PAC38 Update E12-06-108
"Hard Exclusive Electroproduction of π^0 and η with CLAS12"

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Experiment E12-06-108 will be run contemporaneously with DVCS experiment E12-06-119. The running condition will utilize the maximum beam energy and luminosity for CLAS12, $E_e = 11$ GeV and $L = 1 \times 10^{35}$ cm^2 s^{-1}. Additional beam time was also requested and awarded at 8 GeV to enable a $\sigma_L - \sigma_T$ separation. The experimental conditions have not changed since that time. However, there has been considerable new data obtained at JLab and other laboratories, which has stimulated important advances in theoretical interpretation of the new data, and which add a great deal of motivation for this experiment. These theoretical ideas and their connection to experiment E12-06-108 will be reviewed in this update.

Introduction

The understanding of exclusive meson production at high momentum transfers and its potential for the study of short–range nucleon structure have evolved substantially over the last few years. There is a lively interplay of theory and experiment, with connections to elastic form factors, color transparency, chiral dynamics, and other fields of study. Recent theoretical work suggests that a quantitative QCD–based description of hard exclusive meson production may be possible even in situations where non–perturbative interactions play an essential role, as is expected in JLab kinematics. The growing interest in meson production in the larger scientific community is evidenced by the numerous related contributions to topical workshops and conferences [1]. In the following we briefly summarize the main developments.

Recent JLab experimental results and their impact on physics.

Recent experimental data on pseudoscalar (π^0, η) and vector meson $(\rho^0, \rho^+, \omega, \phi)$ channels at $Q^2 \sim$ few GeV^2 from JLab 6 GeV and other facilities provide crucial tests of the production mechanism and have given fresh impetus to theoretical and phenomenological studies of such processes. Some of these measurements have challenged conventional theoretical assumptions about the production mechanism, demonstrating the impact of precise data and the potential for discovery in this field.

Consider π^0 and η electroproduction data at high Q^2 where there have been new measurements of π^0 and η electroproduction with CLAS [3, 4], over an extensive kinematic range. Cross sections were obtained for more that 1600 kinematic values in x_B, Q^2 and t. These provide much information on the exclusive production of neutral pseudoscalars in the deep–inelastic domain. An example of structure functions recent CLAS data and coverage is shown in Fig. 1.

