Thesis for the Degree of Doctor of Science

**Single and Double Spin Asymmetries for Deeply
Virtual Exclusive π^0 Production on Longitudinally
Polarized Proton Target with CLAS**

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(Abstract)

Deeply virtual exclusive processes probe the internal structure of nucleons through measurements of structure functions and their ratios, which are sensitive to the chiral-even generalized parton distributions (GPDs) and the chiral-odd transversity GPDs. The GPDs encode correlations of parton distributions in longitudinal momentum space and transverse impact parameter space and are accessible through the measurements of the x_B and t dependence of meson production. The wide kinematic coverage of CLAS detector allowed measurements of exclusive π^0 electroproduction in full azimuthal range. The target and double spin asymmetries for the deeply virtual exclusive π^0 electroproduction were measured for the first time in the DIS region. The experiment was carried out at Hall B, Jefferson Lab using the longitudinally polarized electron beam with energy of up to 6 GeV and a dynamically polarized NH_3 target with spins of free protons aligned along the beam axis. All four final-state particles from exclusive channel, electron, proton and two photons from π^0 decay, were identified. The asymmetries were fitted according to their angular modulations in the hadronic center-of-mass system, and their moments were extracted. The data comparison with two handbag-based calculations involving the contribution from both chiral-even and chiral-odd GPDs was performed in wide kinematic range. The applicability of a formalism based on generalized parton distributions within the framework of modified perturbative approach is discussed.

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Chapter 1

Introduction

In 1961, Hofstadter was awarded the Nobel Prize 'for his pioneering studies of electron scattering in atomic nuclei' which revealed that the proton explicitly appeared as an extended object and not as a point-like particle [1]. These measurements have shown that as the momentum transfer increases in the elastic scattering, the cross section sharply decreases compared with the electron scattering on a point-like charge. In contrast, for the inelastic scattering process it was found firstly at SLAC that the cross section at large momentum transfers does not show the sharp fall-off as elastic scattering but shows a scaling behavior. This so-called Bjorken scaling put in evidence the presence of point-like charged constituent within the nucleons, for which the 1990 Nobel prize was awarded to Friedman, Kendall and Taylor [2]. Through Feynmans parton model, these constituents were then identified with the quarks introduced earlier by Gell-Mann (who was awarded the Nobel Prize in 1969 for his Eightfold way), based on theoretical symmetry considerations [3].

The electron accelerators in the GeV range allowed to investigate nucleon structure by two main classes of electron scattering processes: inclusive scattering $eN \rightarrow e'X$, also called deep inelastic scattering (DIS), and elastic scattering $eN \rightarrow e'N'$, where $e(e')$ stand for an electron, or more generally a lepton, $N(N')$ for a nucleon and X for an undefined final state. In a first approximation, electron scattering proceeds through a one-photon exchange (we will keep this approximation in the whole of this work) and is characterized $Q^2 = -(p_e - p'_e)^2 > 0$, the squared four-momentum

transferred to the nucleon by the electron. The virtuality Q^2 of the space-like virtual photon can be thought of as the resolution or the scale with which one probes the inner structure of the nucleon [4]. These processes provide us mainly with two types of physical quantities. The first is the longitudinal momentum distribution of the quarks and gluons in the infinite momentum frames, and the second is the spatial distribution of matter (charge or current) in a system, such as elastic form factors. Both observables give us access to the nucleon structure, but have similar deficiencies. The form factors contain no dynamical information on constituents, such as their speed and angular momentum, while the momentum distributions provide no knowledge of their spatial locations.

More complete information about the microscopic structure lies in the correlation between momentum and spatial coordinates. The relevant physical observables are Generalized Parton Distributions (GPDs) that combine the kinematics of both elastic form factors and parton distributions. GPDs were explicitly introduced in Ref. [5] as objects with interesting perturbative QCD (pQCD) evolution, but were largely ignored because of unclear physical significance. They were rediscovered [6, 7] in the study of quark orbital motion and the spin structure of the nucleon in which the physics potential of the distributions began to surface. In the past few years, a full picture of the role of GPDs in studying the quark and gluon structure of the nucleon has emerged.

The description of Generalized Parton Distribution theoretical framework and phenomenology is given in Chapter 2. The details of eg1dvcs experiment and experimental setup are described in Chapter 3. The procedures for data processing, particle identification and corrections are developed in Chapter 4. The selection of exclusive events and corrections to the measured asymmetries are introduced in Chapter 5. χ^2 fitting procedure to extract the asymmetry moments from dependence on azimuthal angle in the center-of-mass system is explained in Chapter 6. The main sources of systematic uncertainties are examined in Chapter 7. The extracted asymmetries are presented in Chapter 8 along with theoretical interpretations and comparisons with previous measurements. The work is summarized in Chapter 9.

Chapter 2

Theory

In recent years, parton distribution functions have been generalized to contain information not only on the longitudinal but also on the transverse distributions of partons in a fast moving hadron. The Generalized Parton Distributions (GPDs) [6, 8, 9] add important piece of information that is missing in one-dimensional parton densities, in particular distribution of partons in the plane transverse to the direction of motion. In the last years GPDs have been identified as a versatile tool to investigate the nucleon internal structure and provide an insight into the hadron at the quark-gluon level. They are closely related to conventional parton distributions as well as nucleon electromagnetic form factors and contain information that cannot be accessed by either of these quantities. The most important aspect is that GPDs can provide detailed knowledge about the space-momentum distributions of quarks and gluons within the nucleon and about the contribution of quark orbital angular momentum to the nucleon spin. GPDs contain the information needed to construct a multi-dimensional image of the internal structure of the nucleon.

Exclusive electroproduction processes $\gamma^*(Q^2) + N \rightarrow M + N$ ($N=nucleon$, $M=\gamma$, *meson*) offer a unique opportunity to study the structure of the nucleon as one varies both the size of the probe - the photon virtuality, Q^2 - and the momentum transfer to the nucleon, t . It has been argued that exclusive productions of photons [6, 8] and mesons [10] effectively proceeds via a partonic mechanism, and can be described in terms of the GPDs in the nucleon. This opens the prospect of using exclusive

electroproduction processes such as Deeply Virtual Compton Scattering and Meson Production as a means to systematically explore the quark structure of the nucleon.

2.1 Generalized Parton Distributions

A new avenue in the study of nucleon structure has opened up over the past two decades with the investigation of exclusive electroproduction processes. Theoretically, the formalism of generalized parton distributions (GPDs) has emerged in the 1990s and experimentally, the latest generation of high-intensity and high-energy lepton accelerators, combined with high resolution and large acceptance detectors, allows one to access such exclusive processes in a precise and systematic way. Deep exclusive scattering (DES), i.e. the exclusive electroproduction of a photon or meson on the nucleon at large Q^2 , is illustrated in Fig. 2.1. The theoretical formalism and the factorization theorems associated with these processes have been laid out in [5, 6, 8, 11, 12].

