

Deeply pseudoscalar meson electroproduction with CLAS and Generalized Parton Distributions

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We discuss the recent data of exclusive π^0 (and π^+) electroproduction on the proton obtained by the CLAS collaboration at Jefferson Lab. It is observed that the cross sections, which have been decomposed in $\sigma_T + \epsilon\sigma_L$, σ_{TT} and σ_{LT} structure functions, are dominated by transverse amplitude contributions. The data can be interpreted in the Generalized Parton Distribution formalism provided that one includes helicity-flip transversity GPDs.

The formalism of Generalized Parton Distributions (GPDs) which has appeared in the last two decades (Refs. [1, 2, 3] for the original articles and Ref. [4] for a recent review) allows to interpret the exclusive electroproduction of photons or mesons on the nucleon in terms of quarks and gluons (i.e. partons), the fundamental degrees of freedom of Quantum Chromodynamics (QCD). It has been shown [5] that for these processes, at sufficiently large virtuality of the photon $Q^2 = (e - e')^2$, there is a factorization between a “hard” elementary scattering part at the quark or gluon level, exactly calculable in perturbative QCD, and a non-perturbative nucleon structure part, which encodes all the complex partonic structure of the nucleon and which is parametrized by GPDs. This factorization is illustrated in Fig. 1 for the case of π^0 electroproduction on the proton, on which we will focus in this article. For pseudoscalar meson production, it is shown that, at leading-twist QCD, this factorization is valid only for longitudinal incoming photons, that the longitudinal part of the cross section σ_L should dominate at asymptotically large Q^2 value and that two quark helicity-conserving GPDs contribute to the process: $\tilde{H}$ and $\tilde{E}$. These two GPDs correspond to the amplitudes where the nucleon spin remains unchanged or has been flipped respectively. At QCD leading-order, the GPDs depend on three independent variables: x , ξ and t . In simple terms, GPDs represent, in a frame where the nucleon goes to the speed of light in a certain direction, the probability amplitude of finding a quark in the nucleon with a longitudinal momentum fraction $x + \xi$ and of putting it back

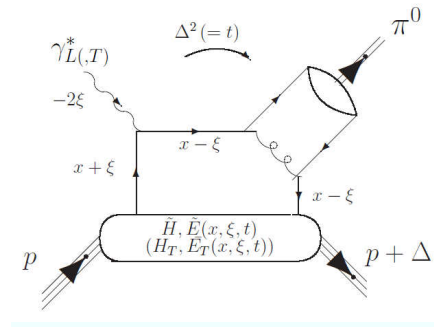


Figure 1: The “handbag” diagram for exclusive π^0 electroproduction on the proton in terms of GPDs. When longitudinal photons are involved, only the helicity-conserving GPDs $\tilde{H}$ and $\tilde{E}$ enter, while for transverse photons, the helicity-flip GPDs H_T and E_T also enter the process. The various kinematical variables are explained in the text.

into the nucleon with a different longitudinal momentum fraction $x - \xi$, plus some transverse momentum “kick”, which is represented by t . For the particular case of $\xi = 0$, the momentum transfer Δ (with $\Delta^2 = t$) is the conjugate variable of the impact parameter $b_\perp$ so that the GPDs encode both the longitudinal momentum distributions of partons inside the nucleon through their dependence on x and their transverse position distributions through their dependence on t . This allows for a sort of tomography of the nucleon where one can probe the transverse size of the nucleon for different quark momentum slices.

Recently, the CLAS collaboration has measured at Jefferson Lab with a 5.75-GeV electron beam the 4-fold differential cross sections $d^4\sigma/dtdQ^2dx_Bd\phi_\pi$ ¹ of the $ep \rightarrow ep\pi^0$ reaction, thus extracting the structure functions $\sigma_T + \epsilon\sigma_L$, σ_{TT} and σ_{LT} as functions of t over a wide range of Q^2 and x_B [6]. Fig. 2 shows a sample of these results (1800 kinematic points in bins of Q^2 , x_B , t and ϕ_π were measured in all). These results are in agreement with the results of Ref. [7], which published high accuracy cross sections in a limited kinematical range in the lower Q^2 , W and $|t|$ regions of the present experiment. One observes that the $d\sigma_{TT}/dt$ structure function (which is negative) is comparable in magnitude with the unpolarized structure function $d\sigma_U/dt = d\sigma_T/dt + \epsilon d\sigma_L/dt$. Furthermore, $d\sigma_{LT}/dt$ is small in comparison with $d\sigma_U/dt$ and $d\sigma_{TT}/dt$. In the same vein, in an earlier CLAS measurement [8], sizeable beam-spin asymmetries (proportional to the fifth structure function $\sigma_{LT'}$), were found for this same channel. Such non-zero asymmetries imply that both transverse and longitudinal amplitudes participate in the process. Similarly, at higher energies, the HERMES collaboration measured the transverse target spin asymmetry in the “cousin” channel of π^+ electroproduction [9]. The sizeable results can also only be explained by significant transverse amplitude contributions.

