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Working Group 6 Summary

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Experimental and theoretical knowledge acquired over the past decades as well as availability of new technology now enables revolutionary access to the multidimensional representation of the nucleon's inner structure. The framework to describe the distribution of quarks and gluons as a function of their longitudinal momentum fraction and respectively transverse position and transverse momentum is given by generalised parton distributions (GPDs) and transverse-momentum-dependent (TMD) PDFs. These proceedings give an overview of experimental and theoretical progress, results and outlook on this subject shown at the Spin Physics working group of the DIS2017 Workshop.

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1. Introduction

The distribution of quarks and gluons as a function of their longitudinal momentum fraction of the nucleon, x_B, is encoded in parton distribution functions (PDFs). Their distribution as a function of their longitudinal momentum fraction and respectively transverse position and transverse momentum is described by generalized parton distributions (GPDs) [1] and transverse-momentum-dependent (TMD) PDFs [2, 3]. The (TMD) PDFs represent probability density distributions, while the GPDs are probability amplitudes. Taking Fourier transforms of GPDs allows to recover a probabilisitic interpretation in terms of finding partons with a given longitudinal momentum fraction at a certain transverse position [4, 5].

The most general information on the nucleon structure is encoded in Wigner distributions [6]. These describe simultaneously the distribution of partons in terms of their longitudinal and transverse momentum components as well as their transverse position. Because of the Heisenberg uncertainty principle, they have a probabilistic interpretation only in the classical limit. Integration over transverse momentum (position) allows to recover the GPDs (TMD PDFs). Until recently, it was not clear if and how Wigner distributions or their Fourier transform, the generalized transverse-momentum-dependent distributions (GTMDs), could be accessed experimentally, but theoretical breakthrough in the last year provided us with hope [7, 8].

Experimental and theoretical knowledge acquired over the past decades, as well as availability of new technology, now enables revolutionary access to the three-dimensional representations of the nucleon's inner structure in terms of TMD PDFs and GPDs. The pioneering efforts of HERMES and COMPASS, together with the 6 GeV JLab, have demonstrated the feasibility of studying TMD PDFs and to access GPDs through exclusive processes like Deeply Virtual Compton Scattering. For example, recent measurements at JLab have demonstrated that high-quality CW polarized electron beams with a combination of large acceptance and precision detectors are excellent tools for measuring these fundamental distributions. Recent data are also available from RHIC at Brookhaven National Lab and Drell-Yan studies at Fermilab.

In the near term, the 12 GeV JLab with its extended kinematic range and new experimental hardware has the potential to reveal new aspects of nonperturbative dynamics and the nucleon valence structure. COMPASS can provide complementary information, at lower Bjorken x (x_B). In the future, an Electron-Ion Collider (EIC) will allow for unprecedented access to the nucleon sea quark and gluon structure.

An overview of experimental and theoretical results presented at the DIS 2017 workshop on the one-dimensional and multi-dimensional nucleon structure is given below.

2. Collinear measurements

The u and d-quark helicity distributions are relatively well constrained for medium values of x_B, while both the gluon and s-quark distributions suffer from large uncertainties, with different fits obtaining distributions of opposite sign in certain x_B ranges. New measurements and extraction techniques for the determination of the gluon and quark distributions were shown.

The STAR Collaboration presented its preliminary results on the longitudinal single-spin asymmetry in $W^{\pm}$ production, measured from data collected in 2013 in proton-proton collisions [9].

Because of parity violation, $W^{\pm}$ offer clean and easy access to specific helicity distributions. In particular, depending on the $W^{\pm}$ rapidity, the $\bar{u}$ and $\bar{d}$-quark helicity distributions can be probed. The new STAR measurement is consistent with the earlier published ones and provides further constraints on the quark helicity distributions.

The COMPASS Collaboration published its final results on the proton and deuteron spin structure functions [10, 11], respectively $g_p^1(x_B)$ and $g_d^1(x_B)$, for photon virtualities squared, Q^2, below and above 1 GeV^2. The measurements on protons (deuterons) cover the range in x_B from 0.7 down to the low region of 0.0025 (0.004), where experimental data are scarce. At these low values of x_B, $g_p^1(x_B)$ is positive, while $g_d^1(x_B)$ is found to be compatible with zero.