Figure 2.1: Schematic diagram of the DVCS (left) and DVMP (right) in the framework of the handbag mechanism. The figure is taken from Ref. [13]

One of the main goals of the ongoing analyses and future studies of hard exclusive processes in electroproduction worldwide is to define the spatial distribution of quarks inside hadrons encoded in different GPDs, as seen by the virtual photon. There are eight GPDs. Four correspond to parton helicity conserving (chiral-even) processes, denoted by $H^q(x, \xi, t)$, $E^q(x, \xi, t)$, $\tilde{H}^q(x, \xi, t)$, $\tilde{E}^q(x, \xi, t)$. Four correspond to parton helicity-flip (chiral-odd) processes [14], $H_T^q(x, \xi, t)$, $E_T^q(x, \xi, t)$, $\tilde{H}_T^q(x, \xi, t)$, $\tilde{E}_T^q(x, \xi, t)$.

The GPDs depend on three kinematic variables: x , ξ and t , where x is the average parton longitudinal momentum fraction and ξ (skewness) is half of the longitudinal momentum fraction transferred to the struck parton. The skewness can be expressed in terms of the Bjorken variable x_B as $\xi \simeq x_B/(2 - x_B)$. The momentum transfer to the nucleon is $t = (p' - p)^2$, where p and p' are the initial and final four momenta of the nucleon.

Figure 2.2: Probabilistic interpretation of form factors, parton densities and generalized parton distributions. The figure is taken from Ref. [15].

In the forward limit where $t \rightarrow 0$, H^q and $\tilde{H}^q$ reduce to the parton density distributions $q(x)$ and parton helicity distributions $\Delta q(x)$ respectively. The first moments in x of the chiral-even GPDs are related to the elastic form factors of the nucleon: the Dirac form factor $F_1^q(t)$, the Pauli form factor $F_2^q(t)$, the axial-vector form factor $G_A^q(t)$ and the pseudoscalar form factor $G_P^q(t)$ [16]:

$$\begin{aligned} \int_{-1}^{+1} dx H^q(x, \xi, t) &= F_1^q(t), & \int_{-1}^{+1} dx E^q(x, \xi, t) &= F_2^q(t), \\ \int_{-1}^{+1} dx \tilde{H}^q(x, \xi, t) &= G_A^q(t), & \int_{-1}^{+1} dx \tilde{E}^q(x, \xi, t) &= G_P^q(t). \end{aligned} \quad (2.1)$$

At the $\xi = 0$, the $\text{GPD}(x, 0, t)$ can be interpreted as the probability of finding a parton with longitudinal-momentum fraction x at a given transverse distance (rela-

tive to the transverse c.m.) in the nucleon. In this way, the information contained in a traditional parton distribution, as measured in DIS, and the information contained within a FF, as measured in elastic lepton-nucleon scattering, are recombined and correlated in the GPD description [4].

GPDs that describe spatial distributions of quarks in a proton for different combinations of quark and nucleon polarizations are listed in the Table 2.1.

Table 2.1: GPDs describing the correlations between quark and nucleon polarizations.

N/q	U	L	T
U	H		$\bar{E}_T$
L		$\tilde{H}$	
T	E		$H_T, \tilde{H}_T$

where $\bar{E}_T = 2\tilde{H}_T + E_T$ [17].

Deeply Virtual Compton Scattering (DVCS) is one of the cleanest processes to extract GPDs from experimental data using the leading-twist handbag diagram amplitude. In fact, in DVCS, the hard perturbative part of the handbag involves only electromagnetic vertices (Fig. 2.1). One quark of the nucleon absorbs a virtual photon producing a real photon with the nucleon left intact. DVCS is most suitable for studying GPDs at moderate energies and in the valence quark regime. However, DVCS observables are only sensitive to chiral-even GPDs describing unpolarized and longitudinally polarized quarks.

In deeply virtual meson electroproduction (DVMP), there are strong vertices involving a gluon exchange (see Fig. 2.1). So there is another soft non-perturbative quantity in addition to the GPDs that enter the calculation: the Distribution Amplitude (DA) of the meson which is produced. As the gluon virtuality needs to be hard to ensure the leading-twist amplitude, the endpoint behavior of the DA can potentially lead to strong power corrections to the leading-twist amplitude. On the hand, Hard exclusive productions of light mesons allow the flavor decomposition of different GPDs by different final state hadrons [14, 16]. In addition they provide

a unique possibility to access “transversity” or chiral-odd GPDs through measurements of polarized structure functions [18].

Even though the power corrections for the absolute cross section of exclusive pion electroproduction analyzed in terms of generalized parton distributions are expected to be large, there is a possibility of a *precocious scaling* in ratios of observables [19]. At large values of Bjorken x at fixed Q^2 the contribution of multiparton correlations or higher twist effects increases, eventually leading to a breakdown of the partonic description. Model calculations indicate that Single Spin Asymmetries (SSAs) are less sensitive to a wide range of corrections than cross section measurements in hard exclusive pion production.

2.2 Deeply Virtual π^0 Production

In the electron scattering process, incoming electrons are scattered off protons, and a virtual photon interacts with a parton in the nucleon. In Fig. 2.3, the DV π^0 P process is sketched. The four-momentum of the incoming electrons is e and after scattering at polar angle θ the four-momentum of scattered electrons is e' . The four-momentum of the virtual (exchanged) photons is q . One also has the initial proton P and the final meson four-momentum π^0 . From these variables, the squared four-momentum of the virtual photon $Q^2 = -(e - e')^2$, the momentum transfer to the proton $t = (p' - p)^2$ and dimensionless variable $x_B = \frac{Q^2}{2pq}$. Bjorken variable x_B is a measure of the inelasticity of the reaction. The kinematic restrictions that are usually imposed on the DV π^0 P process correspond to $Q^2 > 1 \text{ GeV}^2$ and $W > 2 \text{ GeV}$ to ensure that the events are in DIS region. Particularly, the minimum value for Q^2 is needed to ensure the validity of perturbative QCD, while the minimum value for W is needed to stay away from the baryon resonance region.

The differential cross section for exclusive meson electroproduction off an longitudinally polarized proton target is given by [20]:

Figure 2.3: Kinematics of the deeply virtual π^0 production in the target rest frame. The lepton plane is defined by the direction of incoming and scattering electrons, while the hadron plane is defined by the direction of the neutral pion and recoiled proton. ϕ is the angle between lepton plane and hadron plane.

$$\begin{aligned}
 \frac{2\pi}{\Gamma(Q^2, x_B, E)} \frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = & \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT} \cos 2\phi + \sqrt{2\varepsilon(1+\varepsilon)}\sigma_{LT} \cos \phi \\
 & + P_b \sqrt{2\varepsilon(1-\varepsilon)}\sigma_{LT'} \sin \phi \\
 & + P_t \left(\sqrt{2\varepsilon(1+\varepsilon)}\sigma_{UL}^{\sin \phi} \sin \phi + \varepsilon\sigma_{UL}^{\sin 2\phi} \sin 2\phi \right) \\
 & + P_b P_t \left(\sqrt{1-\varepsilon^2}\sigma_{LL} + \sqrt{\varepsilon(1-\varepsilon)}\sigma_{LL}^{\cos \phi} \cos \phi \right) \quad (2.2)
 \end{aligned}$$

where P_b is the beam polarization, P_t is the target polarization, ε is virtual photon polarization, ϕ is an azimuthal angle between the electron scattering plane and the hadronic reaction plane, σ_T , σ_L , σ_{TT} , σ_{LT} , $\sigma_{LT'}$, $\sigma_{UL}^{\sin \phi}$, $\sigma_{UL}^{\sin 2\phi}$, σ_{LL} , $\sigma_{LL}^{\cos \phi}$ are the structure functions depending on Q^2, x_B, t .

