Imaging partons in exclusive scattering processes

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2012-02/98

The spatial distribution of partons in the proton can be probed in suitable exclusive scattering processes. I report on recent performance estimates for parton imaging at a proposed Electron-Ion Collider.

Deeply virtual Compton scattering (DVCS) and exclusive meson production in lepton-proton collisions offer unique possibilities for determining the spatial distribution of quarks, antiquarks and gluons as a function of their longitudinal momentum inside the proton. Such "tomographic images" of the proton can provide insight into key aspects of QCD dynamics, such as the interplay between sea quarks and gluons, the relation between sea and valence quarks, and the orbital angular momentum carried by these partons.

To obtain such images one needs to measure the transverse momentum transfer $\boldsymbol{\Delta}$ to the proton. A Fourier transform then gives the distribution in impact parameter $\boldsymbol{b}$, which is the position of the struck parton in the plane transverse to the proton direction of movement. In the scattering amplitude the longitudinal momentum fraction x of the parton is integrated over, with typical values around $\frac{1}{2}x_B$ for DVCS and $\frac{1}{2}x_V = \frac{1}{2}x_B\,(1 + M^2/Q^2)$ for the production of a meson with mass M. The reconstruction of a joint density in x and $\boldsymbol{b}$ can be envisaged in the framework of generalized parton distributions (GPDs) by making use of their evolution in the resolution scale, which is given by Q^2 in DVCS and by $Q^2 + M^2$ in meson production. This requires precise data in a very wide range of x_B and Q^2.

Measurements from HERA suggest that at x around 10^{-3} gluons have a more narrow impact parameter distribution than sea quarks. Information about the spatial distribution of valence quarks can be inferred from electromagnetic form factors and from lattice calculations, and a direct study of quarks with large momentum fraction x will be possible with the 12 GeV upgrade at Jefferson Lab. The planned DVCS measurement by COMPASS will give us a first glimpse into the x region between 10^{-1} and 10^{-2}. To realize the full physics potential of parton imaging will, however, require a new facility. Here I report on a study of parton imaging at a proposed electron-ion collider (EIC) [1]. For complementary information see [2, 3].

Pseudo-data for $ep \to ep\gamma$ have been generated according to a GPD model that reproduces the existing DVCS measurements of H1 and ZEUS. Technically, the unpolarized distributions H for gluons and for sea quarks are modeled with two SO(3) partial waves each, as described in [3] and in Sec. 3 of [4]. The t dependence of the distributions is $\exp\big[\, t\, (\frac{B}{2} + \alpha' \log \frac{1}{x})\big]$, with different slopes B for gluons and sea quarks and with a small shrinkage parameter α' as suggested by HERA measurements. In DVCS, the invariant momentum transfer t to the proton and its transverse component are related by $-t = (\boldsymbol{\Delta}^2 + x_B^2\, m_p^2)/(1 - x_B)$, where m_p is the proton mass. In the simulation [2] acceptance cuts for the final-state electron, photon and proton have been imposed, and the data have been smeared for the expected resolution in x_B, Q^2 and t.

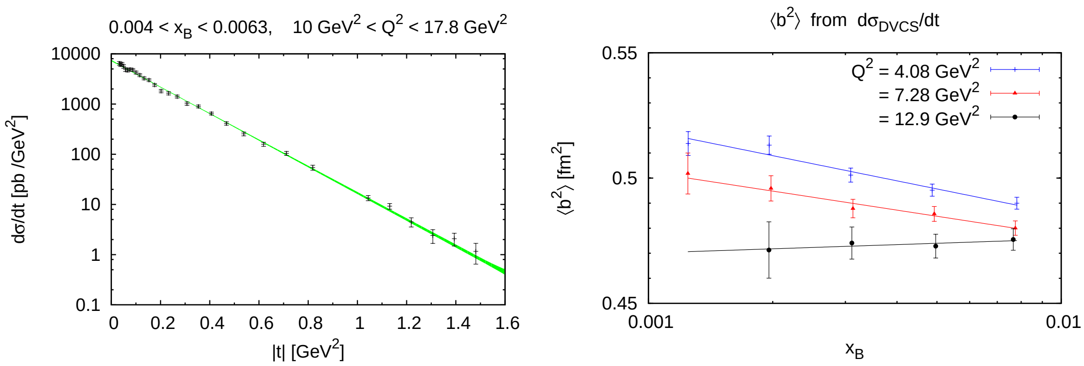

Figure 1: Left: simulated DVCS cross section at EIC for a bin in x_B and Q^2. Right: average squared impact parameter obtained from $d\sigma/dt_{\mathrm{DVCS}}$ for different bins in x_B and Q^2.

An assumed 5% uncorrelated systematic error has been added in quadrature to the statistical error in the cross section. The cross section $d\sigma/dt$ for DVCS ($\gamma^* p \to \gamma p$) is obtained after subtraction of the cross section for the Bethe-Heitler process, with an uncertainty of 3% taken on the latter. Beam energies are $E_e = 20\,\mathrm{GeV}$ and $E_p = 250\,\mathrm{GeV}$. Statistical errors are for an integrated luminosity of $10\,\mathrm{fb}^{-1}$ for the $|t|$ range from $0.03\,\mathrm{GeV}^2$ to $1\,\mathrm{GeV}^2$ and for $100\,\mathrm{fb}^{-1}$ for $|t|$ above $1\,\mathrm{GeV}^2$. Here and in the following the uncertainty in the overall luminosity is not included in the errors, because it does not affect the form of the spectra which are at the center of our interest.

