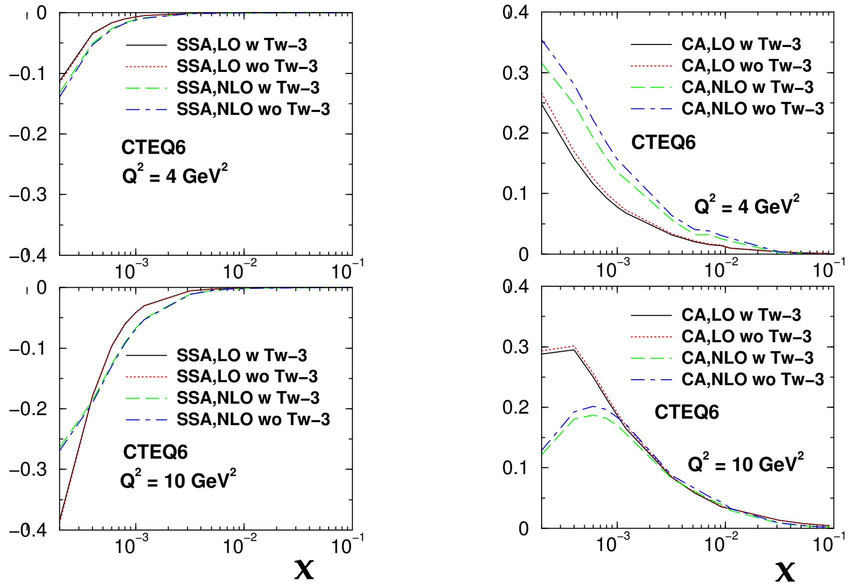

Figure 3. DVCS asymmetries for HERA kinematics as a function of x_{Bj} for two typical values of Q^2 and $\mathrm{t}_{max} = -0.5\ \mathrm{GeV}^2$, modeled in LO and NLO QCD with (w) and without (wo) twist-3 contributions (Tw-3). Left: t integrated single beam spin asymmetry (SSA) for a positron beam. Right: t integrated beam charge asymmetry (CA). Figures taken from [23].

polarized beam sample to get rid of the $\sin\phi$ amplitude contributions, and positron and electron beam data, the beam charge asymmetry sensitive to the ${c_1}^{\mathcal{I}}$ term can be formed for real photon production events. Only HERMES has been able to measure the CA so far [25], employing HERAs unique feature of delivering positron and electron beams. The CA simulation [23] for HERA-collider kinematics shows, in Fig. 3 (right), encouragingly large asymmetry values. A further measurement of the ${c_1}^{\mathcal{I}}$ term can be performed via an azimuthal angle asymmetry that is predicted to have a size similarly to that of the CA [23]. However, this measurement would require a detector with excellent ϕ resolution and control of twist-3 contributions whereas the twist-3 effects for the CA and SSA have been estimated to be negligible [23].

In the second phase of HERA, it is anticipated that the size of the data samples available for the DVCS cross section measurements will be about 10 times larger than those used so far. The measurement of the DVCS associated asymmetries will remain challenging with the present H1 and

ZEUS detectors, since the recoiling proton will not generally be observed, making the determination of ϕ and t difficult [26]. The very forward proton spectrometer (VFPS) [27] recently installed at H1 may help to further reduce the proton-dissociative background in the DVCS sample and to deliver a first measurement of the t-dependence of the DVCS cross section at centre-of-mass energies of the γ^*p-system W of about 20 GeV.

4. Beam Spin Transfer to Λ-Baryons

Studying Λ ($\bar{\Lambda}$) baryon production in unpolarized and polarized DIS processes, allows the exploitation of the 'self-analyzing' decay of the Λ. The Λ-polarization can be measured by studying the angular distribution of the $\Lambda \rightarrow p\pi$ decay (in the Λ helicity rest frame). The polarization of the fragmenting parton is determined by the elementary Standard Model interactions and the initial parton's spin state. Neglecting weak interactions, there are four general DIS observables for involving Λ's that employ the various possible combinations of (un)polarized leptons and nucleons, see e.g. [28].

