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Extracting Spin Dependent Parton Distributions from Deeply Virtual Scattering Processes

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Spin and transverse momentum dependent parton distributions - GPDs, TMDs and GTMDs - are at the interface between the non-perturbative regime of QCD hadron structure and observable quantities. The distributions appear as linear superpositions and convolutions within helicity amplitudes for parton-nucleon scattering processes, which, in turn, occur in amplitudes for leptoproduction processes. The phenomenological extraction of the amplitudes, and hence the distributions, is a challenging task. We will present relations between crucial quark-nucleon or gluon-nucleon helicity amplitudes, sample the rich array of angular distributions in Deeply Virtual Compton Scattering, and suggest novel Multi-hadron photon processes. These provide an important window into the spin structure of the nucleons.

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1. Introduction

The spin of the hadrons depends on the distributions of spin and orbital angular momenta (OAM) of the fundamental constituents, quarks and gluons. The quark and gluon field correlations in the nucleon are indirectly measurable through electroproduction processes. The angular momenta associated with the quark and gluon fields within QCD, are encoded in the transverse momentum distributions (TMDs) [1], the Generalized Parton Distributions (GPDs) [2] and the even more general TMDs (GTMDs) [3]. We have developed an extensive spectator model for the valence quark GPDs that we will summarize.

Of special interest among spin dependent pdf's are the nucleon's *transversity* structure functions, e.g. $h_1(x)$ - the probability of finding a definite transversity quark inside a transversely polarized nucleon. They are chiral odd, and can be observed indirectly in Semi Inclusive Deep Inelastic Scattering (SIDIS), where they are convoluted with fragmentation functions, or in the Drell-Yan process in conjunction with another chiral-odd partner. They also contribute to exclusive electroproduction processes, particularly Deeply Virtual Meson Production (DVMP), through chiral odd GPDs. The *transversity* GPDs $H_T^q(x,\xi,t)$ have the limiting form $H_T^q(x,0,0) = h_1^q(x)$. Brief mention will be made of the gluon GPDs, which can have a major role in processes measurable at lepton accelerators, the LHC and at a future Electron-Ion-Collider. New measurements that relate to GTMDs will be mentioned also.

2. Formalism

A general form of quark and gluon distributions in the nucleon is given by matrix elements of bilocal field operators, the GTMDs [3]

$$W^{[\Gamma]}_{\Lambda\Lambda'}(\bar{P},x,\vec{k}_T,\Delta,N;\eta) = \frac{1}{2}\int dk^- \frac{d^4z}{(2\pi)^4} e^{ikz}\, \langle P',\Lambda' \mid \overline{\psi}\left(-\frac{z}{2}\right)\Gamma \mathscr{W}(-\frac{z}{2},\frac{z}{2}\mid n)\psi\left(\frac{z}{2}\right) \mid P,\Lambda\rangle \tag{2.1}$$

with Γ a Dirac matrix, $\mathscr{W}$ the appropriate gauge link, $\bar{P} = (P+P')/2$, $\Delta = P'-P$ and $N = M^2 n/\bar{P}\cdot n$, with n the usual light-like vector, and $\eta = \mathrm{sign}\,(n_0)$ (see [3] for details). The integration over k^- places the matrix element at $z^+ = 0$ on the light cone. These GTMDs have both the nucleon momentum transfer Δ and the outgoing parton momentum k as variables. As such, they are “unintegrated" parton distributions. Geometrically, the orientation of the partons requires the specification of two planes: the k_T plane formed by $\vec{k}_T$, $\bar{P}_3$; the Δ plane formed by the $\vec{\Delta}_T$, $\bar{P}_3$

