IL NUOVO CIMENTO Vol. 35 C, N. 2 Marzo-Aprile 2012
DOI 10.1393/ncc/i2012-11205-x

Colloquia: Transversity 2011

DVCS and hard exclusive meson production

D. Hasch
INFN, Laboratori Nazionali di Frascati - via E. Fermi 40, I-00044 Frascati, Italy

ricevuto il 16 Dicembre 2011; approvato l' 11 Gennaio 2012
pubblicato online il 26 Marzo 2012

Summary. — Hard exclusive processes have come to the frontier of nucleon structure physics as they offer experimental access to the Generalised Parton Distributions (GPDs). GPDs have quickly risen in importance as they provide a basis for novel representations of the nucleon as an extended object in space ("nucleon tomography"). A lot of excitement about GPDs is connected to the unique possibility for providing access to the total angular momentum carried by quarks and gluons in the nucleon, a question of fundamental importance in QCD spin physics. This contribution aims at giving an overview about existing measurements of hard exclusive processes, which span over a wide kinematic range, as provided by the HERA collider experiments till the JLab fixed target experiments. A brief summary about the status of GPD extractions in global analyses of these data is given as well. More detailed discussions of the various measurements as well as of model calculations and phenomenology of GPDs can be found at `http://ecsac.ictp.it/transversity2011/programma.php`.

PACS 13.60.-r – Photon and charged-lepton interactions with hadrons.
PACS 13.88.+e – Polarization in interactions and scattering.
PACS 13.87.Fh – Fragmentation into hadrons.

1. – Introduction

Generalised parton distributions [1-3], containing the non-perturbative, long distance physics of factorised hard exclusive scattering processes, encompass the familiar parton distributions and nucleon form factors as kinematic limits and moments, respectively. GPDs offer opportunities to study a uniquely new aspect of the nucleon substructure: the localisation of partons in the plane transverse to the motion of the nucleon. As such they provide a nucleon *tomography*. The ability to describe longitudinal momentum distributions at a fixed transverse localisation is a prerequisite for studying the so-called Ji relation [4], which links a certain combination of GPDs to the total angular momentum of a parton in the nucleon. From this quantity, the still hunted orbital angular momentum of partons in the nucleon could possibly be extracted, a question of crucial importance for an understanding of the nucleon structure.

Generalised parton distributions depend upon four kinematic variables: t, x, ξ and Q^2. The Mandelstam variable $t = (p - p')^2$ is the square of the difference between the initial (p) and final (p') four momenta of the target nucleon. The variable x is the average of the initial and final fractions of the target longitudinal momentum carried by the struck parton, and ξ, known as the skewness, is half of the difference between these fractions. In the Bjorken limit of $Q^2 \to \infty$ with fixed t, ξ is related to the Bjorken variable as $\xi \simeq x_B/(2 - x_B)$. The evolution of GPDs with the photon virtuality Q^2 is analogous to that of standard parton distributions. Several GPDs describe the various possible helicity transitions of the struck quark and/or the nucleon as a whole. At leading twist and for a spin-1/2 target, four chiral-even GPDs $(H, \tilde{H}, E, \tilde{E})$ describe processes that conserve the helicity of the struck quark, while other four chiral-odd GPDs $(H_T, \tilde{H}_T, E_T, \tilde{E}_T)$, so-called transversity GPDs, are needed to describe processes that involve helicity flip of the struck quark.

Experimental access to GPDs is provided through the measurement of hard exclusive processes, where the nucleon stays intact and the final state is fully observed. The exclusive production of real photons, Deeply Virtual Compton Scattering (DVCS), appears to be the theoretically cleanest process for studying GPDs. Similar to inclusive DIS, this process however, does not provide direct flavour dependent information. A flavour *tagging* of GPDs could be gained from hard exclusive production of mesons where the quark content of the meson provides flavour dependent information, similar to semi-inclusive DIS. For meson production, the meson distribution amplitude enters as a second soft part the factorised cross-section. In this case, factorisation was proven for longitudinal virtual photons only and an experimental separation of the σ_L and σ_T cross-sections is desirable. At high Q^2, however, the longitudinal part of the cross-section is expected to dominate as in this limit $R = \sigma_T/\sigma_L \sim 1/Q^2$. Recent model calculations also take the transverse part of the cross-section into account [5] and successfully describe a series of different observables in exclusive meson production. GPD model calculations also emphasise the interesting possibility for an access to GPDs for strange quarks from exclusive kaon-hyperon production [6] and highlight the exciting role of transversity GPDs in pseudoscalar meson production [6, 7]. Much progress from theoretical side is expected for the near future.

