Deeply Virtual Compton Scattering at HERA and perspectives at CERN

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Abstract. Standard parton distribution functions contain neither information on the correlations between partons nor on their transverse motion, then a vital knowledge about the three dimensional structure of the nucleon is lost. Hard exclusive processes, in particular DVCS, are essential reactions to go beyond this standard picture. In the following, we examine the most recent data in view of the dipole model predictions and their implication on the quarks/gluons imaging (tomography) of the nucleon.

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INTRODUCTION

Measurements of the deep-inelastic scattering (DIS) of leptons and nucleons, $e+p \rightarrow e+X$, allow the extraction of Parton Distribution Functions (PDFs) which describe the longitudinal momentum carried by the quarks, anti-quarks and gluons that make up the fast-moving nucleons. These functions have been measured over a wide kinematic range in the Bjorken scaling variable x_{Bj} and the photon virtuality Q^2. While PDFs provide crucial input to perturbative Quantum Chromodynamic (QCD) calculations of processes involving hadrons, they do not provide a complete picture of the partonic structure of nucleons. In particular, PDFs contain neither information on the correlations between partons nor on their transverse motion, then a vital knowledge about the three dimensional structure of the nucleon is lost. Hard exclusive processes, in which the nucleon remains intact, have emerged in recent years as prime candidates to complement this essentially one dimentional picture [1].

Indeed, within the investigation of hard exclusive reactions in the Bjorken limit, the probe provided by the photon works as a clean tool reactions in order to extract reliable knowledge on the substructure of strongly interacting particles complementar to exclusive process.

The simplest exclusive process is the deeply virtual Compton scattering (DVCS) or exclusive production of real photon, $e+p \rightarrow e+\gamma+p$. This process is of particular interest as it has both a clear experimental signature and is calculable in perturbative QCD. The DVCS reaction can be regarded as the elastic scattering of the virtual photon off the proton via a colourless exchange, producing a real photon in the final state [1]. The recent measurements from the DESY ep collider HERA at low x_{Bj} ($x_{Bj} < 0.01$) and large Q^2 (above 2 GeV^2) are thus a decisive experimental step forward [2, 3]. In the Bjorken scaling regime, QCD calculations assume that the exchange involves two partons, having different longitudinal and transverse momenta, in a colourless configuration. These unequal momenta or skewing are a consequence of the mass difference between the incoming virtual photon and the outgoing real photon. This skewedness effect can be interpreted in the context of generalised parton distributions (GPDs) [4, 5, 6] or in the dipole model approach [7, 8].

A considerable interest of the high energy situation at HERA is that it gives the important opportunity to constrain the gluon contribution to GPDs and to study the evolution in virtuality Q^2 of the quark and gluon distributions. On the other hand, recently the color dipole formalism has provided a simultaneous description of photon induced process. The inclusive deep inelastic reaction and the photon diffractive dissociation has been successfully described and the study of other exclusive processes such as DVCS is an important test of the color dipole approach.

In the following, we examine the most recent data in view of the dipole model predictions [7, 8] and their implication on the quarks/gluons imaging of the nucleon [2, 9, 10].

THE COLOR DIPOLE MODEL

The colour dipole model provides a simple unified picture of inclusive and diffractive processes and enables hard and soft physics to be incorporated in a single dynamical framework. At high energies, in the proton's rest frame, the virtual photon fluctuates into a hadronic system (the simplest of which is a $q\bar{q}$ dipole) a long distance upstream of the target proton. The formation time of this hadronic system, and of the subsequent formation of the hadronic final state, is much longer than the interaction time with the target.

DVCS is a good probe of the transition between soft and hard regimes in the dipole model for two reasons. Indeed, the transverse photon wave function can select large dipoles, even for large Q^2, and certainly for the Q^2 range $2 < Q^2 < 20$ GeV^2. Also, because the final photon is real, DVCS is more sensitive to large dipoles than DIS at the same Q^2.

Then, in the colour dipole approach, the DIS (or DVCS) process can be seen as a succession in time of three factorisable subprocesses: i) the virtual photon fluctuates in a quark-antiquark pair, ii) this colour dipole interacts with the proton target, iii) the quark pair annihilates into a virtual (or real) photon. The imaginary part of the DIS (or DVCS) amplitude at $t = 0$ is expressed in the simple way [7, 8]

$$\mathscr{I}m\,\mathscr{A}\,(W, Q_1, Q_2) = \sum_{T,L} \int_0^1 dz \int_0^\infty d^2r\, \Psi^*_{T,L}(z,\, r,\, Q_1^2)\, \sigma_{dip}\,(z, r)\Psi_{T,L}(z,\, r,\, Q_2^2)\,, \qquad (1)$$

where $\Psi(z, r, Q_{1,2})$ are the light cone photon wave functions for transverse and longitudinal photons. The quantity Q_1 is the virtuality of the incoming photon, whereas Q_2 is the virtuality of the outgoing photon. In the DIS case, one has $Q_1^2 = Q_2^2 = Q^2$ and for DVCS, $Q_1^2 = Q^2$ and $Q_2^2 = 0$. The relative transverse quark pair (dipole) separation is labeled by r whilst z (respec. $1-z$) labels the quark (antiquark) longitudinal momentum fraction.