The COMPASS Collaboration published in addition results on charge-separated kaon multiplicities in bins of x_B, z, and the lepton energy fraction carried by the virtual photon, y, for x_B down to 10^{-3} [12]. These data constitute important input for the constraint of the s-quark PDFs and fragmentation functions.

Also the presented inclusive cross-section measurements of di-hadrons of charged pions and kaons in electron-positron annihilation by the Belle experiment [13] provide input for the determination of fragmentation functions. Here, the measurement distinguishes hadrons created in opposite hemispheres from those created in the same hemisphere, thus providing sensitivity to the single-hadron fragmentation, where each of the created hadrons originate from a different quark, and the di-hadron fragmentation, where both created hadrons originate from the same quark.

The JAM Collaboration presented its new approach, based on an iterative Monte-Carlo methodology, for the extraction of PDFs [14]. An advantage of this method is the unambiguous, Bayesian determination of the related uncertainties. A global analysis of inclusive deep-inelastic scattering (DIS) data, including up to twist-4 terms, is performed. The twist-3 contributions are found to be non-zero, while the twist-4 contributions are negligible. The twist-2 u-quark and d-quark PDFs are found to be similar to other extractions. Contrary to the analyses including semi-inclusive DIS data, the s-quark PDF is found to be negative, while the gluon distribution is similar to that of recent DSSV fits [15]. Since the analyses based on inclusive DIS data only and those based on a combination of inclusive and semi-inclusive DIS data obtain s-quark PDFs with opposite sign, the fragmentation process needs to be understood in depth. Therefore, the JAM Collaboration extended the iterative Monte-Carlo methodology to the study of fragmentation functions from electron-positron annihilation data [16]. The final goal is to extend the analysis to a simultaneous extraction of PDFs and fragmentation functions from a global analysis of the various, available data sets.

Also the NNPDF Collaboration presented a new determination of fragmentation functions of charged pions and kaons, and (anti-)protons from single-hadron production in electron-positron annihilation [17]. It is based on neural networks, and designed to minimise any procedural bias and present statistically well-founded uncertainties. It follows the NNPDF methodology used for the determination of PDFs. The results are provided at leading, next-to-leading and next-to-next-to-leading order in perturbative QCD, with the higher-order corrections resulting in a better description of the experimental data. In general, reasonable agreement is found between the fragmentation functions extracted by the JAM Collaboration and the NNPDF Collaboration, albeit with important differences existing, of which some can be traced back to target-mass corrections.

Following up on Ref. [18], an update of the extraction of the transversity PDF in di-hadron production was presented [19]. The transversity distribution describes the distribution of transversely polarized quarks in a transversely polarized nucleon. It can be accessed in an independent way in single-hadron production in semi-inclusive DIS and in di-hadron production. The di-hadron case relies on a collinear factorization framework, while the single-hadron case is based on a TMD factorization formalism. These two approaches are complementary to each other. The newly presented analysis is not only based on data from semi-inclusive DIS and electron-positron annihilation, but also includes data from transversely polarized proton-proton collisions. As a result, the extracted transversity distributions have reduced uncertainties. In addition, the d-quark transversity distribution lies further away from the Soffer bound and is more compatible with its analogue obtained in single-hadron production.

3. Transverse-momentum-dependent measurements

The Jefferson Lab Hall A Collaboration has measured the spin-independent cross section in semi-inclusive DIS of charge-separated pions for data collected on a Helium-3 target [20]. The measurement is performed in the valence-quark region in bins of x_B and hadron transverse momentum, $P_{h\perp}$. Model calculations describing the data as a function of $P_{h\perp}$ well in the low x_B region fail to do so at higher x_B values, and vice-versa. The performed measurement provides valuable data to constrain TMD PDFs and fragmentation functions.

The Belle and STAR Collaborations presented preliminary results on the transverse polarization of Λ hyperons [21, 22]. Making use of the self-analysing decay of the Λ, i.e., the parity-violating correlation between the directions in the Λ rest frame of the decay proton and the Λ spin, the measurement of the proton direction allows to access fragmentation functions of polarized, transversely in the present case, final-state hadrons, and at the same time test the universality properties of polarizing TMD fragmentation functions [23]. The STAR Collaboration extracted its result using data from the collision of transversely polarized protons with unpolarized protons, while Belle used electron-positron annihilation data. For STAR, the extracted polarization is consistent with zero for Λ and $\bar{\Lambda}$, both at forward and negative rapidity. For Belle, the Λ polarization shows an unexpected behaviour as a function of $P_{h\perp}$ at intermediate values of hadron energy fraction of the quark.