Pioneering measurements of GPD observables have been performed at different facilities like DESY (HERMES, H1 and ZEUS), CERN (COMPASS) and JLab (Hall-A and CLAS), which complement each other with regard to the covered kinematic phase space and the extracted observables.

2. – Experimental prerequisites

Measurements of hard exclusive processes are much more challenging than traditional inclusive and semi-inclusive scattering experiments. These exclusive processes require a difficult full reconstruction of final state particles and their cross-sections are usually small, demanding high luminosity machines. Various strategies have been successfully applied by the different experiments for measuring exclusive processes. While the HERA collider experiments at DESY, H1 and ZEUS, as well as CLAS (HAll-B at JLab) have the advantage of utilising nearly hermetic spectrometers, the fixed target experiments HERMES (at DESY) and Hall-A (at JLab) had to challenge the restrictions caused by the incomplete event reconstruction due to their forward spectrometers. The latter two experiments employed successfully the so-called missing mass (or missing energy) technique together with a careful background subtraction (see for example [8]). In the case

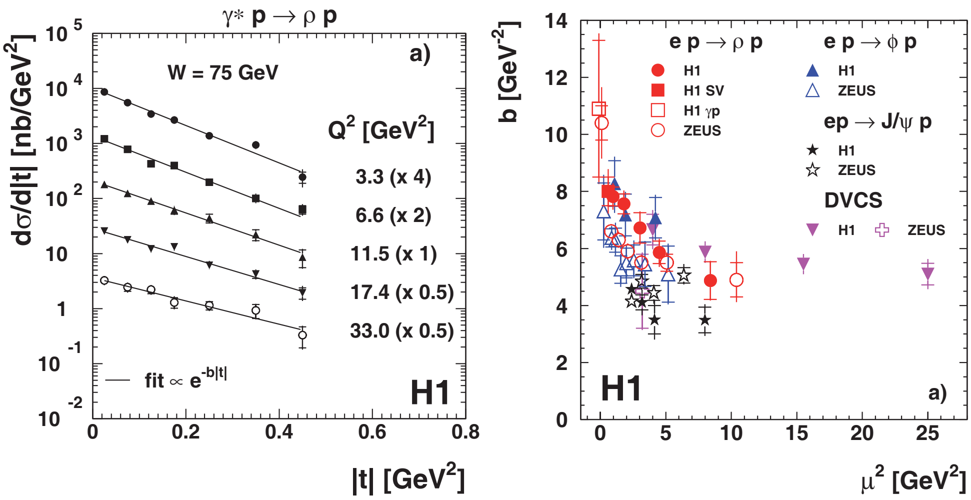

Fig. 1. – Left: t dependence of the ρ production cross-section for several values of Q^2. The curves correspond to exponential fits to the data as indicated in the figure. Right: dependence on the scale $\mu^2 = (Q^2 + M_V^2)/4$ of the slope parameters b for the production of various vector mesons as indicated in the figure and for DVCS (here the scale is taken as $\mu^2 = Q^2$). Figures are taken from [9].

of Hall-A, the low beam energy and high resolution spectrometer allowed for resolving the pure elastic scattering from associated production with an excited nucleon in the final state. The latter contribution is treated as part of the signal in case of results presented here from HERMES (preliminary DVCS results without these contributions are presented elsewhere at this conference [8]).

Except for the HERA collider experiments (H1 and ZEUS), also the information of the spin-dependent cross-sections has been explored using longitudinally polarised lepton beams and/or longitudinally and —in case of HERMES also transversely— polarised targets. GPD observables are then cross-sections and spin-asymmetries with respect to the azimuthal angle between the lepton scattering plane and the plane spanned by the recoiling target and the produced photon or meson. For a transversely polarised target, there is an additional dependence of the cross-section on the azimuthal angle defined by the target polarisation vector.

3. – Vector meson production: from low to high x

A wealth of results from exclusive vector meson production is available spanning over a wide kinematic range. We will be very selective in discussing results, focusing on the transition from the soft to hard regime, the opportunities for the low energy fixed target experiments and the interesting issue of gluon imaging.