It should be noticed that the non-forward kinematics for DVCS is encoded in the colour dipole approach through the different weight coming from the photon wavefunctions in Eq. (1). The off-diagonal effects, which affect the gluon and quark distributions in GPDs models, should be included in the parameterisation of the dipole cross section. At the present stage of the development of the dipole formalism, we have no accurate theoretical arguments on how to compute skewedness effects from first principles. A consistent approach would be to compute the scattering amplitude in the non-forward case, since the non-forward photon wave function has been recently obtained. In this case, the dipole cross section, $\sigma_{dip}(x_1,x_2,r,\vec{\Delta})$, depends on the momenta x_1 and x_2 carried by the exchanged gluons, respectively, and on the total transverse momentum transfer $\vec{\Delta}$. In this case, additional information about the dependence upon $\vec{\Delta}$ is needed for the QCD Pomeron and proton impact factor. A first attempt in this direction is done in [7].

GEOMETRIC SCALING

At very small values of the Bjorken scaling variable x the saturation regime of QCD can be reached. In this domain, the gluon density in the proton is so large that non-linear effects like gluon recombination tame its growth. In the dipole model approach, the transition to the saturation regime is characterised by the so-called saturation scale parametrised here as $Q_s(x) = Q_0(x_0/x)^{-\lambda/2}$, where Q_0, x_0 and λ are parameters. The transition to saturation occurs when Q becomes comparable to $Q_s(x)$. An important feature of dipole models that incorporate saturation is that the total cross section can be expressed as a function of the single variable τ:

$$\sigma_{tot}^{\gamma^* p}(x,Q^2) = \sigma_{tot}^{\gamma^* p}(\tau), \text{ with } \quad \tau = \frac{Q^2}{Q_s^2(x)}. \tag{2}$$

This property, called geometric scaling, has already been observed to hold for the total ep DIS cross section [11] and in diffractive processes [8]. It has also recently been addressed in the context of exclusive processes including DVCS and extended to cases with non-zero momentum transfer to the proton [7]. It is therefore interesting to test if the present DVCS measurements obey the geometric scaling laws predicted by such models.

LATEST NEWS FROM THE EXPERIMENTAL FRONT

Measurements of DVCS cross section have been realised at HERA within the H1 and ZEUS experiments [2, 3]. As mentioned in the introduction, these results are given in the specific kinematic domain of both experiments, at low x_{Bj} ($x_{Bj} < 0.01$) but they take advantage of the large range in Q^2, offered by the HERA kinematics, which covers more than 2 orders of magnitude. It makes possible to study the transition from the low Q^2 non-perturbative region (around 1 GeV^2) towards higher values of Q^2 where the higher twists effects are lowered (above 10 GeV^2). The last data on DVCS cross section as a function of $W \simeq \sqrt{Q^2/x}$ are presented on figure 1. They show a strong W dependence

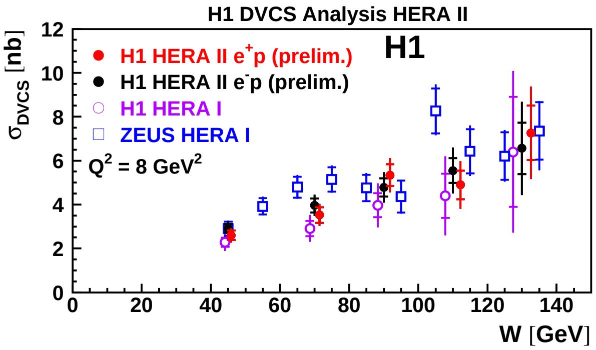

FIGURE 1. DCVS cross section for positrons/electrons samples as a function of W for $Q^2 = 8$ GeV^2.

with $\sigma_{DVCS} \propto W^{0.7}$, characteristic of a hard process, which can thus be described in perturbative QCD as described in previous sections.

