DVCS at HERA and at CERN

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Deeply Virtual Compton Scattering (DVCS) in *ep* collisions has emerged in recent years as a an essential reaction to obtain information on the correlation of partons in the hadron (proton) or on the transverse distribution of these partons. In these proceedings, we examine the lattest data from HERA (at low $x_{Bj} < 10^{-2}$) and their impact on models. We analyse in detail what these data imply on the spatial structure of the proton. In particular, the most recent measurements of the Beam Charge Asymmetry by the H1 experiment is discussed in this context. Perspectives are presented for further measurements of DVCS cross sections at CERN, within the COMPASS experiment.

1 Introduction

Measurements of the deep-inelastic scattering (DIS) of leptons and nucleons, $e + p \to e + X$, 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. 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.

Hard exclusive processes, in which the nucleon remains intact, have emerged in recent years as prime candidates to complement this essentially one dimensional picture. The simplest exclusive process is the deeply virtual Compton scattering (DVCS) or exclusive production of real photon, $e + p \to e + \gamma + p$. 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, 2]. 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) [3] or dipole model [4]. In the following, we examine the most recent data recorded from the DESY *ep* collider at HERA and their implication on the quarks/gluons imaging of the nucleon [1, 2].

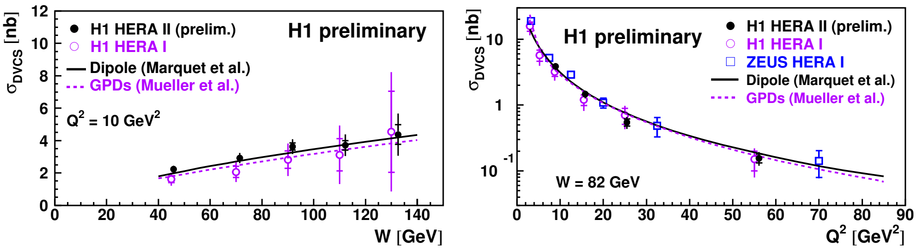

Figure 1: DVCS cross section for the full HERA data as a function of W and Q^2.

2 Latest experimental measurements from HERA

The first measurements of DVCS cross section have been realised at HERA within the H1 and ZEUS experiments [1, 2]. 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, from 1 to 100 GeV^2. 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 DVCS cross sections as a function of Q^2 and $W \simeq \sqrt{Q^2/x}$ are presented on Fig. 1. A good agreement with GPDs [3] and dipole [4] models is observed. A very fundamental observation is the steep W dependence in $W^{0.7}$, visible on Fig. 1. This means that DVCS is a hard process. Thus, it is justified to compare DVCS measurements with perturbative QCD calculations, GPDs or dipole approaches, as displayed in Fig. 1.

3 The colour dipole model

Let's discuss in more details the colour dipole model. Indeed, this approach 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 [4, 5]

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

where $\Psi(z, \boldsymbol{r}, Q_{1,2})$ 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 $\boldsymbol{r}$ 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 [4]. In this case, the dipole cross section, $\sigma_{dip}\,(x_1, x_2, \boldsymbol{r}, \vec{\Delta})$, 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 [4].

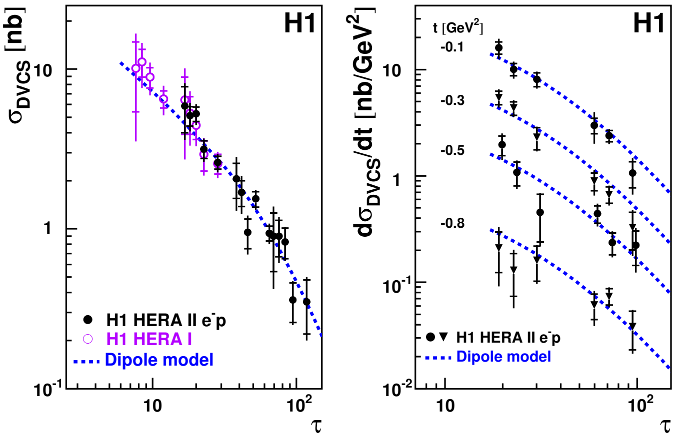

Figure 2: DVCS cross section measurements as a function of the scaling variable $\tau = Q^2/Q_s^2(x)$. Results are shown for the full t range $|t| < 1$ GeV^2 (left) and at four values of t (right). The dashed curves represent the predictions of the dipole model [5].