2.2.1 The handbag approach

Within a standard collinear factorization scheme it was initially proposed that factorization in DVMP works rigorously for longitudinal virtual photons with the transverse photon case being yet unproven. However, factorization for transverse photons has in fact not been disproven although a dedicated proof is missing. Estimates

for electroproduction of pseudoscalar mesons have been performed at small values of skewness within the handbag approach which is based on factorization in hard parton subprocesses and soft generalized parton distributions (GPDs) [21–25] (see Fig. 2.4) under the assumption that a form of factorization working for both longitudinal and transverse virtual photons.

Figure 2.4: π^0 electroproduction in the framework of the handbag mechanism. The helicities of the initial and final nucleons are denoted by v and v' , the incident photon and produced meson by μ and μ' and the active initial and final quark by λ and λ' . The arrows in the figure represent the corresponding helicities. The figure is taken from Ref. [18]

Pseudoscalar meson electroproduction, and in particular π^0 production in the reaction $ep \rightarrow e' p' \pi^0$, was identified as especially sensitive to the helicity-flip subprocesses. While the interpretation of π^+ production is complicated by the dominance of the longitudinal π^+ -pole term, the π^0 production, where that contribution is absent, may become a unique source of information on transversity GPDs [22, 23]. During the past few years, two parallel approaches have been developed utilizing chiral odd GPDs in the calculation of pseudoscalar electroproduction. While different in details, both lead to sizable transverse photon amplitudes, as evidenced in the CLAS data. Inclusion of the chirally-odd twist-3 components of the hard exclusive amplitude brings results into fair agreement with the measured cross sections [18].

Taking into account the helicity structures of GPDs, the formalism proceeds by introducing the helicity amplitudes for $DV\pi^0 P$ $M_{0v'\mu v}$, where the helicities of the virtual photon and the initial proton are, μ and v , and the helicities of the produced pion and final proton are 0 and v' , respectively. The helicity amplitude of the meson electroproduction off the proton reads as a convolution of the partonic subprocess

amplitude $\mathcal{H}$ and GPDs F (see Fig. 2.4):

$$M_{0\pm,\mu\pm}^a = \sum [\langle F^a \rangle] + O(\langle \tilde{F}^a \rangle); \langle F^a \rangle = \sum_{\lambda} \int_{-1}^1 d\bar{x} \mathcal{H}_{0\lambda',\mu\lambda}^a(x, \xi, Q^2, t) F^a(x, \xi, t) \quad (2.3)$$

where a denotes the gluon and quark contribution with the corresponding flavors. They are the analogues of the so-called Compton form factors in DVCS.

2.2.2 Goldstein-Liuti model

In [24] the parameterizations of the chiral-odd GPDs in scope of Goldstein-Liuti (GL) model are presented. Advocating the presence of chiral-odd GPDs in DV π^0 P their parameterization is attained by relating to the chiral-even GPDs.

The extraction of GPDs from experimental data from Jefferson Lab and Hermes is complicated due to their convolution form and complex multi-variable analysis. However, the convolution is neither a substantial or conceptual obstacle if one provides an appropriate initial functional shape. So the parametric form of the chiral even GPDs, that is valid in the multi-GeV, intermediate x_B region accessible in Jefferson Lab and COMPASS, is provided in [26]. The parameterization of the chiral even GPDs is inspired by a physically motivated picture of the nucleon as a quark-diquark system with Regge behavior. The spin structure of each of the four GPDs is determined via a covariant quark-nucleon scattering amplitude, with a diquark exchange. The masses, couplings and Regge power behavior that set the scale for the dependence on the kinematic variables, are determined via a *progressive/recursive* fit to the EM form factors, PDFs, presently available DVCS data from Jefferson Lab and HERMES and some lattice gauge parameters.

Differently from the chiral-even case where the GPDs integrate to the electromagnetic and weak form factors, very little can be surmised on the size/normalization and shape of the chiral odd GPDs. Few constraints from phenomenology exist, namely H_T becomes the transversity structure function, h_1 , in the forward limit, and it integrates to the tensor charge; the first moment of $2\tilde{H}_T + E_T$ can be inter-

preted as the proton's transverse anomalous magnetic moment [27], and $\tilde{E}_T$'s first moment is null [28].

The GL model approach which is based on using the Parity and Charge Conjugation symmetries in a spectator picture allows to overcome this problem and to properly evaluate the size of the various chiral odd GPDs since they are expressed as combinations of the chiral even ones. And chiral even GPDs are known more accurately due to the fact that their parameters have been determined in a fit to all available deep inelastic scattering, and proton form factors data.

The relations between chiral even and chiral odd amplitudes are taken from the structure of the spectator model, parameterized as diquark amplitudes. This led to parameterizing the chiral odd GPDs, normalized by the chiral even GPDs. A set of linear relations resulted for the two possible diquark structures, scalar and axial vector spins. The normalizations set as well as the full x, ξ, t, Q^2 dependence was determined from these relations and the evolution with Q^2 .

2.2.3 Goloskokov-Kroll model

The details of the GK approach are explained in [22, 23, 29]. The partonic subprocess is calculated within the modified perturbative approach in which quark transverse degrees of freedom are taken into account. In other words the transverse size of the produced meson is not ignored as in the collinear (leading-twist) approach. On the other hand, the partons entering the subprocess are viewed as being emitted and reabsorbed by the nucleon collinearly to the nucleon momenta.

The kinematic region of small ξ and small $-t$ but large Q^2 and large photon-proton c.m.s. energy, W , is considered. The helicity amplitudes are calculated as a linear combinations of convolutions of the GPD with an appropriate subprocess amplitude that is calculated from a set of Feynman graphs. In addition to the production amplitudes with longitudinal photons, which in the leading twist is determined by the $\tilde{H}$ and $\tilde{E}$ GPDs, a twist-3 contribution to the amplitudes is required to describe the polarized data at low Q^2 . These amplitudes are generated by transversity GPDs accompanied by twist-3 meson wave functions. For most pseudoscalar-meson channels a combination of $\tilde{H}_T$ and E_T plays a particularly prominent role.

According to this discussion it is required to model GPDs $\tilde{H}$, $\tilde{E}$, H_T and $\bar{E}_T$. They are constructed from double distributions which are parameterized as zero-skewness GPDs multiplied by a Regge-like t dependence and a weight function from which the skewness dependence of the GPD is generated. Then they are constrained by form factors and PDFs. Their isovector combination is fitted to the HERMES data on π^+ electroproduction. Moments of the GPDs are compared to moments obtained from lattice QCD.