Vector meson production at the collider energies has the virtue that the hard scale Q^2 is further enhanced by the mass of the meson M_V. The cross-sections then scale with $\mu^2 = (Q^2 + M_V^2)$. Figure 1 (left) shows exemplary the differential cross-section as function of t for exclusive ρ production and different ranges in Q^2 from H1 [9]. It is well described by an empirical exponential law of the type $\mathrm{d}\sigma/\mathrm{d}t \propto e^{-b|t|}$. The slope parameters b extracted from the exponential fits are presented in fig. 1 (right) as a function of the

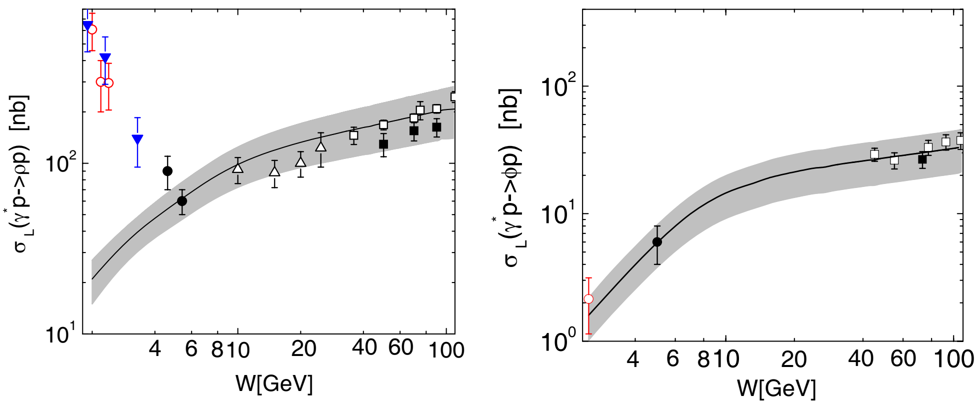

Fig. 2. – Longitudinal part of the cross-section as a function of W, for the exclusive production of ρ (left) and ϕ (right) mesons. The curve is the result of a model calculation from [5] with references for the presented data therein.

scale $\mu^2 = (Q^2 + M_V^2)/4$ for ρ, ϕ, J/Ψ and DVCS measurements from H1 and Zeus. The data clearly cover the transition from the regime where soft diffraction dominates the light vector meson production to the regime where hard diffraction dominates. The universality of the slope parameter at values of $\mu^2 > 5\,\text{GeV}^2$ indicates the onset of the hard regime presented by scattering on point-like configurations.

Both the t and W dependence of these data is well described by the GPD model of [5] based on the handbag factorisation scheme. Here, longitudinal and transverse amplitudes are calculated in the SCHC approximation and both quark and gluon exchange contributions are taken into account. The extension of this model to data from fixed target experiments requires the calculation of higher order and/or power corrections. The results of these calculations are compared in fig. 2 with ρ (left) and ϕ production data spanning a wide kinematic range in W down to fixed target energies (see [5] for references to the data sets). For the production of ρ mesons there is a clear indication for a change in the production mechanism around $W = 4\,\text{GeV}$ and the GPD model fails to describe the data at low W. In contrast, ϕ-meson production is well described over two orders in magnitude in W down to values of about $2\,\text{GeV}$ by the employed GPD model which assumes dominance of gluon exchange for this channel. This underlines the usage of exclusive ϕ-meson production as a very suitable channel for studying gluon GPDs even at fixed target kinematics.

As outlined in the introduction, deep interest in GPDs results from their characteristic to provide a multi-dimensional space resolution of the nucleon. The knowledge about this transverse partonic structure of the nucleon is an essential ingredient for the theoretical analysis of pp and heavy-ion collisions with hard processes. Data from HERA and FNAL on exclusive production of J/Ψ mesons were analysed [10] in order to extract the transverse distribution of gluons in the nucleon at specific values of the gluon momentum fraction x. Figure 3 shows the dependence on $x = M_V^2/W^2$ of the slope parameter B_V of the exponentially falling $|t|$ distributions (B_V is the same parameter as b in fig. 1).

A generalised gluon distribution can then be parametrised as $F_g(x, t|Q^2) = e^{-B_g t/2}$, where B_g is directly related to B_V. The Fourier transform of this function corresponds to a gluon density which, for a given gluon momentum fraction x, also depends on