All these experimental observations point to the model-independent conclusion that the asymptotic leading-order handbag approach for which the longitudinal part of the cross section is dominant is not applicable at the present values of Q^2 . Although model-dependent, this is confirmed by theoretical calculations of the handbag diagram for longitudinal virtual photons based solely on the $\tilde{H}$ and $\tilde{E}$ GPDs which are found to underestimate the measured cross sections by more than an order of magnitude, even after including finite-size corrections through Sudakov form factors[10].

This failure to describe these experimental results for exclusive pseudo-scalar meson electroproduction with quark helicity-conserving GPDs recently stimulated the consideration of the role of the chiral-odd quark helicity-flip contributions (i.e. where the active quark in Fig. 1 undergoes a helicity-flip), in particular through the introduction of so-called transversity GPDs; namely: H_T , which characterizes the quark distributions involved in nucleon helicity-flip, and $\tilde{E}_T (= 2\tilde{H}_T + E_T)$ which characterizes the quark distributions involved in nucleon helicity-non-flip processes [11, 12].

Pseudoscalar meson electroproduction, and in particular π^0 production, was identified [10, 13, 14] as especially sensitive to the quark helicity-flip subprocesses. The produced meson has no intrinsic helicity so that the angular momentum of the incident photon is either transferred to the nucleon via a quark helicity-flip or involves orbital angular momentum processes. In addition, for π^0 production the structure of the amplitudes further suppresses the quark helicity-conserving amplitudes relative to the helicity-flip amplitudes [10].

The results of two GPD-based models which include transversity GPDs [14, 15] are superimposed in Fig. 2. The GL and GK approaches, though employing different models of GPDs,

¹The standard x_B Bjorken variable is related to ξ : $\xi \simeq x_B/(2 - x_B)$ and ϕ_π is the azimuthal angle between the leptonic and hadronic planes.