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:

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

This property, called geometric scaling, has already been observed to hold for the total *ep* DIS cross section and in diffractive processes [5] (see Fig. 2). 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 [4]. It is therefore interesting to test if the present DVCS measurements obey the geometric scaling laws predicted by such models, as illustraded in Fig. 2 (right plot for non-zero momentum transfer to the proton).

4 Nucleon Tomography and Perspectives at CERN

A major experimental achievement of H1 and ZEUS [1, 2] has been the measurement of DVCS cross sections, differential in $t = (p' - p)^2$, the momentum transfer (squared) at the proton vertex. A good description of $d\sigma_{DVCS}/dt$ by a fit of the form $e^{-b|t|}$ is obtained [1, 2]. Hence, an extraction of the t-slope parameter b is accessible and it can be achieved experimentally for different values of Q^2 and W (see Fig. 3). Again, we observe the good agreement of measurements with GPDs and dipole models.

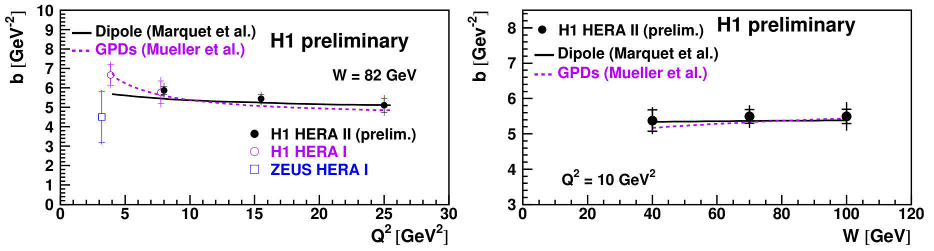

Figure 3: The logarithmic slope of the t dependence for DVCS exclusive production, b as a function of Q^2 and W, extracted from a fit $d\sigma/dt \propto \exp(-b|t|)$ where $t = (p - p')^2$.

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 [3]. 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 GPDs, 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

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

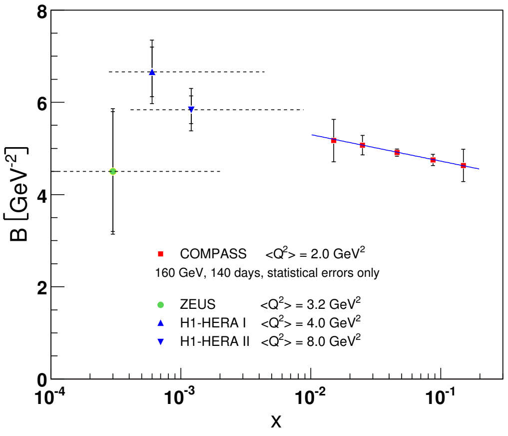

Figure 4: The logarithmic slope of the t dependence for DVCS exclusive production, b as a function of x_{Bj}, extracted from a fit $d\sigma/dt \propto \exp(-b|t|)$ where $t = (p - p')^2$. H1 and ZEUS points are measurements and simulations are displayed for COMPASS (CERN).

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 Fig. 3 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. The fact the perturbative QCD calculations provide correct descriptions of b measurements (see previous section) is a proof that they deal correctly this this non-trivial aspect of the proton (spatial) structure. As already discussed in the context of dipole models, the modeling of the correlation between the spatial transverse structure and the longitudinal momenta distributions of partons in the proton is one major challenge also for the GPDs approach. In Fig. 4, we present a summary of the measurements of $b(x_{Bj})$ by H1 and ZEUS experiments and simulations for COMPASS at CERN. The importance of such measurements of t-slopes as a function of x_{Bj} at CERN is then obvious.