The STAR and COMPASS Collaborations explored the sign-change of the Sivers function [24, 25]. The Sivers distribution function is a TMD PDF that describes the distribution of unpolarized partons in a transversely polarized nucleon, probing the correlation between the transverse momentum of the partons and the nucleon spin. The Sivers distribution measured in semi-inclusive DIS off transversely polarized protons is expected to have opposite sign compared to that extracted from Drell-Yan or $W^{\pm}/Z^0$ production in hadron-proton collisions, because of initial-state and final-state interactions [26, 27]. These interactions form intrinsically part of the Sivers distribution. Various measurements in semi-inclusive DIS have been performed by the COMPASS and HERMES Collaborations. First measurements sensitive to the Sivers distribution extracted from proton-hadron collisions are presented in figure 1. The left panel shows the preliminary results of the transverse single-spin asymmetry measured for Drell-Yan lepton pairs by the COMPASS Collaboration from the collision of pions with transversely polarized protons. The measurement is integrated over the entire kinematic range. The two panels on the right show the asymmetries for W^+ and W^- production, respectively, as obtained by the STAR experiment from the collision of transversely polarized

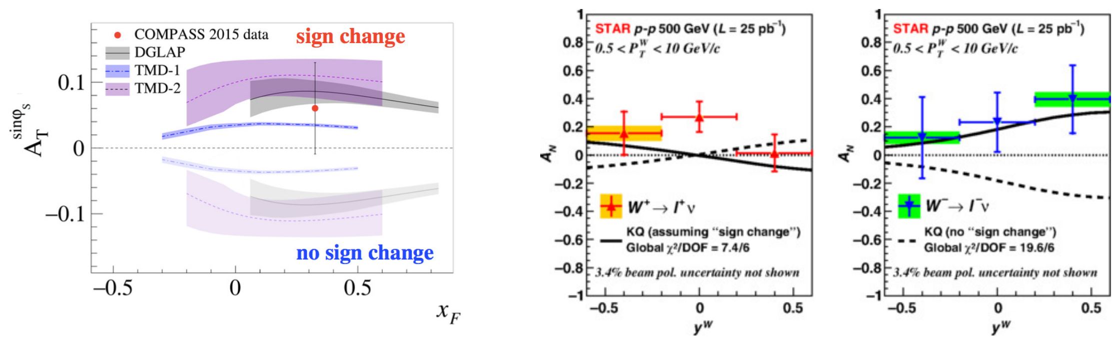

Figure 1: Transverse target-spin asymmetry measurements from COMPASS (left) [25] and STAR (right) [24]. The COMPASS result is integrated over the entire kinematic range, while the STAR measurement is shown as a function of the $W^{\pm}$ boson rapidity. The model calculations are also presented (left, as a function of Feynman x_F), assuming the presence and the absence of a sign change of the Sivers TMD PDF.

protons with unpolarized protons. Also indicated are model calculations (as a function of Feynman x_F in the left panel) with and without a sign change of the Sivers function. As can be seen, both measurements are consistent with a sign change of the Sivers distribution, keeping in mind that both the theoretical and experimental uncertainties are rather large. The present results will be complemented with measurements of additional data. Also, measurements from the PHENIX experiment are to be expected.

The PHENIX and COMPASS experiments presented single-spin asymmetry measurements related to Sivers TMD PDFs of gluons [28, 29]. The COMPASS Collaboration extracts a negative asymmetry, different from zero by more than two standard deviations. The PHENIX Collaboration measured transverse single-spin asymmetries of μ^+ and μ^- from open heavy-flavor decays in polarized proton-proton collisions and finds the asymmetries to be consistent with zero. Comparison of the latter data with model calculations based on twist-3 three-gluon correlations in the collinear framework shows good agreement.