The TMDs are obtained by setting $\Delta = 0$ in Eq. 2.1, leaving k_T plane,

$$\Phi^{[\Gamma]}_{\Lambda\Lambda'}(\bar{P},x,\vec{k}_T,N;\eta) = W^{[\Gamma]}_{\Lambda\Lambda'}(\bar{P},x,\vec{k}_T,\Delta=0,N;\eta), \tag{2.2}$$

while the GPDs are obtained by integrating Eq. 2.1 over all k, leaving Δ plane,

$$\begin{aligned} F^{[\Gamma]}_{\Lambda',\Lambda}(\bar{P},x,\Delta,N) &= \int d^2\vec{k}_T W^{[\Gamma]}_{\Lambda\Lambda'}(\bar{P},x,\vec{k}_T,\Delta,N;\eta) \\ &= \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ix\overline{P}^+z^-}\, \langle P',\Lambda' \mid \overline{\psi}\left(-\frac{z}{2}\right)\Gamma\,\psi\left(\frac{z}{2}\right) \mid P,\Lambda\rangle\Big|_{z^+=0,\mathbf{z}_T=0}, \end{aligned} \tag{2.3}$$

The quark GPDs are defined (at leading twist) as the matrix elements of the projections of the unintegrated quark-quark proton correlator (see Ref.[4] for a detailed overview), where $\Gamma =$

$\gamma^+, \gamma^+\gamma_5, i\sigma^{i+}\gamma_5 (i=1,2)$, and the target's spins are Λ, Λ'. The spin structures of GPDs that are directly related to spin dependent observables are most effectively expressed in term of helicity dependent amplitudes, developed extensively for the covariant description of two body scattering processes (see also Ref.[4]). For the GPDs, decomposing the quark fields into definite helicities, λ, λ', produces a form analogous to 2-body helicity amplitudes, $A_{\Lambda'\lambda',\Lambda\lambda}(X,\zeta,t)$ [4].

There are four chiral-even quark GPDs, $H, E, \widetilde{H}, \widetilde{E}$ [5] and four additional chiral-odd GPDs, at leading twist 2, that flip quark helicity by one unit, $H_T, E_T, \widetilde{H}_T, \widetilde{E}_T$ [4, 6]. There are two questions to address: How to model the 8 GPDs? How to measure them?

3. Flexible Model

The basis of our model of parton distributions is the connection to observables through the "handbag" approximation. The various distributions are then related to quark or gluon plus nucleon scattering-type amplitudes. We model these via nucleon transitions into quark (or gluon) and a spectator (or light front wave functions or lowest Fock states). The quark-proton scattering amplitudes at leading order are convolutions of proton-quark-diquark vertices. The quark proton helicity amplitudes describe a two body process, $q'(k')P \to X \to q(k)P'$, where $q(k)$ corresponds to the "struck quark". The intermediate diquark system, X, can have $J^P = 0^+$ (scalar), or $J^P = 1^+$ (axial vector). The amplitudes for the Scalar diquark are (see [7, 8] for the full set of relations):

$$A^{(0)}_{\Lambda'\lambda',\Lambda\lambda} = \int d^2k_\perp \phi^*_{\Lambda'\lambda'}(k',P')\phi_{\Lambda\lambda}(k,P). \tag{3.1}$$

Next we consider "Reggeization", that is, we extend the diquark model formalism to low X by allowing the spectator system's mass to vary up to very large values. This is accomplished by convoluting the GPD structures obtained in Eqs.(3.1) with a "spectral function", $\rho(M_X^2)$, where M_X^2 is the spectator's mass,

$$F_T^q(X,\zeta,t) = \mathcal{N}_q \int_0^\infty dM_X^2 \rho(M_X^2) F_T^{(m_q,M_\Lambda^q)}(X,\zeta,t;M_X) \approx R_{p_q}^{\alpha_q,\alpha_q'}(X,\zeta,t)\, G_{M_X,m}^{M_\Lambda}(X,\zeta,t) \tag{3.2}$$

