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The Jefferson Lab 12 GeV program on nucleon structure

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Summary. — This talk is intended as a brief overview of the Jefferson Lab program to study the multi-dimensional structure of the nucleon in coordinate and momentum space. The experimental program is extensive and given the available space only selected samples can be discussed.

PACS `13.40.Gp` – Electromagnetic form factors.
PACS `13.60.Fz` – Elastic and Compton scattering.
PACS `13.60.Le` – Meson production.
PACS `13.88.+e` – Polarization in interactions and scattering.

1. – Introduction

The science program at the JLab 12 GeV upgrade is very broad and encompasses four major directions: 1) exploring the multi-dimensional quark structure of the nucleon, 2) probing hadron confinement through the search for gluonic excitations, 3) studying nucleon modifications and QCD in nuclei, and 4) performing precision measurements of fundamental symmetries as a probe of physics beyond the Standard Model. A broader overview can be found in [1]. Over 70% of all approved experiments focus on the study of nucleon structure, and I am restricting this presentation on selected topics of those experiments.

While much is known about the charge and current distribution in transverse impact parameter space through elastic form factor measurements, and quark distribution functions have been determined from deep inelastic inclusive measurements, there are still challenges in reaching kinematic domains where a single quark carries much of the nucleons momentum. Other frontiers have opened up with the possibility to access the multi-dimensional quark-gluon structure as expressed through the generalized parton distributions (GPD) and the transverse momentum distributions (TMDs), which represent the 3D structure in transverse space and longitudinal momentum, and in 3D momentum space, respectively. These new avenues of research can be explored with much higher precision than has been achieved before using the 12 GeV cw beam of the JLab upgrade. Also, the high luminosity available will allow scientists to explore the regime of extreme quark momentum with precision, where a single quark carries 80% or more of the proton's total momentum. In this presentation a brief overview is given of some of the

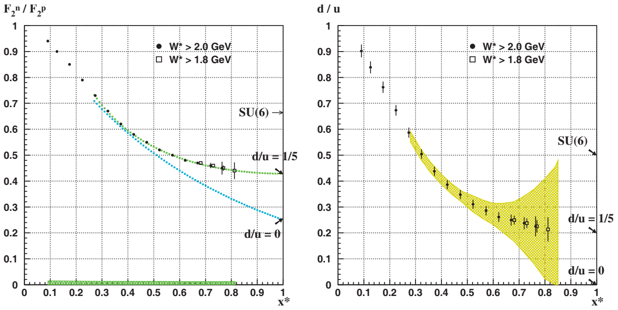

Fig. 1. – Projected CLAS12 data for the ratio F_{2n}/F_{2p} and $d(x)u(x)$ from experiment [2]. The systematic errors are given by the area near the horizontal axis. The yellow band shows the uncertainty of current data due to uncertainties in the nuclear corrections.

experimental studies planned to obtain a much improved understanding of the complex structure of the nucleon.

The JLab 12 GeV upgrade project includes the energy-doubling of the cw electron accelerator to 12 GeV, the construction of a new experimental Hall D for meson spectroscopy, and major equipment upgrades in the existing Hall B and Hall C. Hall A will keep the existing pair of high-resolution spectrometers, and will house major user driven experimental equipment, *e.g.* for experiments at the precision frontier, and to search for physics beyond the Standard Model. A major part of the experimental program on the nucleon will initially be done in Hall B with the new CLAS12 detector and with the magnetic spectrometer pair in Hall C [1].

2. – Inclusive structure functions and parton distributions

Polarized and unpolarized structure functions of the nucleon offer insights into the spin-averaged and spin-dependent parton distribution functions. One uncharted area is their behavior in the kinematic limit $x \to 1$ where contributions from the virtual sea of quark-antiquark pairs are suppressed, making this region simpler to model, and pQCD can make absolute predictions. Experimentally, the large x domain is hard to study because cross sections are kinematically suppressed. First forays into the large x domain became possible at JLab energies of up to 6 GeV [3-6]. The necessity to extend the program to larger x makes this one of the cornerstones of the JLab 12 GeV upgrade physics program. The polarized parton distribution functions have not been determined nearly as well and more precise data especially on structure function $g_1(x, Q^2)$ are needed to determine the polarized gluon density as a function of x.