For the process $\gamma_L^* p \rightarrow \pi^0 p$ with a proven factorization theorems at large Q^2 the relevant amplitudes can be expressed as following:

$$M_{0+0+} = e_0 \sqrt{1 - \xi^2} \langle \tilde{H}_{eff} \rangle = \sqrt{1 - \xi^2} \frac{e_0}{Q} \left[\langle \tilde{H} \rangle - \frac{\xi^2}{1 - \xi^2} \langle \tilde{E} \rangle \right] \quad (2.4)$$

$$M_{0-0+} = -e_0 \frac{\sqrt{-t'}}{2m} \xi \langle \tilde{E} \rangle = -\frac{e_0}{Q} \frac{\sqrt{-t'}}{2m} [\xi \langle \tilde{E} \rangle] \quad (2.5)$$

A possible scenario beyond collinear factorization was introduced for $\gamma_T^* p \rightarrow \pi^0 p$ and involves directly the chiral odd GPDs. The helicity amplitudes are written as:

$$M_{0-++} = e_0 \sqrt{1 - \xi^2} \langle H_T \rangle \quad (2.6)$$

$$M_{0+++}^N = -e_0 \frac{\sqrt{-t'}}{4m} \langle \bar{E}_T \rangle \quad (2.7)$$

where sum and difference of the single helicity flip amplitudes $M_{0\nu',\mu\nu}^{N,(U)}$ are defined as $\frac{1}{2}[M_{0\nu',\mu\nu} + (-)M_{0\nu',-\mu\nu}]$.

Please note, that in GK model the specific hierarchy of helicity amplitudes was assumed [22, 23, 29]. Accordingly, the amplitudes M_{0--} and M_{0+++}^U were suppressed and neglected within the framework of GK approach.

Considering the kinematical region of small ξ and small $-t$ but large Q^2 and large photon-proton c.m.s. energy, W , and neglecting terms of order $\sqrt{-t}/Q$, the beam, target and double spin asymmetries can be expressed as a function of corre-

sponding helicity amplitudes:

$$A_{LU}^{\sin\phi}\sigma_0 = -\sqrt{\varepsilon(1-\varepsilon)} \operatorname{Im} [(M_{0+++}^* - M_{0+-+}^*)M_{0+0+} + (M_{0-++}^* - M_{0--+}^*)M_{0-0+}] \quad (2.8)$$

$$A_{UL}^{\sin\phi}\sigma_0 = -\sqrt{\varepsilon(1+\varepsilon)} \operatorname{Im} [(M_{0+++}^* + M_{0+-+}^*)M_{0+0+} + (M_{0-++}^* + M_{0--+}^*)M_{0-0+}] \quad (2.9)$$

$$A_{UL}^{\sin 2\phi}\sigma_0 = -\varepsilon \operatorname{Im} [M_{0+++}^*M_{0+-+} + M_{0-++}^*M_{0--+}] \quad (2.10)$$

$$A_{LL}^{\text{const}}\sigma_0 = \sqrt{1-\varepsilon^2} \frac{1}{2} [|M_{0+++}|^2 + |M_{0-++}|^2 - |M_{0+-+}|^2 - |M_{0--+}|^2] \quad (2.11)$$

$$A_{LL}^{\cos\phi}\sigma_0 = -\sqrt{\varepsilon(1-\varepsilon)} \operatorname{Re} [(M_{0+++}^* + M_{0+-+}^*)M_{0+0+} + (M_{0-++}^* + M_{0--+}^*)M_{0-0+}] \quad (2.12)$$

where the angle θ_γ describes the rotation in the lepton plane from the direction of the incoming lepton to the virtual photon one. The helicities are labeled by their signs or by zero. The helicity labels appear in the order pion, final state proton, virtual photon, initial state proton. The integrated cross section σ_0 is defined as:

$$\sigma_0 = \frac{1}{2} [|M_{0+++}^*|^2 + |M_{0-++}^*|^2 + |M_{0+-+}^*|^2 + |M_{0--+}^*|^2] + \varepsilon [|M_{0+0+}^*|^2 + |M_{0-0+}^*|^2] \quad (2.13)$$

With introduction of sum and difference of the single helicity flip amplitudes, behaving like a one-particle exchange of either natural (N) or unnatural parity (U) one can rewrite the Eq. 2.8-2.12 as

$$A_{LU}^{\sin\phi}\sigma_0 = -\sqrt{\varepsilon(1-\varepsilon)} \operatorname{Im} [2M_{0+++}^{U*}M_{0+0+} + (M_{0-++}^* - M_{0--+}^*)M_{0-0+}] \quad (2.14)$$

$$A_{UL}^{\sin\phi}\sigma_0 = -\sqrt{\varepsilon(1+\varepsilon)} \operatorname{Im} [2M_{0+++}^{N*}M_{0+0+} + (M_{0-++}^* + M_{0--+}^*)M_{0-0+}] \quad (2.15)$$

$$A_{UL}^{\sin 2\phi} \sigma_0 = -\varepsilon \operatorname{Im} [2M_{0+++}^{U*} M_{0+++}^N + M_{0-++}^* M_{0--+}] \quad (2.16)$$

$$A_{LL}^{\text{const}} \sigma_0 = \sqrt{1-\varepsilon^2} \frac{1}{2} \left[4 \operatorname{Re} (M_{0+++}^{N*} M_{0+++}^U) + |M_{0-++}|^2 - |M_{0--+}|^2 \right] \quad (2.17)$$

$$A_{LL}^{\cos \phi} \sigma_0 = -\sqrt{\varepsilon(1-\varepsilon)} \operatorname{Re} [2M_{0+++}^{N*} M_{0+0+} + (M_{0-++}^* + M_{0--+}^*) M_{0-0+}] \quad (2.18)$$

where $t' = t - t_0$.

Combinations of beam, target and double spin asymmetries allows extraction of the phase and the modulus of M_{0+++}^{U*} , M_{0+0+} , and so on, providing a unique access to transversity GPDs. The measurements for π^0 SSAs over a large kinematic range are challenging, as the cross sections for neutral pions are small (compared to charged pions), and in addition the clean detection of π^0 s requires the measurement of their two decay photons. Extraction of azimuthal moments of polarized cross section moments provides several observables, combined analysis of which may allow separation of contributions from different underlying GPDs.

2.3 Previous measurements

2.3.1 Measurements of Beam Spin Asymmetry

Sizable beam-spin asymmetries for exclusive neutral pion electroproduction off the proton have been measured above the resonance region for the first time [30]. These non-zero asymmetries imply that both transverse and longitudinal amplitudes participate in the process. The determination of the longitudinal cross section in the kinematic regime considered here, and the subsequent extraction of polarized generalized parton distributions, may then necessitate to perform a L/T separation. Regge theory reproduces the magnitude of the asymmetries at intermediate values of t , but does not exhibit the measured kinematic dependencies. As seen in Fig. 2.5, the measured beam spin asymmetries are systematically of the order of 0.04 to 0.11, over a wide kinematic range in Q^2 , x_B and t . In particular, there is no evidence of a decrease of beam spin asymmetries as a function of Q^2 . This is a clear sign of a non-zero LT' interference among the amplitudes describing the $\gamma^* p \rightarrow p\pi^0$ reaction.