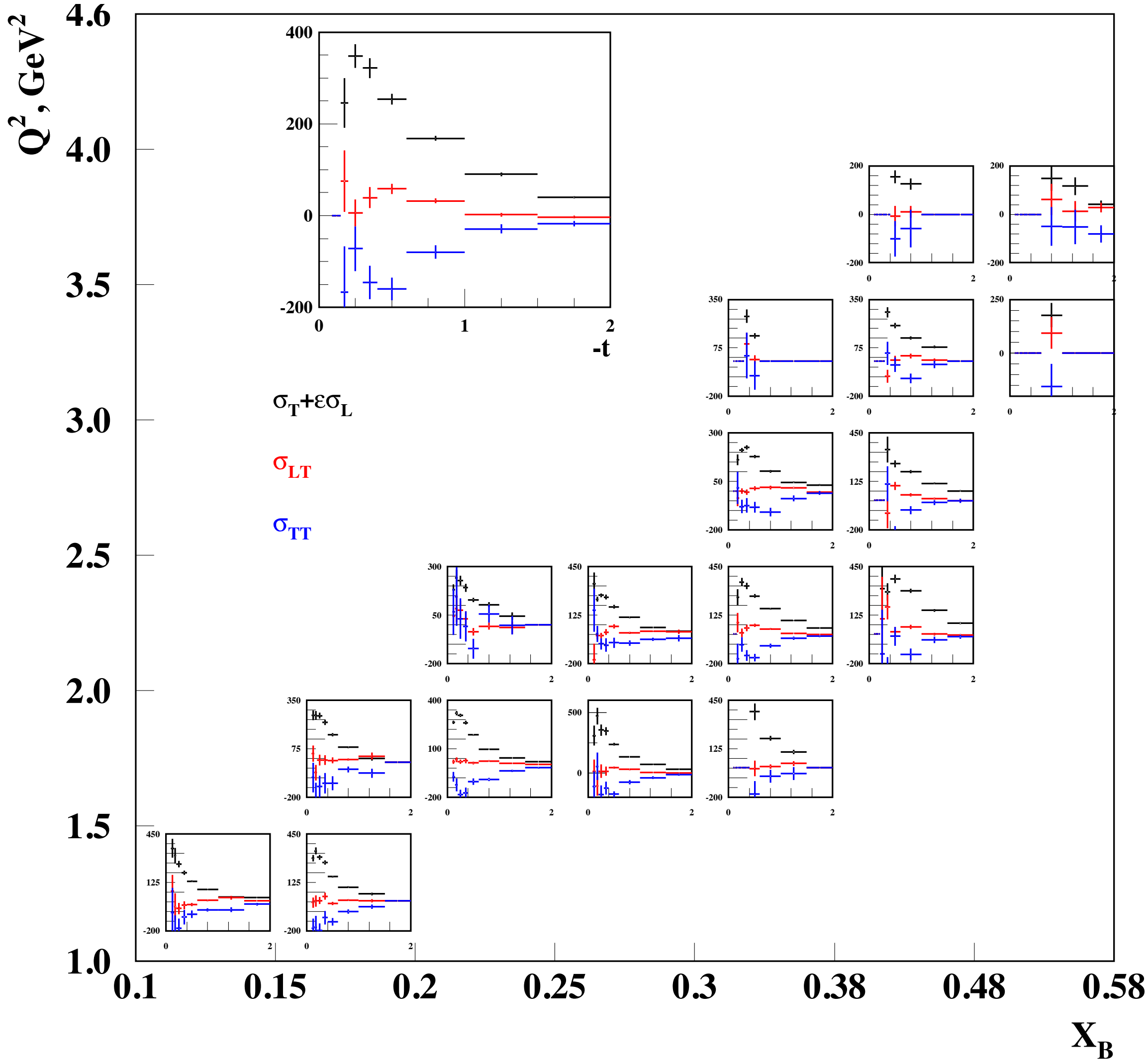

Figure 1: Exclusive π^0 electroproduction structure functions obtained from recent CLAS cross section data

A recent Hall A experiment [2] was performed of π^0 electroproduction at low $-t$. The two experiments are consistent in the region of common coverage. The extensive coverage of the CLAS data has put significant constraints on theory. They show a slower Q^2–dependence of the cross section than the pQCD scaling behavior, indicating that non–perturbative interactions play an important role. The average t–slopes of the cross section, determined by fits over a wide range $|t| < 2\,\mathrm{GeV}^2$, (see Fig. 2) were found to decrease as a function of Q^2 , similar to observations ρ^0 production, and to decrease with x_B in agreement with general expectations; the interpretation of these trends is limited by the strong correlation between Q^2 and x_B at 6 GeV and will become more meaningful with 12 GeV. The new extensive data has stimulated significant new physics, as described below.