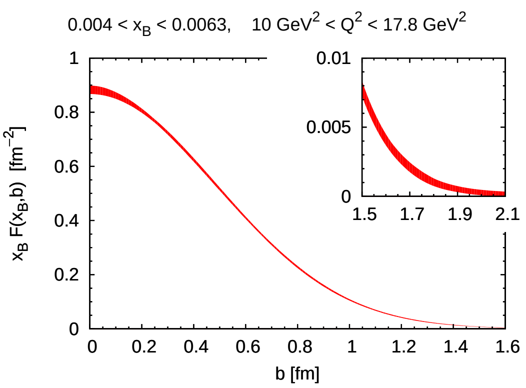

Figure 2: Impact parameter distribution in DVCS obtained from the left panel of Fig. 1. The band reflects the uncertainty in fitting $d\sigma/dt$ and in extrapolating it to the unmeasured t region as specified in Sec. 3.6.1 of [1].

The left panel of Fig. 1 shows the resulting t spectrum for DVCS in a bin of x_B and Q^2, together with an exponential fit. From the t slope one obtains the average squared impact parameter $\langle \boldsymbol{b}^2 \rangle$ for the particular combination of quarks, antiquarks and gluons "seen" in DVCS. The right panel of Fig. 1 shows that with the expected accuracy one can resolve the separate dependence of $\langle \boldsymbol{b}^2 \rangle$ on Q^2 and x_B, which has never been possible so far. In the model used for generating the data, both dependences are small logarithmic effects, which reflect both perturbative and non-perturbative dynamics of sea quarks and gluons in the proton. From $d\sigma/dt$ one obtains the Compton scattering amplitude $|\mathcal{A}_{\gamma^* p \to \gamma p}|$, whose Fourier transform w.r.t. $\boldsymbol{\Delta}$ gives an impact parameter distribution $F(x_B, \boldsymbol{b})$ of partons with momentum fraction of order $\frac{1}{2} x_B$. Figure 2 shows that precise imaging is possible in a wide range of b. Of particular interest at large b is the prediction of an exponential falloff with an x dependent slope of typical size $1/(2m_\pi) \approx 0.7\,\mathrm{fm}$ [5]. Due to partons inside virtual pions, which because of their small mass can fluctuate to large distances, this predicted behavior is a consequence of chiral symmetry breaking in QCD and awaits experimental verification.

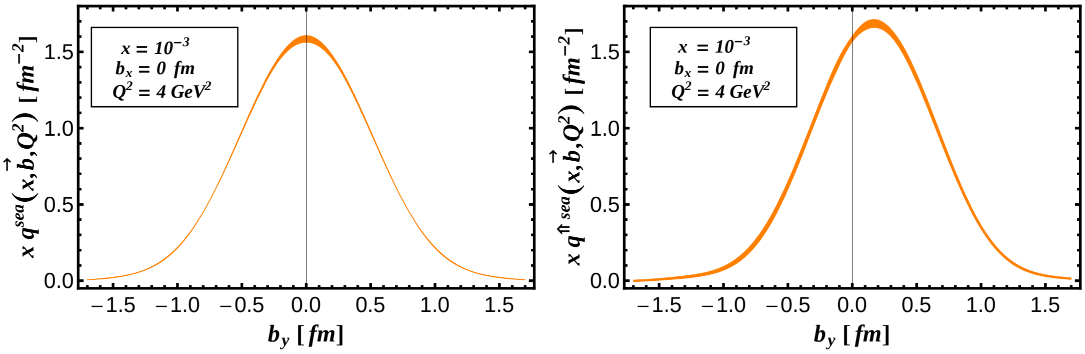

Figure 3: Impact parameter densities of unpolarized sea quarks in an unpolarized proton (left) and in a proton polarized along the x axis (right), obtained from a fit to pseudo-data for the DVCS cross section and the transverse proton spin asymmetry [2, 3].

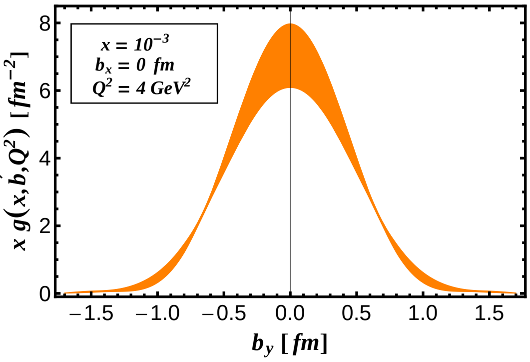

Figure 4: As Fig. 3, but for unpolarized gluons in an unpolarized proton.