The spectral function was constructed in Refs.[8, 9] so that it approximately behaves as $(M_X^2)^\alpha$ for $M_X^2 \to \infty$ and $\delta(M_X^2 - \overline{M}_X^2)$ for M_X^2 at a few GeV^2, where $0 < \alpha < 1$, and $\overline{M}_X$ is in the GeV range, with $\alpha_q'(X) = \alpha_q'(1-X)^{p_q}$. The functions $G_{M_X,m_q}^{M_\Lambda^q}$ and $R_{p_q}^{\alpha_q,\alpha_q'}$ are the quark-diquark and Regge contributions, respectively. The chiral even GPDs integrate to the nucleon form factors, which constrains the GPD t-dependence,

$$\int_0^1 H^q(X,\zeta,t) = F_1^q(t), \int_0^1 E^q(X,\zeta,t) = F_2^q(t), \int_0^1 \widetilde{H}^q(X,\zeta,t) = G_A^q(t), \int_0^1 \widetilde{E}^q(X,\zeta,t) = G_P^q(t). \tag{3.3}$$

where $F_1^q(t)$ and $F_2^q(t)$ are the Dirac and Pauli form factors for the quark q components in the nucleon. $G_A^q(t)$ and $G_P^q(t)$ are the axial and pseudoscalar form factors. Furthermore, $H(x,0,0) = h_1(x)$ and $\widetilde{H}(x,0,0) = g_1(x)$. With these constraints, the quark GPDs that fit DVCS results are shown in Fig. 1.

Our model for evaluating the chiral-odd GPDs extends the Reggeized diquark model for chiral-even GPDs, to the chiral-odd sector, using parity relations for the vertices in Eq. 3.1. We will

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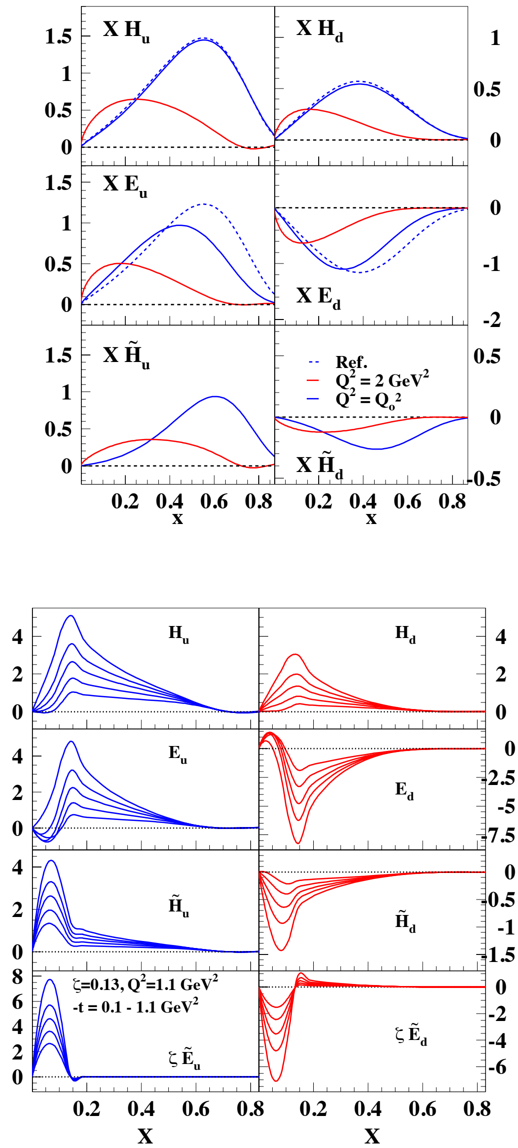

Figure 1: Upper (a): Chiral even u and d-quark GPDs at the initial scale and $Q^2 = 2\text{GeV}^2$ Lower (b): Chiral even u and d GPDs for a range of t values. Adapted from Ref. [8].