Particularly interesting for the upgraded HERA is to consider the spin transfer from a longitudinally polarized charged lepton (helicity S) to the Λ while the proton is unpolarized (helicity 0). In this DIS process, the scattered quark will be polarized and its spin will be transferred to the baryon produced in the fragmentation of this quark. In the QPM, the longitudinal spin transfer to the outgoing Λ is given by [28]:

$$\mathrm{P_{S,0}} = \frac{\mathrm{y(2-y)}}{1+(1-\mathrm{y})^2} \, \frac{\sum_\mathrm{q} \mathrm{e_q^2\, q(x)\, \Delta D_{\Lambda/q}(z)}}{\sum_\mathrm{q} \mathrm{e_q^2\, q(x)\, D_{\Lambda/q}(z)}} \, . \tag{4}$$

Here, $\mathrm{P_{S,0}}$ is the polarization of the hyperon Λ which is measurable in semi-inclusive DIS, and q and D are the usual unpolarized quark distribution and fragmentation functions. The fragmentation of a longitudinally polarized parton into a longitudinally polarized Λ is described by $\mathrm{\Delta D_{\Lambda/q}(z)}$. This polarized fragmentation function may be further related, via the so-called Gribov-Lipatov relation [29], to the polarized quark distribution function of the Λ [30].

From Eq. 4, it follows that a Λ-spin transfer measurement requires high beam polarizations, high virtual photon polarizations (high y values) and a broad range in z, the hadron momentum fraction in the lab frame. For Λ's produced in the current fragmentation region in the DIS process, i.e. originating from the struck quark, the spin of the Λ is entirely due to the strange quark within the naive QPM. On the other hand, e.g. using $\mathrm{SU(3)_f}$, the quark distributions of the Λ can be related to those in the proton [31], or, if both the proton and the Λ spin structures are known, $SU(3)_f$ symmetry may be tested. In recent years, many theoretical models have been proposed for the longitudinal polarization of Λ baryons in DIS, addressing the question of the relationships between the spin structure of the proton and of the other baryons [32,33]. Recent DIS results on longitudinal Λ-polarization have come from HERMES [34] in NC charged lepton-nucleon scattering and from NOMAD in ν_e charged current interactions [35], but all these data are for low W values, which complicates their interpretation. Here, HERA II data could give a significant input, due to the much larger W ranges accessible, although detailed simulations have yet to be performed. The production of Λ ($\bar{\Lambda}$) baryons in polarized charged current $e^{\pm}p$ DIS could provide information on flavor separated polarized quark fragmentation functions, in a manner analogous to the scattering of a neutrino beam on a hadronic target.

5. Conclusion and Outlook

HERA II, with its high luminosity and with longitudinally polarized electrons and positrons, opens new horizons in the study of electroweak theory and parton dynamics, both in inclusive DIS and via the selection of particular final states. The experimental prospects have been illustrated in this talk by discussing the most promising channels: electroweak structure functions and charged current interactions, real photon electroproduction which extends the framework of DIS to the off-forward region of the virtual Compton process and the study of Λ spin structure via its longitudinal polarization.

Beyond the measurements mentioned, there are further subjects awaiting investigation. One may think of e.g. an even more detailed mapping of the GPDs which can be done by studying the complex angular dependence of the cross section for the electroproduction of lepton pairs off an unpolarized or polarized nucleon target [36]. Unfortunately, the cross section is very low thus requiring very high luminosities, but first studies may start at HERA II. Another interesting test of NLO versus twist-3 effects at HERA II may be performed by measuring a single-beam spin asymmetry in semi-inclusive pion production, as was done recently by CLAS at low Q^2, hence making interpretation difficult [37]. Single-beam spin and charge asymmetries may also be observed in the diffractive electroproduction of a $\pi^+\pi^-$ pair. These observables are expected to be sensitive to Pomeron-Odderon interference [38] and could thus give first evidence for the Odderon, which has so far escaped detection.

HERA II has just started. More detailed investigations are required of the huge variety of channels available, and unexpected results may well appear.

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