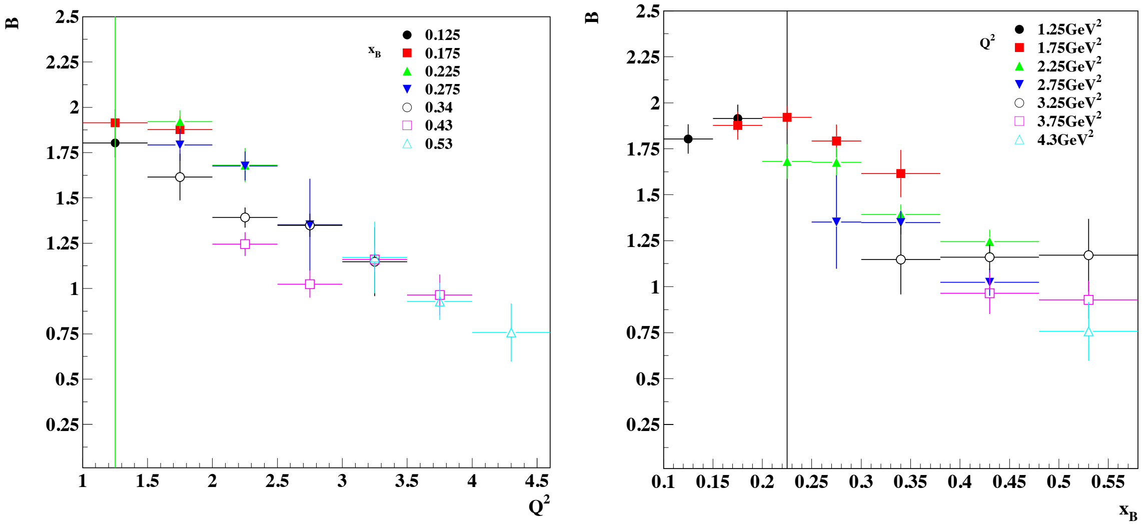

Figure 2: Left: t slope parameter B, in GeV^{-2} as a function of Q^2 for different b_B and Right x_B for different values of Q^2 from CLAS 6 data in exclusive π^0 electroproduction.

Progress with GPD–based description of pseudoscalar electroproduction.

While DVCS is regarded as the most promising exclusive channel for constraining the nucleon GPDs in leading order, DVMP has evolved into a dynamic field giving access to higher twist mechanisms, which are especially accessible at JLab 6 and JLab 12 energies. In particular, the CLAS 6 data has stimulated recent work involving the twist-3 mechanisms and their connection with transversity GPDs which are connected to transverse phenomena such as $k_\perp$ and orbital angular momentum (OAM).

Theoretical calculations based on GPDs found that the leading–twist chirally–even structures in the amplitude do not account for the experimental cross section, even with finite–size corrections through Sudakov form factors [5]. The early efforts to explain π^0, η electroproduction focused on the chiral even (no helicity flip) GPDs, $\widetilde{H}, \widetilde{E}$, as a means to parametrize only the *longitudinal* virtual photon amplitudes [7]. However, in general, there are 8 spin-dependent quark-nucleon GPDs, 4 chiral even J^{PC} 1^{--} and 4 chiral odd J^{PC} 1^{+-} [8], and as noted [9] (GL), the quantum numbers and Dirac structure of π^0 electroproduction restrict the possible contributions to the 4 *chiral odd* GPDs, one of which, H_T, is related to the transversity distribution and the tensor charge.

During the past few years, two parallel approaches - [9] [11] (GL) and [5] (GK) have been developed utilizing chiral odd GPDs in the calculation of pseudoscalar electroproduction. The GL and GK approaches, though differing in detail, leads to sizable *transverse* photon amplitudes, as evidenced in the CLAS 6 data. Both these approaches are evolving as new CLAS data appear. Both GL and GK have prepared for this update brief summaries of their approaches. These are appended at the end of this document.

These results have interesting consequences. In a factorized handbag picture, the chiral odd GPDs will couple to the hard part, $\gamma^* + q \to \pi^0 + q$, providing the π^0 couples through γ^5, which is naively twist 3, rather than the twist 2 $\gamma^+\gamma^5$. In the model of Ref. [9] crossing symmetry and duality are used to connect the hard subprocess amplitude with the $\gamma^*(q\bar{q}) \to \pi^0$ vertex. This introduces OAM into the vertex structure. In the transition to the vector mesons ($J^{PC} = 1^{--}$),