show the successful phenomenology for π^0 electroproduction that follows, below. For the gluon GPDs, the model is generalized from the spectator picture for quark GPDs [10]. The nucleon decomposes into a gluon and a color octet baryon, so that the overall color is a singlet. The color octet baryon contains components that have the same flavor as the nucleon, are Fermionic (with color⊗flavor⊗spin being antisymmetric under quark label exchanges), and include spin 1/2, which we select for simplicity. This provides sufficient parameterization to fit the $H_g(x,0,0)$ to the pdf g(x). Evolving with Q^2 also requires a sea quark contribution, which we take in a spectator picture with $N \rightarrow \bar{u} \oplus (uuud)$ or $\bar{d} \oplus (uudd)$. [10].

4. Observables and data

DVCS accesses Chiral Even GPDs through various cross sections and asymmetries. The GPDs, or their corresponding Compton Form Factors, enter linearly via Bethe-Heitler $\otimes$ DVCS interference. DVπ^0S accesses 2 Chiral Even + 4 Chiral Odd GPDs that enter bilinearly via $d\sigma/d\Omega$ & polarization asymmetries. The result of experimental observations that $d\sigma_T > d\sigma_L$ is that the chiral odd GPDs dominate.

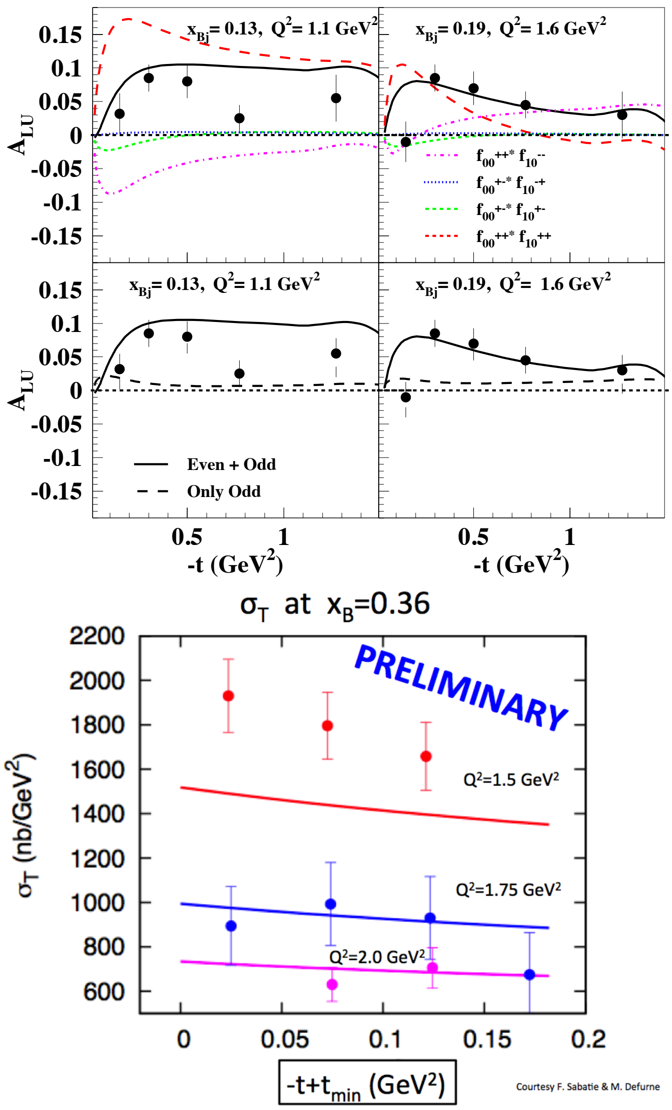

Figure 2: Upper (a): Beam spin asymmetry, A_{LU}, plotted vs. $-t$ for two different kinematics. Experimental data from Ref.[12]. Adapted from Ref. [11]. Lower (b): Transverse differential cross section vs. $(-t + t_{min})$ for $Q^2 = 1.5, 1.75, 2.0$ GeV^2 at $x_{Bj} = 0.36$. Preliminary data from Hall A, courtesy F. Sabatie & M. Defurne [13].