Figure 2.5: Beam spin asymmetry fit parameter α , as extracted from $A = \alpha \sin \phi$, as a function of $-t$. The location of each individual plot corresponds to the approximate coverage in $\{x_B, Q^2\}$. The grey areas indicate the maximal size of systematic uncertainties. For selected kinematics, the curves correspond to the JML model. The figure is taken from Ref. [30].

In the GPD formalism, only the longitudinal amplitude, dominant in the Bjorken regime, is calculated. The present evidence of non-zero transverse terms indicates that it may be necessary to perform a L/T separation in order to isolate the longitudinal part of the cross section.

2.3.2 Measurements of unpolarized structure functions

Differential cross sections of exclusive pion electroproduction have been obtained in the few GeV region over a wide range of Q^2 , x_B and t [18]. The focus of this

letter is on the handbag mechanism in terms of quark and gluon degrees of freedom. Within the handbag interpretation, the data appear to confirm the expectation that pseudoscalar, and in particular π^0 , electroproduction appears to be a uniquely sensitive process to access the transversity GPDs. The measured unseparated cross section is much larger than expected from leading-twist handbag calculations. This means that the contribution of the longitudinal cross section σ_L is small in comparison with σ_T . The same conclusion can be made in an almost model independent way from comparison of the cross section σ_U , σ_{TT} and σ_{LT} .

Figure 2.6: The extracted structure functions vs $-t$. The data and curves are as follows: σ_U - black rounds, σ_{TT} - blue triangles and σ_{LT} - red squares. The figure is taken from Ref. [18].

Chapter 3

Experimental setup

Deeply Virtual π^0 Production offers a unique opportunity to access the internal structure of the nucleon at the parton level. The exclusive reaction gives access to Bjorken scaling variable and momentum transfer to the nucleon at the same time revealing more information about structure of the nucleon. To study these exclusive reactions the dedicated experiments were carried out in Hall B at Jefferson Lab. The "eg1-dvcs" experiment is one of the first experimental studies of $DV\pi^0P$ with a polarized target. Longitudinally polarized high energy electron beam provided by Thomas Jefferson National Accelerator Facility strikes the longitudinally polarized proton in frozen ammonia, and the outgoing particles in the reaction are detected using the CEBAF Large Acceptance Spectrometer and newly installed Inner Calorimeter.

3.1 Thomas Jefferson National Accelerator Facility

Thomas Jefferson National Accelerator Facility adopts the superconducting radiofrequency (srf) technology to produce continuous wave (cw) beams and deliver them to three experimental halls at the same time. Using the five-pass recirculating srf linac shown on Fig. 3.1 the accelerator is able to achieve up to $200\text{ }\mu\text{A}$ high quality cw beams with up to 85% polarization, geometric emittance less than 10^{-9} mrad and relative momentum spread of a few 10^{-5} [31]. The delivery of three beam

Figure 3.1: Schematic overview of Thomas Jefferson National Accelerator Facility.

configurations different in energies and currents became possible due to the use of antiparallel srf linear accelerators (linac) and five-pass beam recirculation.

Initially 100 keV polarized electrons are produced by the beam injector from the cathode using circularly polarized laser light. To ensure that there will be no systematic uncertainty associated with beam polarization the half-wave plate (HWP) is used to switch the beam polarization phase on a regular basis. Three interlaced beams, spaced apart by 120° of rf phase, form a 1497 MHz beam with three bunches of different properties, particularly charge. Each bunch is distributed using rf deflecting cavities providing 499 MHz beam for each of the experimental halls. Then the injector line produces three bunches of electron and boost their energy to 45 MeV by traveling through the 9 cryounits (see Fig. 3.2). These bunches are introduced to the accelerator's North Linac [32].

Each of North and South linacs consists of 160 srf niobium cavities and increases the electron energies by 0.6 GeV. One of the world's largest helium refrigerators is placed in the center of TJNAF and supplies 2.2K helium to cool the cavities well below superconductivity point. The generated RF power is applied to each cavity in resonance with the electron bunch frequency accelerating the electron beam.

Figure 3.2: A cryounit consisting of a pair of five-cell elliptical cavities.

The electron bunch is accelerated in North and South linac with recirculation arcs between them resulting in one circulating "pass". The optical configuration of nine arc beam lines are designed to avoid degradation of the beam quality. Magnetic arcs are constructed in such way that electrons may undergo five passes increasing their energy by 1200 MeV each time.

A beam switchyard separator at the end of South linac can extract the electrons after 2-5 passes providing four possible beam energies. Three bunches are directed to the three aperture Lambertson septum to separate into single bunches for corresponding halls. Two electron bunches for Hall A and C are steered by high-field apertures, while one bunch propagates through the field-free central aperture into Hall B.

3.2 Hall B beam line

The Hall B electron bunch passes through the Moller polarimeter, Beam Position Monitors and Harp Scanners on its way to the target. The electrons that did not interact in target are integrated in the Faraday Cup at the end of the hall.

The Moller polarimeter at the entrance of Hall B takes the measurements of beam polarization by installing the magnetized iron target in front of the beam and determines the polarization through the measurements of elastic electron-electron scattering. The Moller runs were taken periodically during the experiment and have statistical and systematics errors of 1% and 2% respectively [33].

Beam Position Monitors consist of 3 RF cavities and provide the position of

Figure 3.3: Schematic view of Hall B with approximate locations of Moller polarimeter, Beam Position Monitors, Harp Scanners, CLAS and Faraday Cup.

the beam in xy plane to keep it centered on the target. They measure the relative beam intensity as well, cross calibrating the Harp Scanner's position information and Faraday Cup's intensity information.

Harp Scanners are composed of cross-hair movable wires that slowly move perpendicularly to the beam. The scattering electrons are detected via Cherenkov radiation by PMTs and the corresponding beam profile is reconstructed. The harp scans can not be made at the same time with experimental data taking. So they are performed periodically as the Moller runs to keep track of beam configuration changes.

The Faraday Cup is a lead cylinder connected to capacitor measuring the collected charge. The signal from FC is sent to DAQ system to record total and detector live-time counts. Gated by the DAQ state the signal represents the charge accumulated during the actual data taking.

3.3 Polarized target

The egldvcs experiment used the polarized $^{14}\text{NH}_3$ and $^{14}\text{ND}_3$ targets as a source of polarized protons and neutrons respectively [34]. The ammonia was chosen for relatively high percentage of polarizable nucleons and high resistance to radiation damage. The latter allowed the use of electron beam with luminosity higher than in experiments with other polarizable materials as targets. The runs with carbon and empty targets were collected for the nuclear background study purposes. From that point of view the ^{14}N in ammonia can be corrected easier than ^{15}N since it has more similar to ^{12}C structure. On the other hand the disadvantage in term of unpaired proton in ^{14}N doesn't affect the presented analysis since the detection of all final state particles from reaction of interest eliminates the possibility of selection of events from nuclear proton.