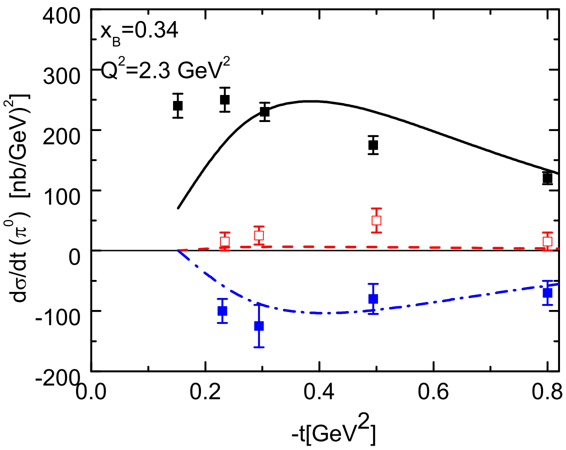

Figure 3: Differential cross section of π^0 electroproduction as a function of $|t|$, in a single x_B and Q^2 bin. Black points: $\sigma_U \equiv \sigma_T + \epsilon\sigma_L$. Red points: σ_{LT}. Blue points: σ_{TT}. The curves show result of the GPD model based on Ref. [5].

and the π^0, ($J^{PC} = 0^{-+}$), the quark-antiquark pair carries OAM $L = 0$, both in the initial and final state ($\Delta L = 0$). The transition between the axial-vector mesons $J^{PC} = 1^{+-}$, and the π^0, is instead characterized by a change of OAM ($\Delta L = 1$). This transition corresponds to larger spatial partonic configurations, and is therefore suppressed of $\mathcal{O}(1/Q^2)$. Since chiral odd GPDs are much more loosely constrained by experiments – the most "robust" constraint is provided by transversity – $H_T(x, 0, 0) = h_1(x)$ – a very important result of Ref. [10] is that using helicity amplitudes the *chiral odd GPDs are directly related to the chiral even GPDs*, thus providing the otherwise missing normalizations for the latter.

Inclusion of the chirally–odd twist–3 components of the hard exclusive amplitude gives results in fair agreement with the measured cross section for both the GL [11]and GK [5] approaches, respectively shown in Figs. 3 and 4.

GK [12] estimate the ratio of σ_η/σ_π^0 electroproduction employing the new transversity GPD, and compared with the CLAS6 data in Fig. 5. At very small t they obtain a ratio of approximately 1, in accord with with the original GPD approach of Ref. [13]. However at larger t where $\bar{E}_T$ ($\bar{E}_T = 2\widetilde{H}_T + E_T$) dominates the ratio becomes 1/3. This is interpreted by GK as an indication of the dominance of $\bar{E}_T$ in π^0 electroproduction. However, the preliminary data appears to rise above the theoretical value at larger t, indicating the possible the necessity of inclusion of additional physics. We would like to investigate this phenomena at larger t with CLAS12.

It is interesting how this evolution will manifest itself as an evolution of the $R = \sigma_L/\sigma_T$ ratio. Both GK and GL find that at lower Q^2 the strong impact of the transversity GPDs results in the cross section being dominated by transverse photons. In the proposal leading to experiment E12-06-108, we included time at 8 GeV beam energy to perform a Rosenbluth separation in order to extract σ_L for which the GPD factorization was theoretically shown ([13]) to be valid. However, at this point it becomes apparent that it is crucially important to obtain σ_L and σ_T, as well as the interference structure functions σ_{TT}, σ_{LT} and $\sigma_{L'T}$, which were all shown by the CLAS 6 data to be important.