In Ref.[7], after showing how DVπ^0P can be described in terms of chiral-odd GPDs, we estimated all of their contributions to the various observables with particular attention to the ones which were sensitive to the values of the tensor charge. The connection of the correlator, Eq.(2.3), with the helicity amplitudes for π^0 electroproduction proceeds by introducing a factorized form [7, 11],

$$f^{\Lambda\Lambda'}_{\Lambda_\gamma 0}(\zeta,t) = \sum_{\lambda,\lambda'} g^{\lambda\lambda'}_{\Lambda_\gamma 0}(X,\zeta,t,Q^2) \otimes A_{\Lambda'\lambda',\Lambda\lambda}(X,\zeta,t), \tag{4.1}$$

where the helicities of the virtual photon and the initial proton are, Λ_γ, Λ, and the helicities of the produced pion and final proton are 0, and Λ', respectively. This describes a factorization into a "hard part", $g^{\lambda\lambda'}_{\Lambda_\gamma 0}$ for the partonic subprocess $\gamma^* + q \to \pi^0 + q$, and a "soft part" given by the quark-proton helicity amplitudes, $A_{\Lambda',\lambda';\Lambda,\lambda}$ that contain the GPDs. The expressions for the chiral-odd helicity amplitudes in terms of GPDs [4] are of the form

$$A_{++,--} = \sqrt{1-\xi^2}\left[H_T + \frac{t_0 - t}{4M^2}\widetilde{H}_T - \frac{\xi^2}{1-\xi^2}E_T + \frac{\xi}{1-\xi^2}\widetilde{E}_T\right], \ldots \tag{4.2}$$

where we use the symmetric notation for the kinematic variables. Analogous forms have been written for the chiral even and odd sectors [4].

The fitting procedure of GPDs is quite complicated owing to its many different steps. A more detailed description of the other transversity functions including the first moment of $h_1^\perp \equiv 2\widetilde{H}_T^q + E_T^q$ is given in [11]. In Fig.2 we show a small sampling of results. The various GPDs enter the helicity amplitudes and those, in turn, determine all the cross section terms for π^0 electroproduction. The transverse and longitudinal cross sections have been separated experimentally at small t [13]. Some preliminary data compare favorably with our predictions in Fig 2(b).

5. Observing GTMDs

We introduced the GTMDs above, without reproducing the extensive decompositions into many structure functions [3]. Since these functions appear like unintegrated parton + nucleon amplitudes, with both k_T and Δ_T, we ask whether or not the GTMDs can be accessed experimentally. We briefly note here that processes that have 3 irreducible planes, like exclusive electroproduction of $\gamma + \pi^+ + \pi^- + N$, are candidates for indirect measurements of interesting GTMDs, particularly F_{14}, connected to orbital angular momentum [14].

6. Conclusions & Outlook

Among all the distributions that can be accessed with our "flexible spectator" model, we focused particularly on the transversity parton distributions in the nucleon that can be accessed through deeply virtual exclusive π^0 meson production. We addressed the feasibility of experimental extraction. This represents a consistent quantitative step with respect to our previous work [7]. In particular, H_T and the combination $2\widetilde{H}_T + E_T$, now are separated. A similar simplified approach was taken also in Ref.[15] - we differ in the importance attached to the skewedness dependence of $E_T, \tilde{E}_T$.

We see the results of our extended approach for some of the many measured and measurable observables. What is especially gratifying is that certain asymmetries constrain the GPDs well enough to separately determine H_T, and consequently transversity through the limit $H_T(x,0,0)$, and the combination $2\widetilde{H}_T + (1 \pm \xi)E_T$.

We sketched the extension of the model to the gluon distributions and suggested an experimental means to indirectly measure some GTMDs.

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