The ammonia polarization was achieved using the well-established technique known as Dynamic Nuclear Polarization (DNP). The 1 mm ammonia beads were frozen at 80 K temperature and then irradiated using the low energy electron beam with high intensity to produce paramagnetic radicals. The frozen beads are then placed into the LHe bath lowering the temperature to ~ 1 K and strong magnetic field (5T) combined with microwave frequency initiates the DNP process. The DNP method can be roughly described in terms of the technique called "well-resolved solid effect" that is not directly applicable to the irradiated ammonia but provides intuitive understanding of the undergoing process. Within this framework the microwaves with specifically adjusted frequency flip the electrons and protons spin along the high magnetic field. Due to the significantly higher spin-relaxation time protons near the free electrons gather in one spin state reaching the net polarization that stays constant as long as magnetic field, microwaves and low temperature are maintained.

The target was polarized continuously in the target cryostat (see Fig. 3.4) that is designed to fit the confined space at the end of beam pipe and inside the CE-BAF Large Acceptance Spectrometer. Additionally the target system should take into account the effect of the polarizing magnet on outgoing particles and Moller electrons background, as well as the requirement of large angular acceptance for

Figure 3.4: Polarized target cryostat.

particle detection.

Five major subsystems in the polarized target cryostat:

- **Superconducting magnet**

The large pair of superconducting Helmholtz coils produces a 5 T strong magnetic field in the area inside CLAS detector. The magnetic field is nearly uniform over a cylindrical volume parallel to the beam axis effectively blocking the Moller electrons with low energy. Due to the space limitations the liquid helium reservoir is placed outside CLAS and used to maintain low temperature necessary for superconductivity.

- **Refrigerator**

In order to keep the polarized target material at low temperature a 1K refrigerator is embedded into the evaporation chamber at 25° angle from the horizontal. The liquid helium is delivered into the chamber from the LHe reservoir outside CLAS. The chamber has $71\ \mu\text{m}$ thick entrance and exit windows at the upstream and downstream ends of the chamber.

- **Target insert**

The target materials are placed in four cups at the end of the target stick (see Fig. 3.5). The position of insert is controlled by stepping motor and can be moved vertically effectively changing the target cups as needed. During the eg1dvcs experiment two top cups contained the crashed beads of irradiated ammonia (NH_3/ND_3), the third contained the disk of amorphous carbon and the last cup was left empty.

Figure 3.5: Insert stick for polarized target.

- **Microwave system**

Extended Interaction Oscillator (EIO) generates the microwave field which is used to polarize the target material. The microwave frequency can be tuned over wide bandwidth allowing to switch between the positive and negative spin state without changing the direction of magnetic field.

- **NMR system**

The target polarization was monitored real-time using the NMR system. The coils wrapped around the target cup serve as a resonant RLC circuit. An alternating RF at a constant current is sent through the circuit, and its voltage de-

pendence on frequency is measured. When the driving RF coincides with nuclear Larmor frequency the spin flip occurs causing the voltage spike to occur. The area under the voltage readings is proportional to the proton polarization, where the constant of proportionality is calibrated using the measurements of well known and calculable thermal equilibrium polarization, effectively taking into account the specific setup configuration and parameters.

3.4 CEBAF Large Acceptance Spectrometer

Figure 3.6: CEBAF Large Acceptance Spectrometer.

The fact that CEBAF Large Acceptance Spectrometer (CLAS) shown of Fig. 3.6 is capable of the detection of multiple neutral and charged particles simultaneously provides us the opportunity to make high statistics measurements of exclusive π^0 events with low background-to-signal ratio. The reaction of interest has four final state particles, all of whom are detected in CLAS [33] housed in Hall B, Jefferson Lab.

CLAS design is based on six superconducting coils aligned around the beam line and creating a toroidal magnetic field for reconstruction of momentum with good

resolution. The Drift Chambers produce the charged particle tracks for further momentum calculation. The gas Cherenkov Counters provide additional information to confirm electron identification. The Scintillation Counters measure time-of-flight information primarily used to separate protons, kaons and pions. The Electromagnetic Calorimeters supply additional timing information and allow identification of neutral particles. A view of the CLAS detector and its major subsystems is shown on Fig. 3.7. Each subsystem is constructed in form of six nearly independent identical segments surrounding the beam line.

Figure 3.7: Schematic top-view cross section of CLAS detector. Green, blue and red lines represent the reconstructed tracks of photon, electron and proton respectively.

3.4.1 Torus Magnet

The magnetic field in CLAS detector which is generated by torus magnet provide the reconstruction of particle momentum through the examination of path curvature. The toroidal geometry of the coils results in generation of magnetic field nearly homogeneous in ϕ direction as shown of Fig. 3.8. The region in the center of the detector is field-free, so the installation of dynamically polarized target system is possible without interference of magnetic fields. The kidney-shape field has an advantage of bending the charged particle in polar direction only. The bending is stronger due to the higher field integral for forward angle particles that usually have higher momentum and weaker for the particles at larger angles. Depending on the torus polarization and charge of particle the bending direction is different.

Figure 3.8: CLAS Magnetic field in the midplane between two kidney-shape torus coils. Lines represent the contours where the magnetic field stays constant.

The eg1dvcs experiment accumulated events with torus current of 2250A. Positive torus current results in magnetic field that bends scattered electrons into the beam line, and proton out. Small fraction of data was collected with negative torus current. Magnetic field produced by positive (negative) current is called inbending (outbending).

The map of the magnetic field is not thoroughly determined so the calibration is required for proper momentum reconstruction using the well known events such as elastic ep events.

3.4.2 Drift Chambers

The first detectors that the charged particle interact with are drift chambers. They are used to reconstruct the tracks of charged particles. The curvature of trajectories in known magnetic fields allows to reconstruct the momentum of the particle. Following the "six sectors" geometrical layout of CLAS determined by six coils of toroidal magnet the drift chambers are divided into 3 virtually independent detectors, called "regions", for each sector. The R1, R2, R3 regions are located at specific distances from the target. The R1 region is located inside the torus coils where magnetic field is very low. The R2 region is located between torus coils in the area with strong magnetic field, and the R3 region is located in diminishing magnetic field outside of the coils [35].

Every DC region consists of two separate superlayers. Two endplates corresponding to them are clearly visible on Fig. 3.9a. Each superlayer has six layers¹ assembled from a sense or anode wires which are perpendicular to the torus magnetic field in one superlayer and tilted at 6° stereo angle in another. This configuration allows to reconstruct ϕ direction of charged particle.

Figure 3.9: Drift Chambers.

The wires are stretched between endplates and form the hexagonal shape cell

¹The superlayer 1 in DC region 1 consists of 4 layers due to space constraints

with sense wires at the center of hexagon and field wires at the vertices. The cells are filled with 90% of argon and 10% of CO₂ gas mixture. This specific mixture was chosen to minimize the multiple scattering and due to its properties as having relatively high velocity and high ionization gain. When a charged particle moves through it, the gas atoms ionize and free electrons start to drift at 4 cm/ μ s till they reach the sense wires as shown on Fig. 3.9b. The circuit boards fixed on the chamber endplates read and collect the preamplified signals and then send them to the data acquisition system.