Such chirally odd structures are expected to arise due to the spontaneous breaking of chiral symmetry in the QCD vacuum. More direct evidence for these structures in the amplitude comes

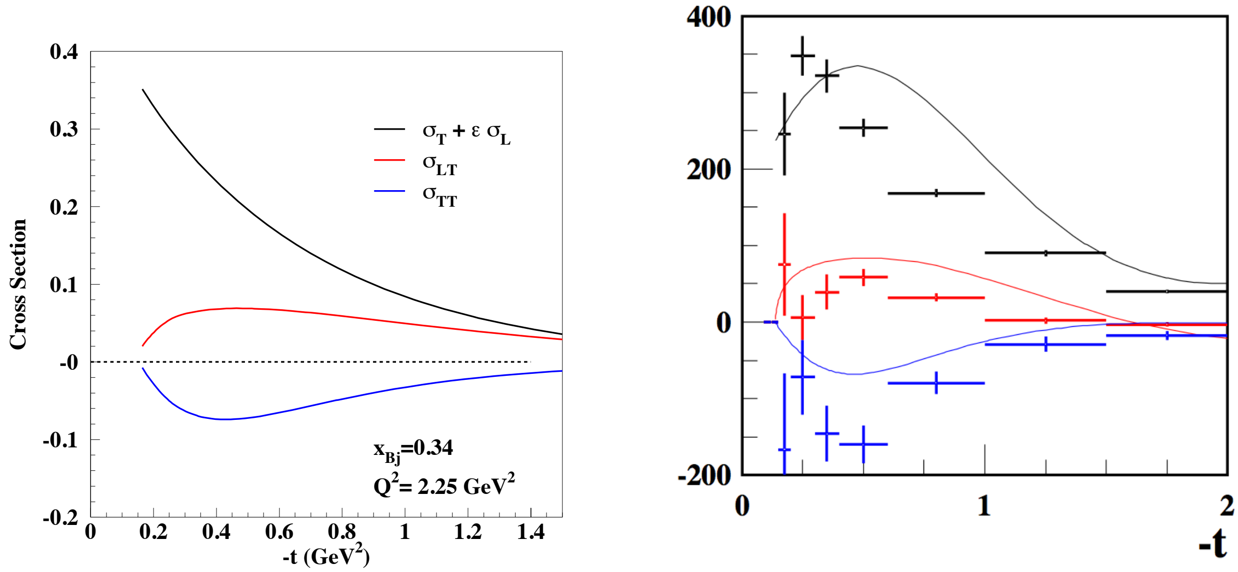

Figure 4: Left: GL prediction for π^0 cross sections [9, 10] vs. $-t$. Right: Hall B data. The curves are due to a Regge based calculation [6]Here, $Q^2 = 2.25$ GeV^2, and $x_{Bj} = 0.34$.

from the measured t–dependence of the cross sections, as well as from the η/π^0 ratio, which is in good agreement with the theoretical prediction. These findings represent a major advance in the phenomenology of exclusive pseudoscalar meson production and open up the prospect of a quantitative GPD–based description of such processes at 12 GeV. A more phenomenological description of pseudoscalar meson production, based on a combination of t–channel exchanges and s–channel resonances constrained by Bloom–Gilman duality, was developed in Refs. [14], and describes well the existing π^+ and π^0 data; this model can be used to make accurate projections for the expected 12 GeV data.

$\gamma^*\gamma \to \pi^0$ as a challenge for perturbative QCD.

The BABAR measurement [15] of the $\gamma - \pi^0$ transition form factor in e^+e^- annihilation has caused considerable excitement in the QCD community. The data show that $Q^2 F_\pi(Q^2)$ keeps rising for momentum transfers as large as $30\,\mathrm{GeV}^2$, showing no sign of the scaling behavior $Q^2 F_\pi(Q^2) \to$ const expected from leading–twist QCD factorization. Several explanations of this surprizing observation have been proposed in the literature, including a non–standard shape of the pion distribution amplitude [16], the axial anomaly of QCD [17], instanton effects [18], or higher–twist effects within the conventional modified hard–scattering approach [19]. Even more interesting, recent measurements of the η and η' transition form factor [20] shows the conventional QCD scaling behavior. One possible explanation may be that the π^0 wave function has an anomalous quasi–pointlike component related to the spontaneous breaking of chiral symmetry in the QCD vacuum. These developments have greatly increased interest in π^0 and η electroproduction throughout the QCD community and provide additional motivation for measuring high–Q^2 production on the proton. The results of the quoted theoretical studies of the pion wave function and finite–size effects in hard electroproduction will directly benefit the analysis of the nucleon data.