2˙1. *Valence quark structure and flavor dependence at large x.* – The unpolarized structure function $F_{2p}(x)$ has been mapped out in a large range of x leading to precise knowledge of the quark distribution $u(x)$. The corresponding structure function $F_{2n}(x)$ of the neutron is well-measured only for $x < 0.5$ as nuclear corrections are not well controlled at large x. A new technique tested recently with CLAS was shown to be very effective in reducing the nuclear corrections [3]. The experiment detects the low-energy spectator proton in the reaction $en(p_s) \to ep_sX$. Measurement of p_s for momenta as low as 70 MeV/c and at large angles minimizes the nuclear corrections at large x. The techniques will be used at 12 GeV to accurately determine the ratio d/u to larger x values. Figure 1 shows the projected data for $F_2^n(x)/F_2^p(x)$ and $d(x)/u(x)$. A dramatic improvement is achieved at large x.

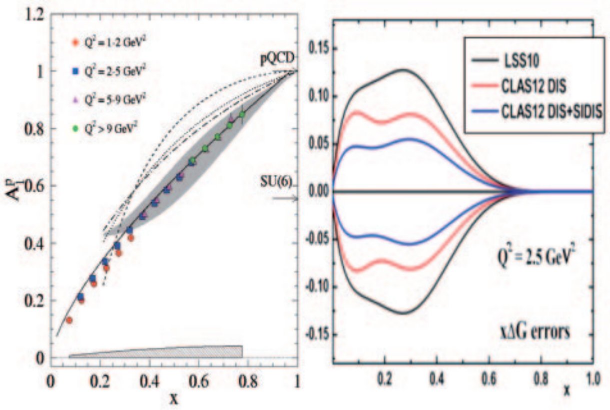

Fig. 2. – Projected results on A_1^p in DIS (left). The four different symbols in the left panel represent four different Q^2 ranges. The statistical uncertainty is given by the error bars while the systematic uncertainty is given by the shaded band. The right panel shows the improvement on $\Delta G(x)$ (red line) using A_1^p from DIS only. The blue line includes information from A_1^p with SIDIS from π^+, π^- and kaons collected in the same experiment.

2·2. *Spin structure functions and parton distributions.* – A new experiment [7] will study polarized parton distribution functions at large x. Using standard detection equipment, a redesigned longitudinally polarized target NH_3 (ND_3) target adapted to CLAS12 will allow high-precision measurements. The left panel in fig. 2 shows the expected precision for the helicity asymmetry $A_1^p(x)$.

2·3. *Global analysis of polarized parton distributions.* – The large window that will open up in the DIS domain with the 12 GeV upgrade will permit constraints of global fits to improve our knowledge of the polarized parton distributions. JLab data at lower energies had already unique impact at large x. The improvements from the 12 GeV upgrade are also significant at low and moderate x, noticeably for the polarized gluon distribution ΔG which is still much poorer defined compared to the quark spin distributions. If the Q^2 dependence of the structure function $g_1^p(x, Q^2)$ is well measured the polarized gluon distribution $\Delta G(x)$ may be extracted as can be seen from the expression

$$\Delta g_1(x,Q^2)_{pQCD} = \frac{1}{2}\sum_q^{N_f} e_q^2 \left[(\Delta q + \Delta\bar{q}) \otimes \left(1 + \frac{\alpha_s(Q^2)}{2\pi}\delta C_q\right) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G \frac{\delta C_G}{N_f}\right].$$

The right panel in fig. 2 shows the impact on the NLO analyses of the polarized gluon distribution using the evolution equation [8]. The data will not only reduce the error band on ΔG, but will likely allow a more detailed modeling of its x-dependence.

3. – Generalized parton distributions

The GPDs describe the simultaneous distribution of particles with respect to both transverse coordinate and longitudinal momentum. GPDs allow us to quantify how the orbital motion of quarks in the nucleon contributes to the nucleon spin — a question of crucial importance to our understanding of the dynamics underlying nucleon structure.