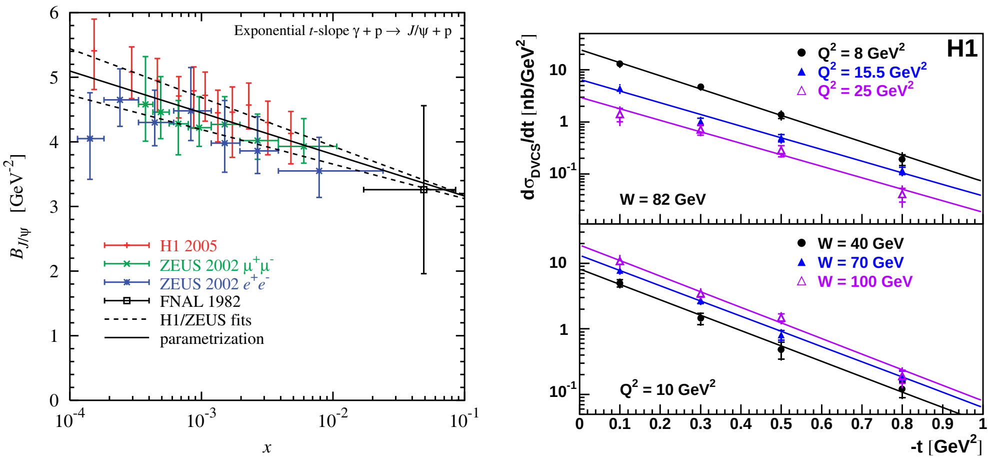

Fig. 3. – Left: dependence on $x = M_V^2/W^2$ of the slope parameter B_V of the exponentially falling $|t|$ distributions for the exclusive production of J/Ψ mesons measured by the HERA collider experiments H1 and ZEUS and the FNAL E401/E458 experiments. The figure is taken from [10] with references for the data therein. Right: the DVCS cross-section differential in t for different values of Q^2 and W as indicated in the figure. The curves are results of fits of the form $e^{-b|t|}$. The figure is taken from [11].

a spatial degree of freedom: a transverse size or so-called *impact* parameter [12,13]. This impact parameter provides an estimate of the transverse extension of the gluons probed during the hard process. Clearly, the HERA data at $x < 10^{-2}$ indicate an increase of the transverse gluonic size with decreasing x. A similar analysis for DVCS data would provide information about the transverse distribution of singlet quarks $(q + \bar{q})$.

4. – Deeply virtual Compton scattering

Among the various hard exclusive processes, DVCS provides one of the cleanest ways to access GPDs, as it has both a clear experimental signature and is calculable in pertubative QCD. DVCS measurements were therefore a focus of all experiments discussed so far or —in case of COMPASS— are a main physics motivation for upgrade projects [14]. The DVCS process is experimentally indistinguishable from the electromagnetic Bethe-Heitler (BH) process because of their identical initial and final states. The real photon is radiated from the struck quark in DVCS or from the initial or scattered lepton in BH. The interference of both processes yields a wealth of interesting asymmetry observables explored with polarised beams and/or targets or different beam charges at the fixed target experiments, while the HERA collider experiments H1 and ZEUS, as well as Hall-A at JLab, measured DVCS cross-sections.

Cross-section measurements differential in t for the high energy and low x regime are exemplary shown from the H1 experiment in fig. 3 (right). The data are well described by the empirical exponential law of type $d\sigma/dt \propto e^{-b|t|}$, already employed to describe vector meson production, with slope parameters b summarized in fig. 1 (right). From these fits, the impact or transverse size parameter discussed before was extracted too. It yields an estimate that is complementary to the usage of vector meson production data.