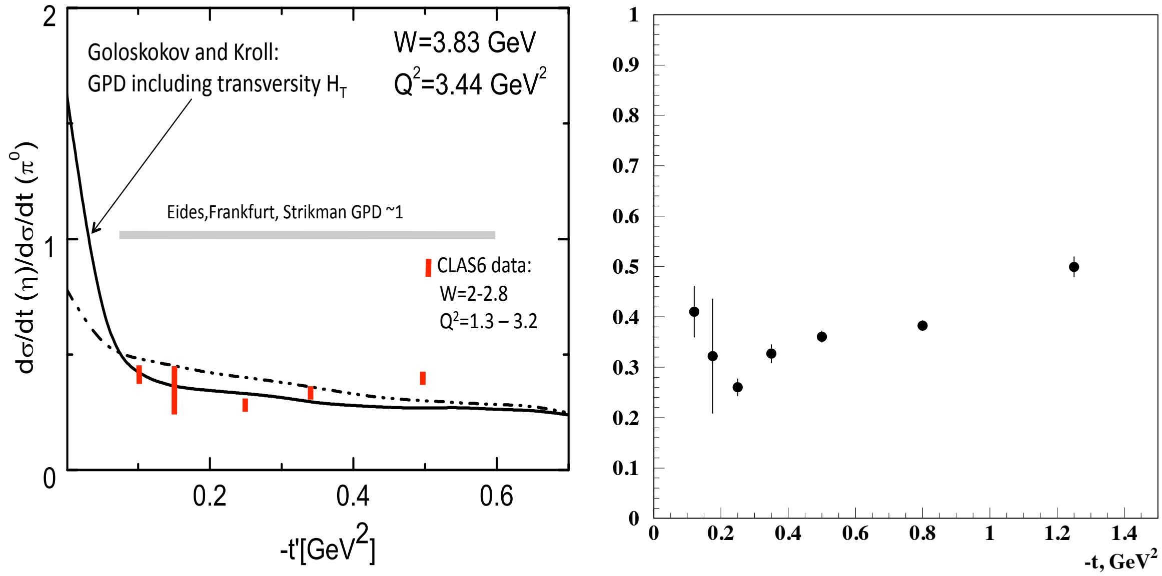

Figure 5: Left: The ratio σ_η/σ_π^0. The solid curve is due to the calculation of GK [12] and the red bars are obtained from preliminary CLAS data [3]. Right: The CLAS data over the full range of t. The ratio appears to rise relative to the calculation.

Pseudoscalar vs. vector meson production at low W.

CLAS recently completed a measurement of several vector meson electroproduction channels $(\rho^0, \rho^+, \omega, \phi)$ at 6 GeV [21]. These data permit the first detailed comparisons between the different channels in the same kinematic range and have greatly enhanced our understanding of the reaction mechanism. The ρ^0 cross section at $W \sim 2-4$ GeV drops with increasing W, in striking contrast to present GPD models. Comparison between the ρ^0 and ρ^+ (which shows the same drop with energy) shows that this behavior is due to quark exchange processes that are not included in the present GPD–based description; see Ref. [22] for a model study. The same processes should be at work in pseudoscalar production, where quark exchange is required by quantum numbers. This calls for a comparative study of pseudoscalar and vector meson electroproduction at $W \sim$ few GeV, as envisaged in the present proposal. We also note that ϕ electroproduction, which is known to be dominated by gluon exchange even in JLab kinematics, is well reproduced by a GPD–based calculation including finite–size effects [23]. This again shows the potential of the GPD approach to describe meson production cross sections once the relevant structures have been identified.