The tracks are reconstructed using the information from DC in conjunction with time-of-flight information from scintillator counters. The SC time is chosen as reference time to convert the DC time into a distance between charged particle track and hit sense wire increasing the precision of track measurements.

3.4.3 Cherenkov Counters

Once the particle leaves the drift chambers with an angle below 45° it enters the Cherenkov detector [36]. The Cherenkov counters (CC) provide the information for electron triggers and allow to separate electrons from light hadrons (primarily pions). One of six CC sectors consisting of 18 segments is shown of Fig. 3.10a. In order to maximize the angular acceptance most of the available space is covered with elliptical, hyperbolic and cylindrical mirrors, while the PMTs are placed in the shadows of the magnet coils. Each of the segment covers a specific θ region and is divided into 2 mirrored sections (see Fig. 3.10b). Considering that toroidal configuration of magnetic field preserves the ϕ direction of charged particles the optics in CC segments is designed to focus light ϕ direction providing additional information on particle's θ angle. The space in the optical modules between elliptical and hyperbolic mirrors is filled with Cherenkov radiator gas - perfluorobutane (C₄F₁₀) which has a refraction index of 1.00153. This gas is chosen for its high photon yield and excellent transmission of light with short wavelength.

The major components of light collection module with the typical electron track are schematically drawn on Fig. 3.10b. The charged particles enter one of the segments of Cherenkov counters and produce Cherenkov radiation due to its velocity

(a) One of the six sectors of Cherenkov detector consisting of the 36 optical modules.

(b) Diagram showing the Cherenkov radiation emitted along the typical electron track in CC and focused onto a photomultiplier tube.

Figure 3.10: Cherenkov Counters.

being higher than the velocity of light in the same medium. The cone of Cherenkov light then travels through radiator volume and focuses on the nearest of two PMTs in the segment through the mirrors reflection. The nearly massless electrons produce light at much lower energies than pions allowing to differentiate these two particles within momentum range up to $2.5 \text{ GeV}/c$.

3.4.4 Scintillation Counters

The scintillation counters are placed outside of the tracking system, i.e. drift chambers, and Cherenkov counters. The coverage of this system includes the polar angle between 8° and 142° and the entire active range in azimuthal angle [37]. Each sector consists of 48 scintillation counter strips that are aligned to be perpendicular to the average particle trajectory (see Fig. 3.11). Each BC-408 scintillator bar has a PMT on either end connected via short stubby light guides at forward angles and bent light guides at large angles (except for the last four).

The SC measure the time of flight with excellent timing resolution using the event start time from the RF in the accelerator. The main contributor to the resolution comes from the photon's path length variations in scintillator bar due to its several meters length. The flight time information can serve as an independent mean to determine velocity in specific instances. The accuracy of this method is bet-

Figure 3.11: Schematic representation for one sector of TOF system.

ter than the magnetic analysis for slow particles such as protons when the tracking resolution is dominated by multiple scattering.

3.4.5 Electromagnetic Calorimeters

The electromagnetic calorimeters form the last layer of detectors that serves a multiple purposes: detect and trigger electron above approximately 0.5 GeV, detect photons above 0.2 GeV and neutrons [38]. The EC is constructed with alternating layers of lead sheets and scintillator strips. The lead-scintillator sandwich has a total thickness of 16 radiation length and absorbs energy of scattered particles. Each EC sector has a triangular shape and made of 39 layers of 10 mm thick scintillator strips and 2.2 mm lead sheets. There are three planes (labeled U,V,W) formed by 13 layers each with scintillator bars oriented parallel to each of the triangle sides (see Fig. 3.12). The layer strips rotated to each other by 60° provide spacial locations of reconstructed energy depositions.

The EC differentiate the particles by the reactions they are having in the calorimeters: ionization process in case of the incident hadrons or showers of electron/positron pairs and Bremsstrahlung photons in case of the incident electrons/positrons. For the showering particles, such as electrons and photons, the energy deposit in calorimeter is proportional to particle's total energy with a coefficient of proportionality

Figure 3.12: Electromagnetic Calorimeters.

equal to the lead-scintillator thickness ratio, called sampling fraction. For the minimum ionizing particles, such as pions, calorimeter's energy deposit is independent of the particle energy. This provides the electron/pion separation for the cases that can not be resolved by Cherenkov Counters. Additionally the EC provides the only mean for detection of neutral particles such as photons and neutrons that are obviously not affected by magnetic field. In order to distinguish the photons from neutrons for momenta up to $2.5 \text{ GeV}/c$ the time of flight information is used.

3.5 Inner Calorimeter

The standard CLAS set-up allows the detection of photons in the EC detector with decreasing acceptance as the polar angle decreases. However, the certain reactions, including the exclusive π^0 electroproduction, require the detection of photons at smaller angles. The eg1dvcs experiment has additional detector, called inner calorimeter (see Fig. 3.13), inserted to the standard CLAS configuration down-

stream of the target. The IC coverage includes the detection of photons in smaller azimuthal angle in the range from 5° to 16° for energies between 1 and 5 GeV. IC slightly overlaps with the CLAS acceptance reducing the charged particle acceptance at small angles up to approximately 18° . The operation of such a small angle calorimeter becomes possible only in conduction with the strong magnetic field produced by the target magnet, that shields the IC from the extremely high ratio of Moller electrons at small angles.

Figure 3.13: A photograph of the Inner Calorimeter detector.

The IC is constructed out of 424 lead tungstate crystals 16 mm length that are pointed to the target direction. The photon interacts with the calorimeter producing the electromagnetic shower. The deposited energy of this shower is distributed between several crystals that are combined into a cluster. The particle position is then determined as an average position of all cluster hits weighted with deposited energies.

Chapter 4

Data processing

The CLAS data acquisition stores the data from time-to-digital converters (TDCs) and analog-to-digital converters (ADCs) using the "raw" data format. In order to reconstruct the momentum of charged and neutral particles one should "cook" the raw data, i.e. convert the raw values into hits and tracks. For these purposes each detector element is calibrated and the data are processed using the calibration constants stored in the database. Then the reconstructed data are ready to be used in physics analysis.

The data obtained during the experiments are divided into "runs", where each run consists of about 100 flat files. The one run usually is taken during 2-4 hours of experiment heavily depending on beam current and quality. During the processing the run/file structure (so called "cooking") is preserved saving the ability to associate the cooked data with online database information of run conditions or accidents happened during the run data taking.

4.1 Run summary

In the eg1dvcs experiment the data were collected between February and September 2009. The typical beam current was around 7 nA. The integrated luminosity was approximately 75 fb^{-1} . The beam polarization was measured using Moller polarimeter which measures an average polarization of 85%. The target polarization

is measured in real-time using Nuclear Magnetic Resonance (NMR) system. The average hydrogen polarization for NH_3 target is 78% and 74% for positively and negatively polarized targets, respectively.