Data and model comparisons are presented on figures 2 and 3. They show that the dipole approach is very efficient in describing the DVCS measurements for the HERA kinematics. It must be noticed here that the non-forward kinematics for DVCS is encoded only through the different weights coming from the photon wavefunctions in Eq. (1). It means that without taking into account non-diagonal effects that drive all the physics of GPDs, we can get a good descritption of all existing low x_{Bj} data in the framework of the dipole model.

Beside W and Q^2 DVCS cross sections, a major experimental achievement of H1 [2] has been the measurement of DVCS cross sections, differential in $t = (p' - p)^2$, the momentum transfer (squared) at the proton vertex. Some results are presente on figure 4: we observe the good description of $d\sigma_{DVCS}/dt$ by a fit of the form $e^{-b|t|}$. Hence, an extraction of the t-slope parameter b is accessible for different values of Q^2 and W (see figures 4 and 5). We exploit these values of b in a section below.

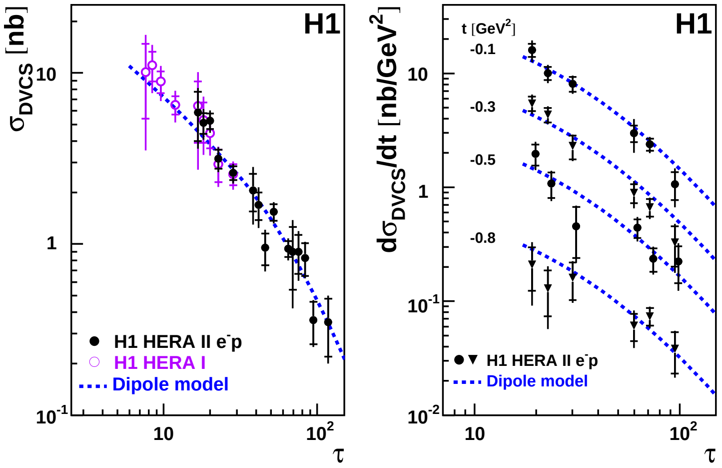

FIGURE 2. DVCS cross section measurements as a function of the scaling variable $\tau = Q^2/Q_s^2(x)$. Results are shown for the full t range $|t| < 1$ GeV^2 (left) and at four values of t (right). The dashed curves represent the predictions of the dipole model [8].

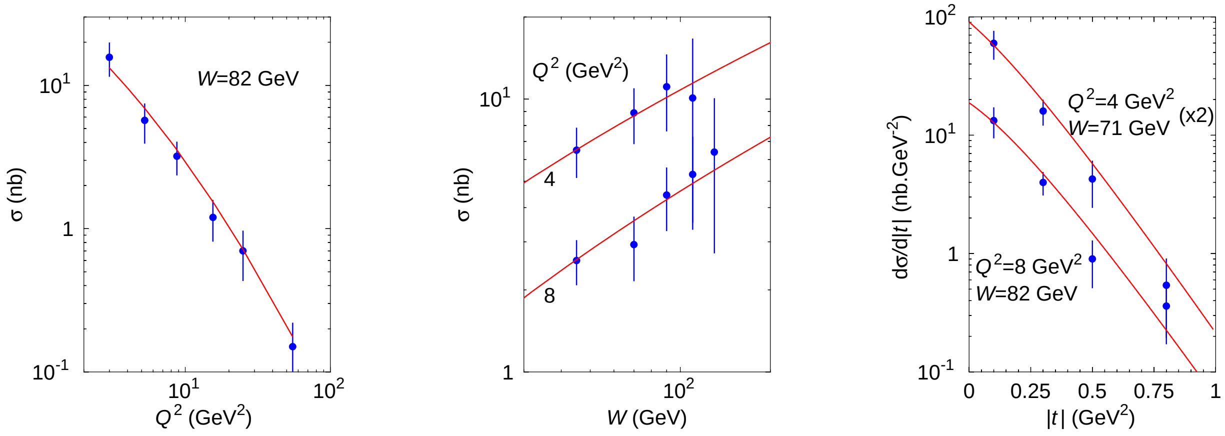

FIGURE 3. Predictions for the DVCS cross section [7] with H1 data.

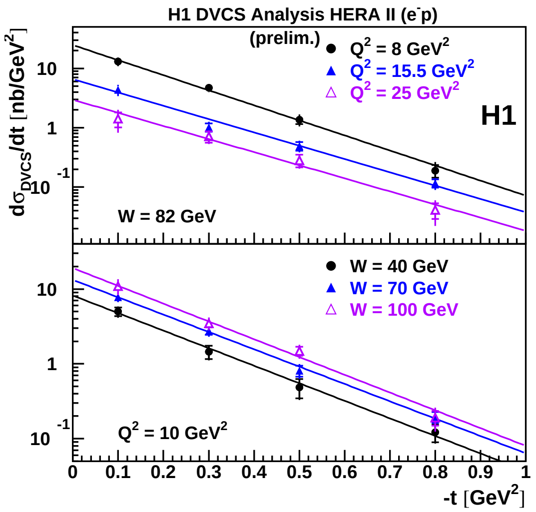

FIGURE 4. DVCS cross section, differential in t presented with a fit of the form $e^{-b|t|}$.