GPDs in high–t processes..

A unique feature of the present proposal is the ability to measure meson production at high t as well as high Q^2. Recent theoretical work [24] developed a partonic description of high–t 2–to–2 scattering processes in hadron–hadron and photon–hadron scattering, which may serve as a framework for interpreting the high–t measurements planned in the present experiment. The possibility to vary Q^2 in addition to t provides an independent test of the assumption that high–t processes are dominated by small–size configurations in the participating hadrons, something that is not feasible with real photon– or hadron–induced reactions.

Conclusion.

The new CLAS data have already stimulated a lot of activity in the theoretical community. A breakthrough has been the realization that there is a strong connection between exclusive pseudeoscalar electroproduction and the transverse structure of the nucleon via twist-3 chiral-helicity flip odd GPDs, which are related to the transverse structure, of the nucleon including OAM. This subject comprises one of the main directions of experimental and theoretical research in nuclear physics. Separation of the $\sigma_L, \sigma_T, \sigma_{LT}, \sigma_{TT}, and \sigma_{L'T}$ via unpolarized differential cross section, polarized beam spin asymmetry, and L-T separations through significantly larger values of $t, Q^2 and x_B$ is important. This promises to give new insights into the evolution from hard to soft phenomena reaction mechanisms and the longitudinal and transverse structure of the nucleon through the evolution of chiral-odd and chiral-even GPDs.

Appendix-1

The Goldstein-Liuti Approach to Pseudoscalar Exclusive Electroproduction

Prepared by G. Goldstein and S. Luiti

In general, there are 8 spin-dependent quark-nucleon GPDs, 4 chiral even and 4 chiral odd [8]. The early efforts to explain π^0, η electroproduction focused on the chiral even $\widetilde{H}, \widetilde{E}$ as a means to parametrize only the *longitudinal* virtual photon amplitudes [7]. However, in the approach of Goldstein, Liuti and collaborators [9] (GL), the quantum numbers and Dirac structure of π^0 electroproduction restrict the possible contributions to the 4 *chiral odd* GPDs, one of which, H_T, is related to the transversity distribution and the tensor charge. The GL approach leads to sizable *transverse* photon amplitudes, as indicated in early Hall B data. The reasoning involves the t-channel perspective in which the leading contributions to π^0 will have J^{PC} 1^{--} and 1^{+-}, *i.e.* C-parity odd, Parity odd or even. The transverse photon receives contributions from both, while longitudinal photons couple primarily to the axial vector components. To see the implications of these observations for the GPDs entering π^o exclusive electroproduction, we use the helicity amplitude formalism. By working out the connection between the t-channel and the s-channel J^{PC} quantum numbers one can see the relevance of the chiral odd GPDs.

These results have interesting consequences. In a factorized handbag picture, the chiral odd GPDs will couple to the hard part, $\gamma^* + \text{quark} \to \pi^0 + \text{quark}$, providing the π^0 couples through γ^5, which is naively twist 3, rather than the twist 2 $\gamma^+\gamma^5$. Nevertheless, the previous arguments support this choice. In [9] a new model was proposed, using crossing symmetry and duality, which connected the hard subprocess amplitude with the $\gamma^*(q\bar{q}) \to \pi^o$ vertex. This introduces OAM in the vertex structure. In the transition between the vector mesons $J^{PC} = 1^{--}$, and the π^o, $J^{PC} = 0^{-+}$, the quark-antiquark pair carries OAM $L = 0$, both in the initial and final state ($\Delta L = 0$). The transition between the axial-vector mesons $J^{PC} = 1^{+-}$, and the π^o, is instead characterized by a change of OAM ($\Delta L = 1$). This transition corresponds to larger spatial partonic configurations, and is therefore suppressed of $\mathcal{O}(1/Q^2)$. Summarizing, the distinction between the J^{PC} quantum numbers in the t-channel allows also for a more flexible model of the Q^2 and x_B dependence of deeply virtual exclusive processes.