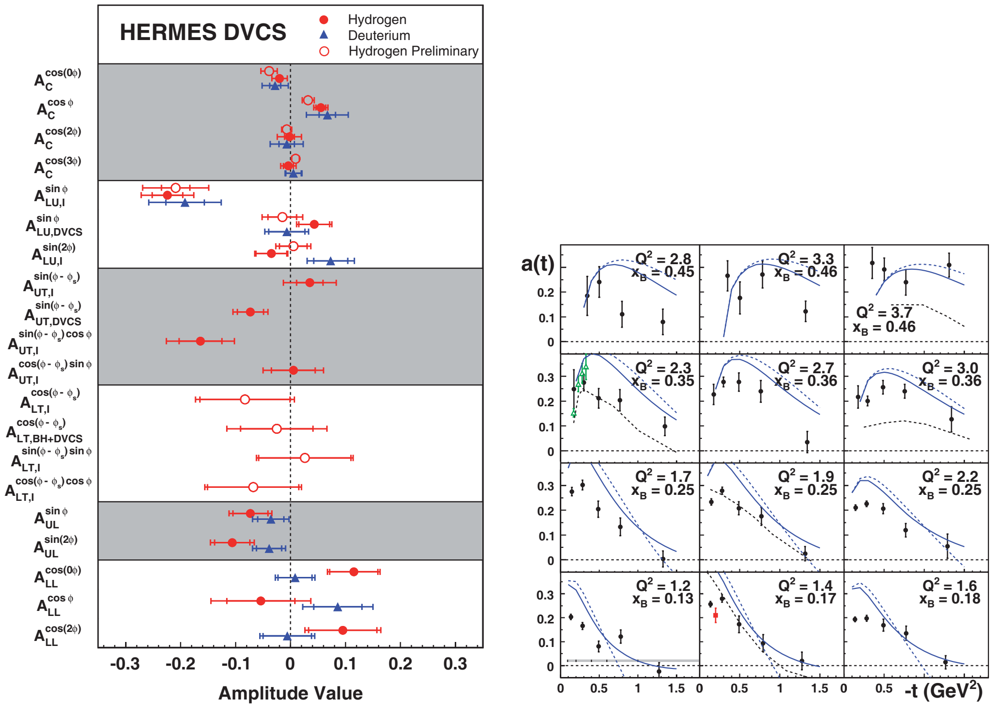

Fig. 4. – Left: overview about all DVCS azimuthal asymmetry amplitudes measured at HERMES with proton and deuterium targets, given at the average kinematics [15-17]. Right: CLAS measurement of the beam-spin asymmetry amplitudes extracted in the fit $A_{LU} = a(t)\sin\phi$ differential in t, x and Q^2 (see [18] for the presented curves).

Most of the fixed target experiments employed polarization and —in case of HERMES also— charge dependent observables in order to access information from the DVCS-BH interference term. Two strategies were followed over the last years: while JLab experiments studied their accessible observables fully differentially, HERMES was exploring the advantages of using simultaneously polarization and charge observables in order to cleanly isolate the interference term and obtained the most complete set of DVCS observables measured so far. Figure 4 (left) shows a summary of the HERMES DVCS measurements with polarised proton and deuterium targets [15-17] at the average kinematics. Here, A_C is the charge asymmetry and A_{XY} are the polarisation-dependent asymmetries with X and Y indicating the beam and target polarisation, respectively, which could be longitudinal (L) or transverse (T). The subscript I indicates an extraction of the pure interference term. The measured asymmetries are subject to a harmonic expansion with respect to the azimuthal angle(s) as given by the superscript (for details see [8]). All data are also available in projections *versus* $-t$, Q^2, and x_B.

An example of high statistic data sets available at JLab is shown in fig. 4 (right) for the beam-spin asymmetry A_{LU} measured fully differentially by CLAS [18]. The presented data contain an admixture of the $A_{LU,I}^{\sin\phi}$ and $A_{LU,DVCS}^{\sin\phi}$ contributions from the interference and pure DVCS terms, which cannot be separated here.

5. – The quest for the orbital angular momentum

Much excitement about GPDs results from their relation to the total angular momenta carried by partons in the nucleon, via the Ji relation [4]

$$J_{\rm q} = \frac{1}{2} \lim_{t\to 0} \int_{-1}^{1} {\rm d}x\, x \left[H^q(x,\xi,t) + E^q(x,\xi,t) \right]. \tag{1}$$

From this relation —in principle— the hunted orbital angular momentum could be extracted, given the involved longitudinal momenta (as the spin) are measured already. From the two GPDs entering the relation, E is essentially unknown. It cannot be related, like the GPD H, to a standard PDF in the forward limit as it describes a helicity flip at the proton vertex and hence requires orbital angular momentum for being non-zero.

The far major part of exclusive observables measured so far is predominantly sensitive to the GPD H and the contributions from the function E are usually damped by kinematic factors of the orders $|t|/M_p^2$, with an average $|t|$ value generally much smaller than $1\,{\rm GeV}^2$. There are however a few "golden" observables, which provide unsuppressed sensitivity to E. These are DVCS and vector meson asymmetry amplitudes measured with transverse target polarisation and DVCS cross-sections from a neutron target. Measurements have been performed already for all channels [19-21]. Despite the lack of precision for these data sets, an attempt to extract information —in a very model dependent way and plagued by the issues discussed in the next section— has been performed, too. The obtained results agree surprisingly well with model and lattice calculations. This first attempt paves the way for future refined analyses based on upcoming high statistic data sets and improved theory developments for GPDs.