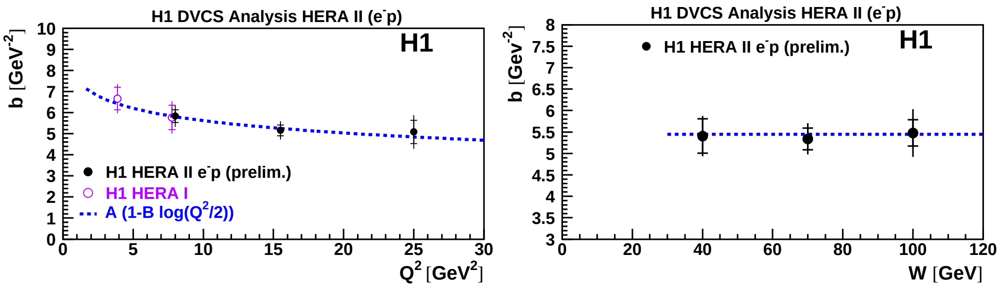

FIGURE 5. The logarithmic slope of the t dependence for DVCS exclusive production, b as a function of Q^2 and W, extracted from a fit $d\sigma/dt \propto \exp(-b|t|)$ where $t = (p - p')^2$.

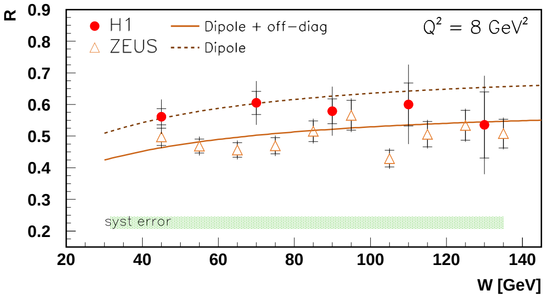

FIGURE 6. *The skewing factor R as a function of W at $Q^2 = 8$ GeV^2. The curves represent the theoretical predictions of the dipole approach (see text).*

QUANTIFYING SKEWING EFFECTS

Let's define a basic quantity giving an overall measurement of the skewing properties [12, 13], which includes both the non-forward kinematics and the possible non-diagonal effects. Namely, we set the ratio between the imaginary parts of the DIS and DVCS (forward) scattering amplitudes at zero momentum transfer:

$$R \equiv \frac{Im\,\mathscr{A}\,(\gamma^* + p \rightarrow \gamma^* + p)|_{t=0}}{Im\,\mathscr{A}\,(\gamma^* + p \rightarrow \gamma + p)|_{t=0}}\ , \tag{3}$$

where t is the square of the four-momentum exchanged at the proton vertex.

In [12, 13], it has been shown how to extract this quantity from the DVCS cross sections. The factor R is presented as a function of energy W in figure 6. An almost flat W dependence is observed within the present precision. This feature can be easily understood since the W dependence of both the DIS and DVCS cross section is power-like having a proportional effective power. Namely, $\sigma_{\mathrm{DIS}} \propto W^{2\lambda}$ and $\sigma_{\mathrm{DVCS}} \propto W^{4\lambda}$. The mean value $R \simeq 0.5$ is consistent with its early theoretical estimates using the aligned jet model and the colour dipole model (see figure 6). We also display a dipole model prediction with an 'ad hoc' parametrisation for the off-diagonal effects. It does not improve the quality of the description of data within the present uncertainties.

NUCLEON TOMOGRAPHY

Measurements of the t-slope parameters b are key measurements for almost all exclusive processes, in particular DVCS. Indeed, a Fourier transform from momentum to impact parameter space readily shows that the t-slope b is related to the typical transverse distance between the colliding objects [6]. At high scale, the $q\bar{q}$ dipole is almost point-like, and the t dependence of the cross section is given by the transverse extension of the gluons (or sea quarks) in the proton for a given x_{Bj} range. More precisely, from the generalised parton distribution defined in the introduction, we can compute a parton density which also depends on a spatial degree of freedom, the transverse size (or impact parameter), labeled $R_\perp$, in the proton. Both functions are related by a Fourier transform

$$PDF(x,R_\perp;Q^2) \;\equiv\; \int \frac{d^2\Delta_\perp}{(2\pi)^2}\, e^{i(\Delta_\perp R_\perp)}\; GPD(x,t=-\Delta_\perp^2;Q^2).$$