New predictions were more recently obtained (see Fig.4) by extending the physically motivated parametrization for the GPDs of Refs.[11, 25] to the chiral-odd sector. This parametrization uses the quark-diquark model, and it has Regge behavior at small x. The GPD model parameters are constrained by data on PDFs (at $\zeta = 0, t = 0$), $H^q(X, 0, 0) = f_1^q(X)$, $\tilde{H}^q(X, 0, 0) = g_1^q(X)$, $H_T^q(X, 0, 0) = h_1^q(X)$ on nucleon form factors $F_1(t)$, $F_2(t)$, $g_A(t)$, $g_P(t)$, and by recent DVCS measurements [2] [3]. Since chiral odd GPDs are much more loosely constrained by experiments –

the most "robust" constraint is provided by transversity – $H_T(x,0,0) = h_1(x)$ – a very important result of the new GL reggeized diquark approach [10] is that using helicity amplitudes the *chiral odd GPDs are directly related to the chiral even GPDs*, thus providing the otherwise missing normalizations for the latter. As a result, with the GL *ansatz* all observables can be determined (in parallel with corresponding Regge predictions), extending the initial work [9] with far more extensive parameterization, and several new predictions [11, 10]. (Recently a similar emphasis on chiral odd contributions for π electroproduction has been proposed [5], although the details of that model are quite different.) An example of the GL cross sections at one set of measured kinematics are displayed in Fig. 4.

Appendix-2

Goloskokov-Kroll Electroproduction of pseudoscalar mesons

Prepared by P. Kroll

Electroproduction of pseudoscalar mesons may behave differently from the usual expectation that the contributions from longitudinally polarized photons dominate. That there are substantial contributions from transversally polarized photons is in particularly obvious from the $\sin\phi_s$ - moment, $A_{UT}^{\sin\phi_s}$, of the π^+ cross section measured with a transversally polarized target by the HERMES collaboration [26] (ϕ_s specifies the orientation of the target spin vector with respect to the lepton plane). As it is argued in Ref. [5] the contributions from transversally polarized photons can be calculated within the handbag approach as a twist-3 effect consisting of a twist-3 pion wave function and the leading–twist transversity GPD H_T. The twist–3 effect is strongly enhanced by the chiral condensate for pseudoscalar mesons. With this contribution which feeds the leading helicity non–flip amplitude $M_{0-,++}$ the peculiar features of $A_{UT}^{\sin\phi_S}$ can be described.

Another hint that transversity GPDs may be important comes from lattice QCD. In a recent study [27] large moments of the combination $\bar{E}_T = 2\widetilde{H}_T + E_T$ have been found. Interestingly, the u and d quarks moments have the same sign in contrast to the moments of $\widetilde{H}$ and H_T. The lattice QCD findings are corroborated by large N_C considerations [28] and by a number of models.

In Ref. [12] the role of the transversity GPDs, H_T and $\bar{E}_T$, in electroproduction of pseudoscalar mesons has been examined and a strong increase of the π^0 and η cross sections found. The GPD $\bar{E}_T$ generates a strong helicity flip amplitude, $M_{0+,\pm+}$, for transversally polarized photons. This amplitude dominates the cross sections for π^0 and η production except in the near forward region where contributions from H_T and $\widetilde{H}$ dominate. A signal for the dominance of $\bar{E}_T$ would be a dip in the forward π^0 cross section. Due to the relative sign of $\bar{E}_T$ for u and d quarks the ratio of the η and π^0 cross sections is smaller than 1, in fact about 1/3, except in the near forward region where H_T and $\widetilde{H}$ dominate. Since their u and d quark contributions have opposite signs the η/π^0 ratio is expected to be about 1 in that region.

The dominance of the transversity GPDs in π^0 electroproduction has also beed advocated for in Ref. [9].

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