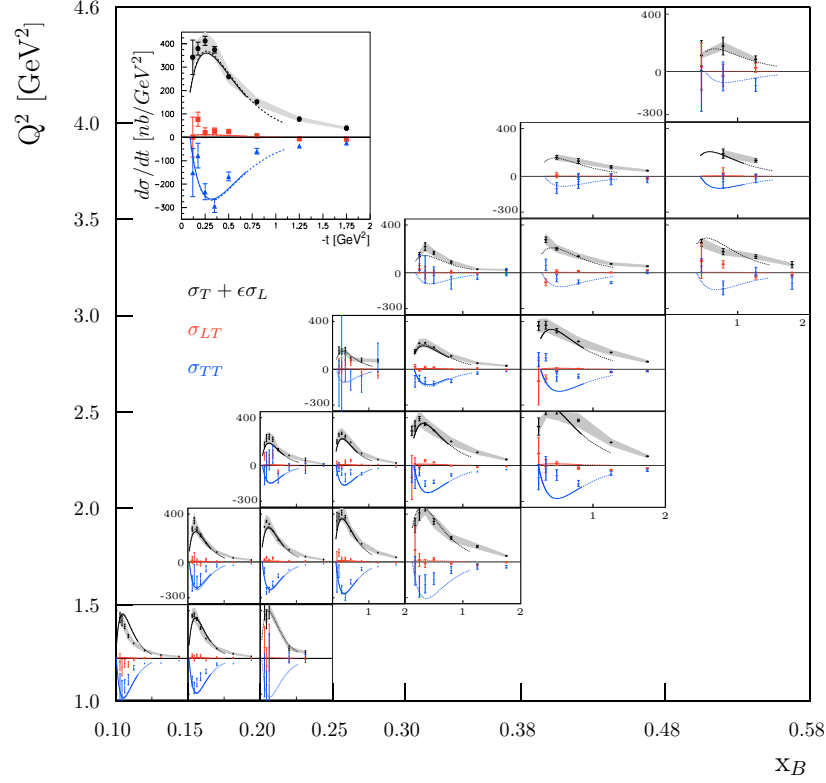


Figure 2: The extracted structure functions vs. t as measured by CLAS. The data and curves are as follows: black (filled circles) - $d\sigma_U/dt = d\sigma_T/dt + \epsilon d\sigma_L/dt$, blue (triangles) - $d\sigma_{TT}/dt$, and red (squares) - $d\sigma_{LT}/dt$. The curves are theoretical predictions produced with the models of Refs. [14] (solid) and [15] (dashed).

lead to transverse photon amplitudes that are much larger than the longitudinal amplitudes. These latter account for only a small fraction (typically less than 10%) of the unseparated structure functions $d\sigma_T/dt + \epsilon d\sigma_L/dt$ in the kinematic regime under investigation. With such inclusion of the quark-helicity non-conserving chiral-odd GPDs, which contribute primarily to $d\sigma_T/dt$ and $d\sigma_{TT}/dt$ and, to a lesser extent, to $d\sigma_{LT}/dt$, the model of Ref. [14] agrees rather well with the data. Deviations in shape become greater at smaller $-t$ for the unseparated cross section $d\sigma_U/dt$. The behavior of the cross section as $|t| \rightarrow |t|_{min}$ is determined by the interplay between H_T and $\bar{E}_T$. For the GPDs of Ref. [14] the parameterization was guided by the lattice calculation results of Ref. [12], while Ref. [15] used a GPD Reggeized diquark-quark model to obtain the GPDs. The results in Fig. 2 for the model of Ref. [14] (solid curves), in which $\bar{E}_T$ is dominant, agree rather well with the data. In particular, the structure function σ_U begins to decrease as $|t| \rightarrow |t|_{min}$, showing the effect of $\bar{E}_T$. In the model of Ref. [15] (dashed curves) H_T is dominant, which leads to a large rise in cross section as $-t$ becomes small so that the contribution of $\bar{E}_T$ relative to H_T appears to be underestimated. One can make a similar conclusion

from the comparison between data and model predictions for σ_{TT} . This shows the sensitivity of the measured π^0 structure functions for constraining the transversity GPDs.

We also mention that π^+ electroproduction has also been measured by the CLAS collaboration [16] in the same phase space. It is found that the GK model describes also qualitatively the low- t unseparated cross sections over the whole (x_B, Q^2) domain, when the same transversity GPDs are included. In π^+ production, the role of transversity GPDs is less apparent because of the presence and dominance of the longitudinal π^+ -pole term (which is absent in π^0 production). However, this latter contribution has an important contribution only in the low $|t|$ domain and only for the lowest x_B and the largest Q^2 values, leaving sensitivity to other contributions, namely transversity GPDs.

In conclusion, differential cross sections of exclusive π^0 (and π^+) electroproduction on the proton have been obtained in the few-GeV region in a wide Q^2, x_B, t, ϕ_π phase space with the CLAS detector at JLab, from which the structure functions $d\sigma_U/dt$, $d\sigma_{TT}/dt$ and $d\sigma_{LT}/dt$ could be extracted. It is found that $d\sigma_U/dt$ and $d\sigma_{TT}/dt$ are comparable in magnitude with each other, while $d\sigma_{LT}/dt$ is very much smaller than either pointing to the dominance of transverse amplitude contributions to the process.

Within the handbag interpretation, there are two independent theoretical calculations [14, 15] which confirm that the measured unseparated cross sections are much larger than expected from leading-twist handbag calculations which are dominated by longitudinal photons. When including transversity GPDs, the general shapes and magnitudes of the various structure functions are reproduced. Extensive new CLAS measurements of beam spin, target spin and double-spin asymmetries for exclusive pseudo-scalar electroproduction on the proton are currently under analysis. Comparison of these results with theoretical models will allow to confirm (or not) the GPDs interpretations that we have outlined here.

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