The COMPASS experiment also presented the full series of longitudinal target-spin and double-spin asymmetries [30]. The asymmetries are extracted from data collected with longitudinally polarized proton and deuteron targets and a longitudinally polarized muon beam. The asymmetries are extracted for single-hadron and di-hadron production. Asymmetries measured on deuteron are compatible with zero, while some measured on proton are non-zero. These results allow to access various twist-2 and twist-3 (TMD) PDFs, complementing data previously extracted by experiments at Jefferson Lab and HERMES.

The PHENIX Collaboration investigated the nuclear dependence of transverse single-spin asymmetries [31]. Large single-spin asymmetries in very forward neutron production in proton-proton collisions had been previously observed and explained by a one-Reggeon exchange model with interference between π^+ and a_1 mesons. This model predicts a moderate dependence of the asymmetry on the atomic mass number. Contrary to expectations, large single-spin asymmetries of opposite sign and three times larger in magnitude have been observed in proton-gold collisions, while asymmetries extracted from proton-aluminium collisions are small. The asymmetries are presented in figure 2 as a function of the atomic mass number. The development of a Monte-Carlo

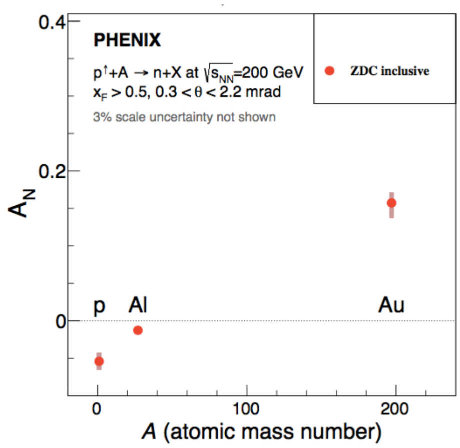

Figure 2: Single-spin asymmetries in very-forward neutron production in proton-ion collisions as a function of the atomic mass number [31].

simulator including ultra-peripheral collisions leads to the interpretation that the large asymmetries originate from ultra-peripheral collisions, thus from the interaction of a photon emitted by the ion with the transversely polarized proton. The amount of ultra-peripheral collisions is much larger for collisions with gold ions than with aluminium ions, since the photon flux emitted by ions is proportional to the square of the electric charge of the ion.

From phenomenological side, the global fits of spin-independent TMD PDFs were presented [32], where for the first time the authors included the data collected in semi-inclusive DIS, Drell-Yan and Z-boson production in proton-proton collisions. The fit is performed at next-to-leading log accuracy and TMD evolution is used in order to connect the data taken at different scales, varying from $Q^2 = 10^0$ GeV^2 to $Q^2 = 10^2$ GeV^2. Eleven parameters were fit to more than 8000 data points: four parameters for the TMD PDFs, six for the TMD fragmentation functions and one for the TMD evolution. The extraction is limited to small values of transverse momentum, where the TMD factorization formalism is applicable.

For large transverse momenta, the collinear formalism needs to be used instead of the TMD-PDF formalism. In order to combine both formalisms into one, valid over the entire transverse-momentum range, the Collins-Soper-Sterman (CSS) formalism combines the cross sections into an additive form, $W+Y$, where W is based on the TMD-PDF and Y on the collinear formalism [33]. Depending on the momentum region, one term dominates over the other. The prescription is designed to combine both formalisms at intermediate transverse-momentum values, but does no specifically address the integration of the cross section over transverse momentum. In order to address the latter point, the prescription has now been adjusted [34] by redefining the W term, but keeping the exact, usual definitions of the TMD PDFs and fragmentation functions as derived in factorization proofs. This improved prescription is at present applicable for spin-independent cross sections, but will be extended to the spin-dependent case.

Further constraints on TMD PDFs and fragmentation functions will be provided by future experiments. As such, various experiments using longitudinally and transversely polarized targets and the SoLID spectrometer in Hall A at Jefferson Lab will allow for a four-dimensional precision mapping of extracted asymmetries [35]. Also CLAS12 at Jefferson Lab will perform cross-section

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and asymmetry measurements using a longitudinally polarized lepton beam and longitudinally and transversely polarized targets [36], while Hall C plans precision measurements of charge-separated kaons and pions as well as neutral pions as a function of their transverse momentum [37]. Also from STAR more measurements of Drell-Yan and $W^{\pm}$ production sensitive to twist-3 effects and the Sivers and transversity distributions are planned [38].