Thus, the transverse extension $\langle r_T^2\rangle$ of gluons (or sea quarks) in the proton can be written as

$$\langle r_T^2\rangle \;\equiv\; \frac{\int d^2R_\perp\, PDF(x,R_\perp)\, R_\perp^2}{\int d^2R_\perp\, PDF(x,R_\perp)} \;=\; 4\,\frac{\partial}{\partial t}\left[\frac{GPD(x,t)}{GPD(x,0)}\right]_{t=0} = 2b$$

where b is the exponential t-slope. Measurements of b presented in figure 5 corresponds to $\sqrt{r_T^2} = 0.65 \pm 0.02$ fm at large scale Q^2 for $x_{Bj} < 10^{-2}$. This value is smaller that the size of a single proton, and, in contrast to hadron-hadron scattering, it does not expand as energy W increases. This result is consistent with perturbative QCD calculations in terms of a radiation cloud of gluons and quarks emitted around the incoming virtual photon. In short, gluons are located at the preiphery of the proton as measured here and valence quarks are assumed to form the core of the proton at small value of $\sqrt{r_T^2}$.

In other words, the Fourier transform of the DVCS amplitude is the amplitude to find quarks at $R_\perp$ in an image plane after focusing by an idealized lens. The square of the profile amplitude, producing the PDF (in transverse plane) is positive, real-valued, and corresponds to the image, a weighted probability to find quarks in the transverse image plane.

PERSPECTIVES AT CERN

The complete parton imaging in the nucleon would need to get measurements of b for several values of x_{Bj}, from the low $x_{Bj} < 0.01$ till $x_{Bj} > 0.1$. Experimentally, it appears to be impossible. Is it the breakout of quark and gluon imaging in the proton? In fact, there is one way to recover x_{Bj} and t correlations over the whole x_{Bj} domain: we need to measure a Beam Charge Asymmetry (BCA) [1, 12, 14].

A determination of a cross section asymmetry with respect to the beam charge has been realised by the H1 experiment by measuring the ratio $(d\sigma^+ - d\sigma^-)/(d\sigma^+ + d\sigma^-)$ as a function of ϕ, where ϕ is the azimuthal angle between leptons and proton plane [1, 5]. The result is presented on figure 7 with a fit in $\cos\phi$. After applying a deconvolution method to account for the resolution on ϕ, the coefficient of the $\cos\phi$ dependence is found to be $p_1 = 0.17 \pm 0.03(stat.) \pm 0.05(sys.)$. This result represents obviously a major progress in the understanding of the very recent field of the parton imaging in the proton. We are at the hedge of the giving a new reading on the most fundamental question to know how the proton is built up by quarks and gluons.

Feasabilities for future BCA measurements at COMPASS have been studied extensively in the last decade [15]. COMPASS is a fixed target experiment which can use 100 GeV muon beams and hydrogen targets, and then access experimentaly the DVCS process $\mu p \to \mu\gamma p$. The BCA can be determined when using positive and negative muon beams. One major interest is the kinematic coverage from 2 GeV^2 till 6 GeV^2 in Q^2 and x_{Bj} ranging from 0.05 till 0.1. It means that it is possible to avoid the kinematic domain dominated by higher-twists and non-perturbative effects (for $Q^2 < 1$ GeV^2) and keeping a x_{Bj} range which is extending the HERA (H1/ZEUS) domain.

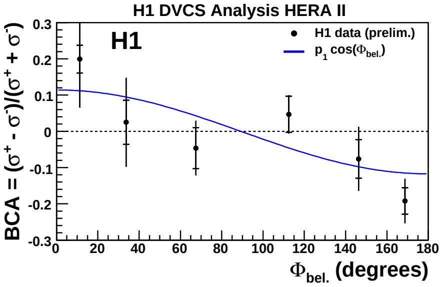

FIGURE 7. Beam charge asymmetry as a function of ϕ measured by H1 [1, 14].

SUMMARY

DVCS measurements in the HERA kinematics at low x_{Bj} are well described within a dipole approach, which encodes the non-forward kinematics for DVCS only through the different weights coming from the photon wavefunctions. Note that the dipole model presents the great advantage to define a unique framework that gives a good description of all hard processes accessible at HERA. For the first time, we have also shown that proton tomography enters into the experimental domain of high energy physics, with a first experimental evidence that gluons are located at the periphery of the proton. A new frontier in understanding this structure would be possible at CERN within the COMPASS experimental setup.

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