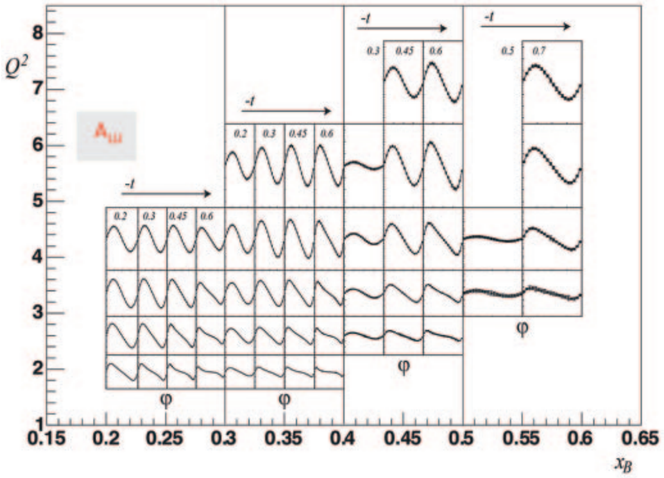

Fig. 3. – Projected data with error bars for the beam spin asymmetry A_{LU} for the DVCS-BH interference for experiment [13].

The mapping of the nucleon GPDs through deeply virtual exclusive processes such as DVCS, are key objectives of the JLab 12 GeV upgrade. Through certain moments, GPDs encode information on the angular momentum distribution of the quarks, their mass-energy distribution, and their pressure and force distribution [9]. For example, the quark angular momentum form factor $J^q(t)$ of the nucleon is given by the 2nd moment of two GPDs: $J^q(t) = \int_{-1}^{+1} \mathrm{d}x x[H^q(x,\xi,t) + E^q(x,\xi,t)]$. At JLab energies GPDs can be best accessed through measurement of cross sections and polarization asymmetries of deeply virtual Compton scattering (DVCS). For example, the beam helicity-dependent cross section is given in leading twist as $\sigma_{LU} \approx \sin\phi[F_1(t)H + \xi(F_1+F_2)\tilde{H}]d\phi$, where ϕ is the azimuthal angle between the electron scattering plane and the hadronic plane. Similar expressions with different sensitivity relate to longitudinal and transverse target polarization asymmetries.

First generation DVCS experiments carried out at JLab [10] and DESY [11] yielded promising results in terms of the applicability of the handbag mechanism to probe GPDs, and first information on GPDs $H(x_B,t)$ and $\tilde{H}(x_b,t)$ was extracted from these data [12].

The 12 GeV upgrade offers much improved possibilities for accessing GPDs, in terms of kinematic reach and precision. Figure 3 shows an example of projected data for the polarized beam asymmetry at 12 GeV upgrade. Measurements of unpolarized cross sections and of all 3 polarization asymmetries will allow for the separate determination of GPDs H, $\tilde{H}$ and E in the same kinematics. Through a Fourier transformation the t-dependence of GPD H and GPD E can be used to determine the quark distribution in transverse impact parameter space: $\rho_X(x,\vec{b}_T) = \int \frac{\mathrm{d}^2\vec{\Delta}_T}{(2\pi)^2}[H(x,0,t) - \frac{E(x,0,t)}{2M}\frac{\partial}{\partial b_y}]e^{-i\vec{\Delta}_T\vec{b}_T}$. Projected results for $\rho_X(x,\vec{b}_T)$ on a transversely polarized proton are shown in fig. 4.

4. – Transverse momentum dependent parton distributions and SIDIS

Semi-inclusive deep inelastic scattering (SIDIS), when a hadron is detected in coincidence with the scattered electron allows for "flavor tagging", and provides more direct access to contributions from different quark species. In addition, SIDIS give access to