Leaning towards the longer-term future, it has been demonstrated that quark GTMDs, hence quark orbital angular momentum, can in principle be accessed in double Drell-Yan production [39], while the gluon orbital angular momentum can be accessed via exclusive diffractive dijet production [40, 41], for example, at a future electron-ion collider (EIC). Studies have also shown that the gluon helicity distribution can be accessed at an EIC via jet production [42], while at small x_B, the importance of studying TMD PDFs and probing the color-glass condensate have been highlighted [43].

4. 3D Spatial Mapping - GPDs

GPDs encode the correlation between the quark/gluon transverse position in the nucleon and its longitudinal momentum, and can be measured in exclusive scattering processes at large Q^2, in which the nucleon is observed intact in the final state. It is recognized that Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) are two powerful processes to probe GPDs. Together they offer a path to a full 3-dimensional tomography of the nucleon structure [62].

The key to extracting GPDs from experiment are QCD factorization theorems, which allow the amplitudes for deep exclusive processes to be expressed in terms of GPDs. The value of Q^2 at which this formalism is valid experimentally needs to be determined and the contributions of higher twist components to observables need to be quantified.

Deeply Virtual Compton Scattering is the cleanest or golden channel to study GPDs. As the DVCS process interferes with the Bethe-Heitler process, one can access the DVCS amplitudes. At leading twist and leading order, one determines Compton Form Factors, which are integrals of GPDs over Bjorken x with a kernel to describe the hard photon-quark interaction.

The worldwide DVCS experimental program, including experiments at JLab with a 6 GeV electron beam and HERMES with 27 GeV electron and positron beams, has given the first insight into the nucleon GPDs by allowing initial comparisons with models [62]. These experiments have measured large asymmetries, in the 10-20% range, and suggest an early approach to the hard scattering regime. Experiments at 6 GeV JLab by the DVCS Hall A Collaboration and at COMPASS provided a set of precision (un)polarised cross sections, as well as the spin asymmetries A_{LU}, A_{UL} and A_{LL} [68]. Measurements at two different beam energies allowed for disentangling the DVCS cross section and demonstrated that there is a substantial contribution of the DVCS^2 term [46] (see Fig. 3). The results suggest that it is not sufficient to assume dominance of several GPDs, validity of twist-2 dominance, and a leading-order formalism in the data analysis and interpretation. To go beyond this, one has to fully disentangle Compton scattering, Bethe-Heitler contributions, and their interference (after subtracting the known Bethe-Heitler contribution) [64].

DVCS cross sections and polarized asymmetries can provide detailed and precise information about GPDs, but are sensitive only to a particular flavor combination. Exclusive meson produc-

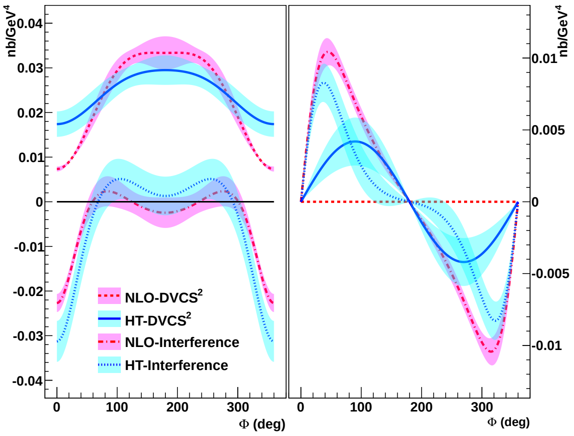
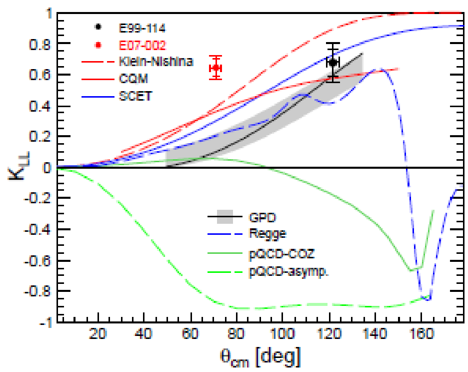