Another natural way to address the problem of the correlation between x and t kinematical variables proceeds from a determination of a cross section asymmetry with respect to the beam charge. It has been realised recently 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. The result is presented on Fig. 5 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 $p_1 = 0.16 \pm 0.03(stat.) \pm 0.05(sys.)$ (at low $x_{Bj} < 0.01$). This result represents a major experimental progress and is challenging for models (see Fig. 5). Let's note that

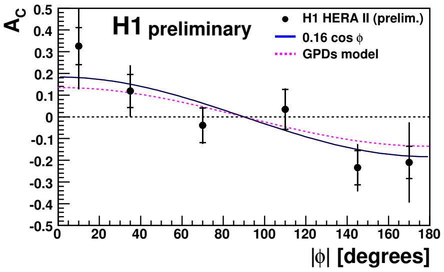

Figure 5: Beam charge asymmetry as a function of ϕ measured by H1. Statistical and systematical uncertainties are shown. Data are corrected from the migrations of events in ϕ. A comparison with the GPDs model described in Ref. [3] is presented. It fits very nicely with the best fit to the data, in $p_1 \cos\phi$ ($p_1 = 0.16$).

models of GPDs can use present HERA data at low x_{Bj}, as well as JLab and HERMES data at larger x_{Bj} ($x_{Bj} > 0.1$), in order to provide a first global understanding of exclusive real photon production [3]. However, as already mentioned above, some efforts have still to be made in the intermediate x_{Bj} domain.

Feasibility for future Beam Charge Asymmetry (BCA) measurements at COMPASS have been studied extensively in the last decade [6]. 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. As mentioned above, this is obviously an essential measurement to cover the full kinematic range and give some results in the intermediate x_{Bj} range between H1/ZEUS and JLab/HERMES experiments. Simulations done for COMPASS [6, 7] are shown in Fig. 6 for BCA in a setup described in the legend of the figure. Two models of GPDs, with a factorised and non-factorised t dependence, are shown in Fig. 6 and we can observe easily the great discrimination power offered by COMPASS, with the proton recoil detector fully operational. Of course, the discrimination is large in Fig. 6 due to the fact that α' is taken to be large ($\alpha' \sim 0.8$ GeV^{-2}) in simulations. If it happens to be much smaller, as measured at low x_{Bj} by H1 [1], both predictions for BCA in Fig. 6 would be of similar shape, as both curves would converge to the factorised case. This shows clearly the high level of sensitivity of this experimental quantity on the modeling of GPDs. This makes this observable very interesting and challenging for GPDs models in the future, once these measurements at CERN would be realised in 2011/2012.

5 Summary and outlook

DVCS measurements in the HERA kinematics at low x_{Bj} ($x_{Bj} < 0.01$) are well described by recent GPDs models, which also describe correctly measurements at larger values of x_{Bj} in

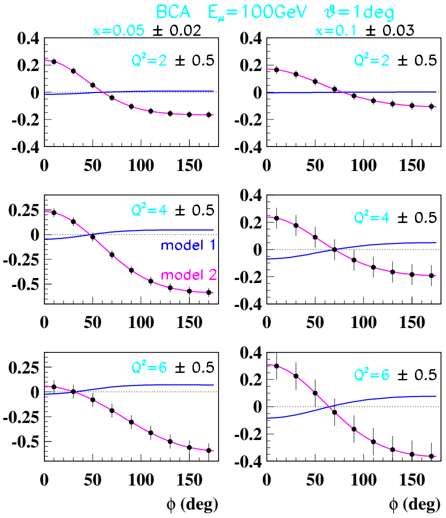

Figure 6: Azimuthal distribution of the beam charge asymmetry measured at COMPASS at E_μ= 100 GeV and $|t| \leq 0.6$ GeV^2 for 2 domains of x_{Bj} ($x_{Bj} = 0.05 \pm 0.02$ and $x_{Bj} = 0.10 \pm 0.03$) and 3 domains of Q^2 ($Q^2 = 2 \pm 0.5$ GeV^2, $Q^2 = 4 \pm 0.5$ GeV^2 and $Q^2 = 6 \pm 0.5$ GeV^2) obtained in 6 months of data taking with a global efficiency of 25% and with $2 \cdot 10^8$ μ per SPS spill ($P_{\mu^+} = -0.8$ and $P_{\mu^-} = +0.8$). More recent simulations are on going which does not change the conclusions of this plot.

the JLab kinematics. DVCS measurements in the HERA kinematics are also nicely described within a dipole approach, which encodes the non-forward kinematics for DVCS only through the different weights coming from the photon wavefunctions. Recently, H1 and ZEUS experiments have also shown that proton tomography at low x_{Bj} 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. Major advances have already been done on the design of the project and simulation outputs.

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