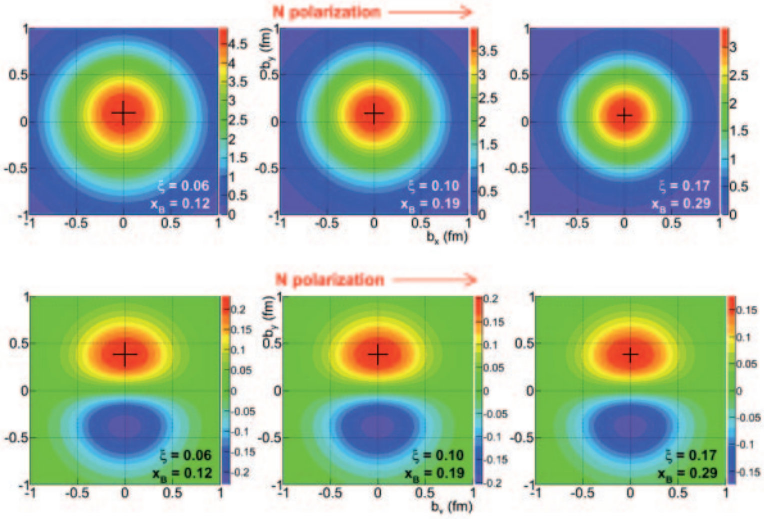

Fig. 4. – Quark densities for different x_B in a transversely polarized proton target from proposed experiment [14]. The upper row shows the shrinkage of the transverse charge densities with increasing x_B. The bottom row is the contribution of the E GPD only, and shows the emergence of a flavor dipole due to a separation of the positive and negative charge densities.

the transverse momentum distributions of quarks, that are not accessible in inclusive scattering. Azimuthal distributions of final state particles in SIDIS processes give access to the orbital motion of quarks and play an important role in the study of the nucleon TMDs. The TMDs contain structural information that is complementary to the GPDs, and encode the quark spin distributions in 3D momentum space. TMDs describe transitions of a nucleon with one polarization in the initial state to a quark with another polarization in the final state. They can be accessed through measurement of SIDIS

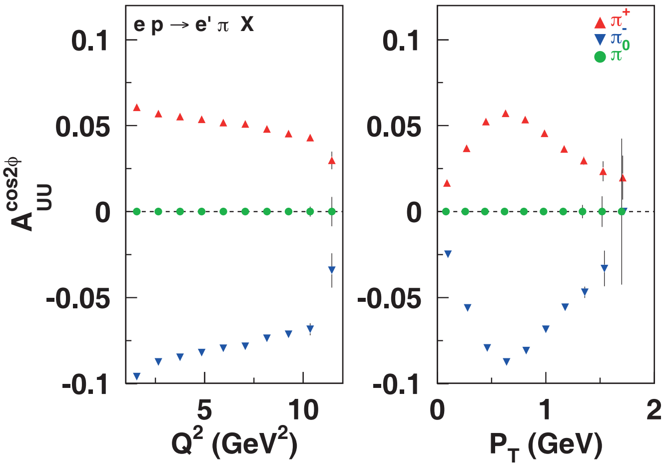

Fig. 5. – The $\cos 2\phi$ moment (Boer-Mulders asymmetry) for pions as a function of Q^2 (left) and P_T (right) with CLAS12 at 11 GeV for 2000 hours of running.

processes using unpolarized, longitudinally polarized, and transversely polarized nucleon targets. Extraction of TMDs generally requires knowledge of the quark fragmentation functions. Several of the TMDs are related to wave function overlap of $L = 0$ and $L = 1$ Fock states of the nucleon and relate to the real and imaginary parts of the corresponding interference terms. For example, the TMDs $f_{1T}^{\perp}$ and $h_1^{\perp}$ (known as the Sivers and Boer-Mulders functions), are related to the imaginary part of the interference of wave functions for different orbital momentum states, and describe unpolarized quarks in the transversely polarized nucleon and transversely polarized quarks in the unpolarized nucleon, respectively. The most simple mechanism that can lead to a Boer-Mulders function is a correlation between the spin of the quarks and their orbital angular momentum. Examples of expected uncertainties [15] for the Boer-Mulders asymmetry $A_{UU}^{\cos 2\phi}$ are presented in fig. 5.

5. – Conclusions

The JLab energy upgrade is well matched to an exciting scientific program aimed at studies of the complex nucleon structure in terms of the GPDs and TMDs. They provide fundamentally new insights in the complex multi-dimensional structure of the nucleon. In addition, the high precision afforded by the high luminosity and the large acceptance detectors, and the development of novel techniques to measure scattering off nearly free neutrons, will enable the exploration of phase space domains with extreme conditions that could not be studied before. The CLAS12 detector will play a crucial role in exciting program.

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