Figure 3: A generalized Rosenbluth separation of the DVCS cross section [64]. DVCS^2 and DVCS-BH interference contributions are shown at Q^2=1.75 GeV^2, x_B=0.36, t=-0.30 GeV^2 and electron beam energy of 5.55 GeV for the helicity-independent (left) and helicity-dependent (right) cross sections. The lines denote the contributions of twist-3 (solid and dotted, blue), Next-to-Leading-Order (dashed and dashed-dotted, red) to the DVCS^2 and interference term, respectively.

tion provides key additional information allowing the separation of different quark and anti-quark flavors [44]. The theoretical description of these processes is more complicated, and thus measurements that provide information about the reaction mechanism, e.g., tests of hard-soft factorization, are essential. In particular, the emerging transversity GPDs [49–51] may be accessed if dominance of the transverse cross section at small values of t <0.3 GeV^2 can be experimentally verified. First measurements were carried out at 6 GeV JLab by the DVCS Hall A Collaboration and a substantial contribution of the transverse π^0 cross section was found [45, 47, 71].

To validate the meson factorization theorems and potentially extract flavor separated GPDs from experiment, one has measure the separated longitudinal and transverse cross sections and their t and Q^2 dependencies. Only L/T separated cross sections can unambiguously show the dominance of longitudinal or transverse photons and allow one to determine possible correlations in t and Q^2. First measurements were carried out with at 6 GeV JLab in Hall C and demonstrated the validity of the method for QCD factorisation studies [52, 66]. New results from deeply virtual vector meson production are available from COMPASS and HERMES [67, 68]. The ρ^0 helicity amplitude ratios with nucleon-helicity flip were found to be small and consistent with zero, while the non-flip amplitudes were found to be non-zero [53, 67]. New spin-dependent matrix elements were found to be in partial agreement with the GK model. Existing DVMP data are consistent with the QCD factorization prediction over a limited Q^2 range. In the near future this will be verified over a wider kinematic range with experiments at the 12 GeV JLab [66].

Wide-Angle Compton Scattering (WACS) offers a complementary way to GPDs in accessing nucleon structure. In this process one measures the nucleon form factors at large t that could constrain GPDs. One of the main predictions of the pQCD mechanism for WACS is the constituent scaling rule for the cross section. Also of interest are the polarisation observables, K_{LL} and K_{LS}. First data were obtained by the WACS Collaboration at 6 GeV JLab in Hall A/C [48, 65]. Theoretical models are in fair agreement with these data as illustrated in Fig. 4.



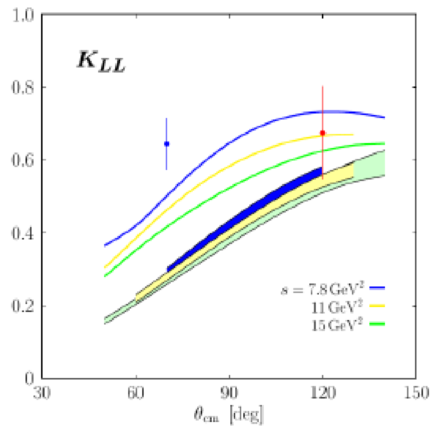


Figure 4: Wide-angle Compton Scattering results from JLab 6 GeV [65].

Global fits play an essential role in extracting information on nucleon structure from and interpretation of experimental data. The PARTONS (PARtonic Tomography of Nucleon Software) Collaboration is developing a platform for such GPD studies [54]. Its architecture includes a comprehensive database of experimental results and theoretical predictions. Initial fits to precision DVCS data from 6 GeV JLab provided a good description of the experimental data. Ongoing efforts are on the way to develop methods for implementing global fits with encoded access to tomography and a small number of parameters with capability to work over a wide kinematic range [69, 70].

The increased energy of the JLab electron beam to 12 GeV offers the kinematic reach where the leading order GPD formalism is anticipated to be applicable. It also provides the highest polarized luminosity for precision measurements of key polarization observables crucial in these studies. A set of approved DVCS experiments planned in Hall B with CLAS12 and Hall A/C will provide the necessary high-precision data for different channels and reactions over a wide kinematic range [63]. These data will be critical in the extraction of GPDs and parametrizations, while constraints from dispersion-relation techniques and from the lattice calculations of the moments of GPDs, will minimize the model dependence in those parametrizations. The first DVCS experiment at 12 GeV JLab has already completed 50% of the data taking in Hall A [64]. Fig. 5 shows the projected impact of the CLAS12 data. The new Neutral Particle Spectrometer (NPS) presently being constructed will offer the required instrumentation to enable DVCS measurements in Hall C. The NPS, together with a Compact Photon Source (CPS) [58] also allows for complementary measurements of polarisation observables and nucleon form factors at large t through the Wide-Angle Compton Scattering process [65].