6. – A few words about GPD extractions

Global fits of GPDs in the same spirit of existing PDF fits have to face intriguing theoretical issues. Apart from defining precisely the many facets of the partonic interpretation of GPDs, there is a substantially increased level of complication. The dependence of GPDs on the variable x is not directly accessible, as x represents a mute variable which is integrated over. Extractions further require the extrapolation $t \to 0$. In the interpretation of DVCS observables one has to deal with complex amplitudes and the GPDs are embedded in so-called Compton form factors, which are convolutions of GPDs with the hard scattering kernel. Despite these complications and the early stage of global fits for GPDs, exciting results have already been obtained, as for example by [5, 22-26]. These efforts are complemented by recent progress in lattice calculations of GPDs, which provide information on moments of GPDs from first principles. Significant progress in the extraction of GPDs will only be made on the basis of new, high precision data from exclusive processes measured over a wide kinematic range. Such data would especially allow for exploring evolution effects and for extracting elusive "golden" observables like double-DVCS, which contains richer information about GPDs.

7. – Perspectives

A detailed study of GPDs is one of the central topics of ongoing and near-future experiments at COMPASS-II [14] and JLab. COMPASS-II will cover a complementary kinematic range between existing results from fixed target experiments and the HERA collider experiments and will also feature lepton beams of different charges. Most Importantly, the JLab 12 GeV upgrade [27] and a future Electron-Ion Collider (EIC) [28] will provide the unique combination of high energy, high beam intensity (high luminosity) and polarisation, as well as advanced detection capabilities necessary for studying low rate exclusive processes. A high luminosity EIC is an ideal machine that would cover a wide kinematic range and complement the planned fixed target experiments at JLab12 and COMPASS-II.

REFERENCES

[1] Mueller D., *Fortschr. Phys.*, **42** (1994) 101.
[2] Radyshkin A. V., *Phys. Lett. B*, **380** (1996) 417.
[3] Ji X., *Phys. Rev. D*, **55** (1997) 7114.
[4] Ji X., *Phys. Rev. Lett.*, **78** (1997) 610.
[5] Goloskokov S. V. and Kroll P., *Eur. Phys. J. C*, **42** (2005) 281; **53** (2008) 376; **54** (2009) 809.
[6] Goloskokov S. V. and Kroll P., *Eur. Phys. J. A*, **47** (2011) 112.
[7] Ahmad S., Goldstein G. R. and Liuti S., *Phys. Rev. D*, **79** (2009) 054014.
[8] Yaschenko S., these proceedings.
[9] Aaron F. D. *et al.* (H1 Collaboration), *JHEP*, **05** (2010) 032.
[10] Frankfurt L., Strikman M. and Weiss C., *Phys. Rev. D*, **83** (2011) 054012.
[11] Aaron F. D. *et al.* (H1 Collaboration), *Phys. Lett. B*, **659** (2008) 796.
[12] Burkardt M., *Phys. Rev. D*, **62** (2000) 071503.
[13] Diehl M., *Eur. Phys. J. C*, **25** (2002) 223.
[14] *COMPASS-II proposal, CERN-SPSC-2010-014*, http://cdsweb.cern.ch/record/1265628.
[15] Airapetian A. *et al.* (HERMES Collaboration), *JHEP*, **06** (2008) 066; **11** (2009) 083; **06** (2010) 019.
[16] Airapetian A. *et al.* (HERMES Collaboration), *Nucl. Phys. B*, **829** (2010) 1; **842** (2011) 265.
[17] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Lett. B*, **704** (2011) 15.
[18] Girod F. X. *et al.* (CLAS Collaboration), *Phys. Rev. Lett.*, **100** (2008) 162002.
[19] Airapetian A. *et al.* (HERMES Collaboration), *JHEP*, **06** (2008) 066.
[20] Airapetian A. *et al.* (HERMES Collaboration), *Phys. Lett. B*, **679** (2009) 100.
[21] Camacho C. M. *et al.* (Hall-A Collaboration), *Phys. Rev. Lett.*, **97** (2006) 262002.
[22] Guidal M., *Phys. Lett. B*, **689** (2010) 156; **693** (2010) 17.
[23] Guidal M. and Moutarde H., *Phys. Rev. D*, **79** (2009) 094021.
[24] Kumericki K., Muller D. and Schafer A., *JHEP*, **07** (2011) 073.
[25] Kumericki K. and Muller D., *Nucl. Phys. B*, **841** (2010) 1.
[26] Goldstein G. R., Osvaldo Gonzalez Hernandez J. and Liuti S., *Phys. Rev. D*, **80** (2009) 071501; **84** (2011) 034007.
[27] https://www.jlab.org/12-gev-upgrade.
[28] INT report on the EIC science case INT-PUB-11-034, arXiv:1108.1713.