With transverse proton polarization one gains access to distributions E, which carry characteristic information about orbital angular momentum of partons in the proton. Transformed to b space, these distributions describe how the impact parameter distribution of partons is shifted sideways in a transversely polarized proton. Pseudo-data for the DVCS cross section and for the transverse proton spin asymmetry have been generated [2] assuming a model of E for sea quarks and for gluons of the same type as the model of H described above. Parameter are chosen to satisfy the positivity requirements on E. The simulation is for $E_e = 20\,\text{GeV}$ and $E_p = 250\,\text{GeV}$, with errors for an integrated luminosity of $100\,\text{fb}^{-1}$ and for 80% transverse proton polarization measured with 5% accuracy. Systematic uncertainties of 5% are added in quadrature. As shown in Fig. 3, a fit of the generated data for the DVCS cross section and the transverse proton spin asymmetry allows the simultaneous extraction of the GPDs H and E for sea quarks. The fitted data covers the kinematic range $3.2\,\text{GeV}^2 < Q^2 < 17.8\,\text{GeV}^2$, $10^{-4} < x_B < 10^{-2}$ and $0.03\,\text{GeV}^2 < |t| < 1.5\,\text{GeV}^2$. Thanks to the effect of logarithmic scaling violations, even the extraction of H for gluons is possible in this fit, as shown in Fig. 4, whereas the errors on E for gluons are very large.

Selective information about gluons can be obtained in exclusive J/Ψ production. We have generated pseudo-data for $e^- p \to e^- J/\Psi\, p \to e^- (e^+ e^-)\, p$ with a version of PYTHIA modified to describe the H1 and ZEUS measurements of this process. We assume an acceptance in pseudorapidity of $\eta < 5$ for all final-state leptons and an acceptance for the recoil proton as in the DVCS studies above. The t spectra and corresponding impact parameter distributions in Fig. 5 show that EIC can provide accurate images of gluons in the proton over two orders of magnitude in x.

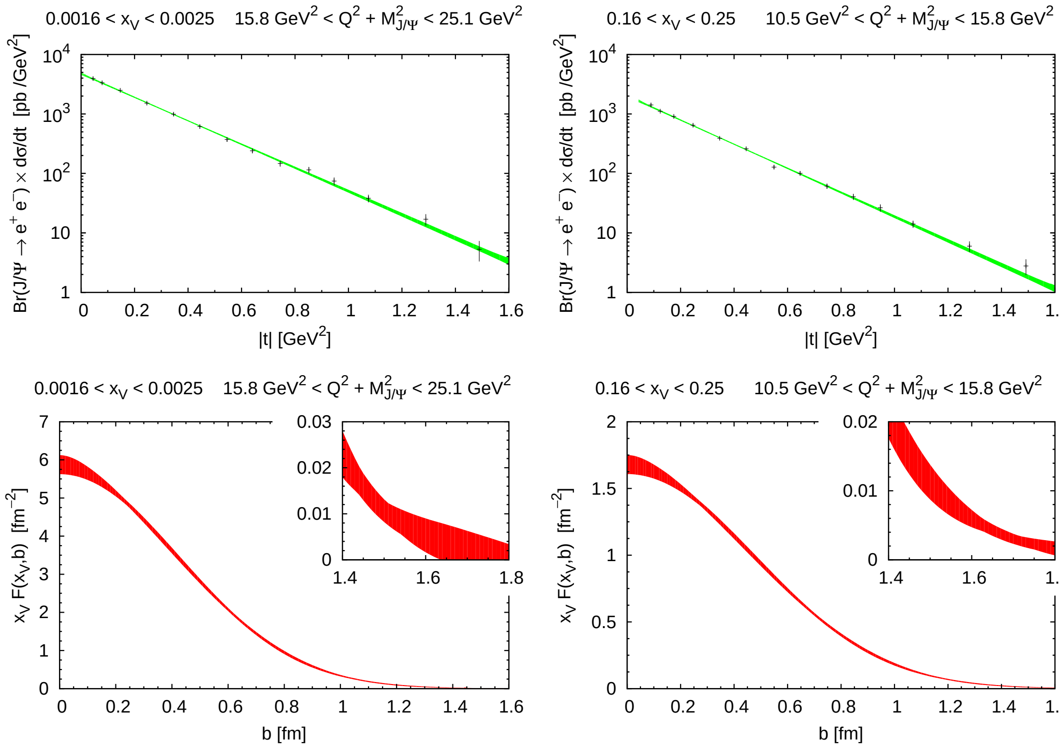

Figure 5: Simulated cross sections for $\gamma^* p \to J/\Psi\, p$ and the corresponding impact parameter distributions for gluons. The left panels are for $E_e = 20\,\mathrm{GeV}$, $E_p = 250\,\mathrm{GeV}$ and the right panels for $E_e = 5\,\mathrm{GeV}$, $E_p = 100\,\mathrm{GeV}$, with $10\,\mathrm{fb}^{-1}$ integrated luminosity in both cases.

Acknowledgments

I gratefully acknowledge collaboration with E.-C. Aschenauer, S. Fazio, K. Kumerčki and D. Müller, who performed the simulations and fits on which the result presented here are based.

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