There is an equally ambitious program of experiments at 12 GeV JLab involving DVMP, which are able to access GPDs, or combinations thereof, that are inaccessible to DVCS. In Hall B, in parallel with the DVCS measurements of cross sections, structure functions and beam spin asymmetries both for vector mesons and pseudoscalar mesons will be explored over the largest phase space ever probed in the valence regime. Experiments in Hall C will focus on L/T separation for pion electroproduction, and for the first time make precision measurements of K^+ cross sections adding strangeness information to the DVMP program [66]. The onset of factorization for

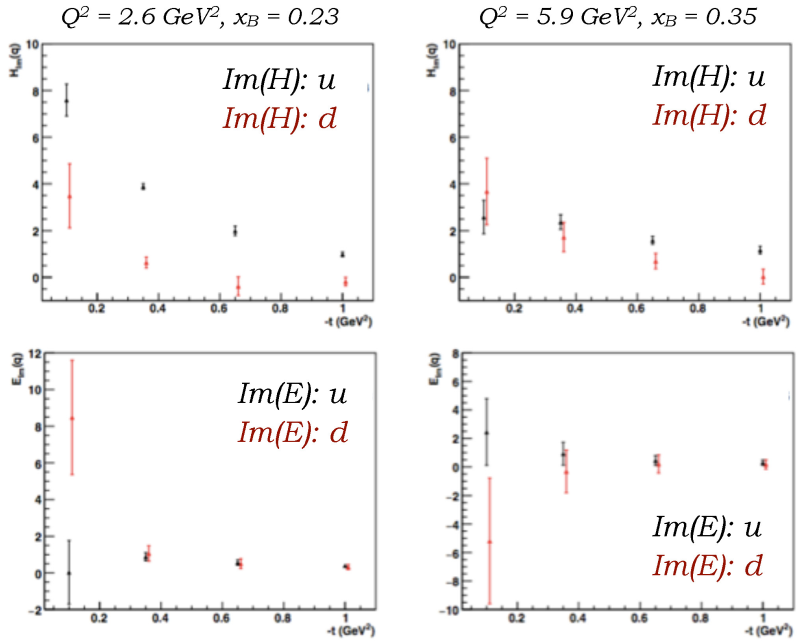


Figure 5: Projections for CLAS12 at JLab of the imaginary part of the Compton form factor $\mathscr{H}$ (upper row) and $\mathscr{E}$ (lower row) for up quarks (black) and down quarks (red) as a function of $-t$ [GeV^2], for $Q^2 =$ 2.6 GeV^2 and $x_B = 0.23$ (left) and for $Q^2 = 5.9$ GeV^2 and $x_B = 0.35$ [63].

light mesons may be expected earlier than for heavier ones. Recent calculations predict the onset for pions and kaons in the 5-10 GeV^2 regime, a region accessible with planned 12 GeV Jefferson Lab (JLab) experiments [55–57]. Thus, if meson factorization is to be observed it is most probable for pion and kaon and it can be realized in the next few years. Measuring L/T separated cross sections places strong demands on experimental facilities requiring rigorous control over systematic uncertainties. Hall C at JLab with its precision focusing spectrometers and particle identification detectors is the only facility available for carrying out these measurements.

Possible future measurements include quark flavour separation through neutrino production of *D*-mesons [72]. Calculations show that such measurements are within the reach of planned medium and high energy neutrino facilities [59]. In addition, studies of the polarisation dependence of chiral-even and chiral-odd components may be possible at JLab and/or COMPASS, or the future Electron-Ion Collider (EIC). The KEKB facility may allow for GPD studies of exotic hadrons [60]. The analysis method uses Generalised Distribution Amplitudes (GDAs) extracted from data takes advantage of *s*-*t* crossing to access these GPDs [73]. A first trial to extract GDAs from data was presented. The JPARC facility may offer access to GPDs through timelike processes using the exclusive Drell-Yan reaction channel with pion beams [61]. Feasibility studies were presented [74].

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