The data were divided into three blocks called part A, B and C. Each part consists of run groups with different experimental configurations. The summary of all parts is given in Table 4.1.

Name	Beam Energy [GeV]	Main Target	Torus Current [A]	Target Position [cm]	Start Run
A	5.887	NH_3	2250	-57.95	58799
A	4.730	NH_3	2250	-57.95	59161
B	5.954	NH_3	2250	-67.97	59221
B	5.954	NH_3	-2250	-67.97	59978
B	5.954	NH_3	2250	-67.97	60006
C	5.752	ND_3	2250	-68.18	60223
C	5.752	ND_3	-2250	-68.18	60566

Table 4.1: The "egldvcs" experiment summary.

The current analysis uses data from the first 2 parts of experiment: A and B.

The different types of targets and NH_3 polarizations were used throughout the experiment. Approximately 15% of these data were collected on the carbon target and 3% on the empty target. A small fraction of data were also collected with reversed torus field for background studies.

4.2 Data format

The data were processed using the standard CLAS analysis software converting raw data into physics quantities and producing over 50000 files. The 85 files, on average, were grouped into one run with fixed experimental configuration. Several cooking iterations were made with different calibrations. The skimmed version of final data format was stored on disk in a compact format (ntuple 22). Loose selection criteria on electron were used to keep only events with good electron as a first particle. The file size was reduced using bit compression and removing variables not used in the final analysis. The analysis described further is performed using this filtered ROOT files.

4.3 Data quality check

The selection of good files and runs were made based on some quality checks.

- Check of the electron rate on a file-by-file and run-by-run basis for each sector were done to determine the periods with drop in efficiency of particle detection due to the CLAS subsystems tripping off. We calculate the rate of inclusive electrons as a ratio of the detected electron number to the gated charge accumulated in the Faraday Cup. After monitoring the electron rate over the whole experiment the files or runs with different rates were discarded to avoid systematic effects in the asymmetries. The stability of the inclusive electron rate is illustrated on Fig. 4.1. Please note that this method also allowed us to correct wrong targets in the run data base since the rate is different for ammonia and carbon targets, as clearly seen on the plot.
- A few runs were discarded from the analysis due to beam scraping on target side walls.
- Some runs were removed due to lower target polarization.
- The beam helicity and target polarization signs were checked using the inclusive electron double spin asymmetry. The Fig. 4.2 shows the final results for the double spin asymmetry as a function of run number for part A and B. The sign of asymmetry allowed us to check the beam and target polarization signs and beam half-wave plate status. Finally, polarized target runs show non-zero asymmetries, while the carbon runs are consistent with zero.

4.4 Corrections

Due to the presence of the torus magnetic field, Drift Chambers misalignments and target magnetic field the reconstructed momentum of charged particles requires small corrections. Some particles that pass through materials in target and CLAS detector lose fractions of their energy before detection. Therefore corrections to the charged and neutral particles are discussed.

(a) before quality check

(b) after quality check

Figure 4.1: The stability of electron file rate for different sectors and targets during the experiment.

(a) part A

(b) part B

Figure 4.2: Inclusive electron double-spin asymmetries vs run number. Green vertical lines indicate the runs where half wave plate status is switched resulting in asymmetry sign switch.

4.4.1 Raster correction

In "eg1dvcs" the beam position was constantly moving over the circle with 1.5 cm diameter in order to avoid non-uniform target depolarization. However, the reconstruction algorithm does not take it into account and assumes that beam coordinates are fixed to zero, resulting in incorrect measurements of vertex coordinate (see Fig. 4.3).

Figure 4.3: Schematic side view of raster geometry. The black line shows the reconstructed direction of emitted particle. The red point is vertex reconstructed by standard CLAS tracking software. The green point is vertex reconstructed after raster correction, taking into account the beam coordinates in xy plane. The ellipse represents the area over which the beam was rasterized.

The raster correction is used to calculate the actual beam position [39]. Two sets of perpendicular dipole magnets vary the entry point of the beam, and their currents are stored in data stream using ADCs. The signals are synchronized and recorded for each event. Then by minimizing the width of the target vertex position along the beam line for charged tracks the relation of raster ADC readings to beam positions were found. As one of the fitting parameters, the average target position in z was determined providing us the nominal values shown in Table 4.1. These values are about 0.5 cm different than the physical survey measurements.

4.4.2 Target field correction

The standard reconstruction package (RECSIS) was used to track the particles taking into account the 5 T target magnetic field as well as the CLAS torus magnet. RECSIS swims particles backwards to a plane perpendicular to the given sector. But in "eg1dvcs" we are looking for events with vertices in the target, so we can swim

particle back to the point with (x,y) beam coordinates known from raster correction described above.

Figure 4.4: Beam energy before (red) and after (black) target field correction.

The method uses the track coordinates at Region 1 of DC and a fit to a large ensemble of simulated forward-swimming particles. The target angular resolution is improved by a factor of roughly two, compared to original RECSIS results. The improvements are clearly visible in Fig. 4.4, where beam energy distributions from ep elastic events are shown before and after this correction. It can also be seen that the peaks for each sector align much better with each other due to accounting for the shift of target magnet axis relative to the CLAS axis.

4.4.3 Energy loss correction

The momentum of charged particles in CLAS is determined from their trajectories in the magnetic field with drift chambers. The electrons and protons lose part of their energy due to ionization losses when they pass through the target and CLAS

detector materials, however, the CLAS tracking code does not account for the energy losses along the track. Therefore the momentum corrections are necessary especially for low energy particles due to substantial energy losses. The effect is seen on Fig. 4.5, where MM_{epX}^2 shows strong dependence on proton momentum. The protons are chosen for demonstration because their losses are significantly higher compared to electrons.

(a) before correction

(b) after correction

Figure 4.5: The dependence of MM_{epX}^2 on proton momentum

Derived from standard GSIM simulation modified to include the geometry of eg1dvcs polarized target [40, 41], the energy loss showed no dependence on particle angles. So it is parameterized as a function of reconstructed momentum only. Following the discussion from [42] the functions used to correct the momentum are the following.

- for protons:

$$p_{corr}^p = p \left(a + \frac{b}{p} - \frac{c}{p^2} + \frac{d}{p^3} \right) \quad (4.1)$$

- for electrons:

$$p_{corr}^{e^-} = p \left(a + \frac{b}{p} - \frac{c}{p^2} \right) \quad (4.2)$$

The correction parameters for part A and B are listed in Table 4.2.

Parameters	electrons (part A)	protons (part A)	electrons (part B)	protons (part B)
a	0.999452	0.997204	0.999736	0.992767
b	0.00615979	0.00562253	0.0105136	0.0147232
c	0.00304068	0.00348868	0.00515416	0.0084665
d		0.00229922		0.0032769

Table 4.2: Parameters values for proton energy loss correction.

4.4.4 EC photon energy correction

The energy of the reconstructed photon in EC is calculated using the formula $E = \frac{E_{dep}}{f}$, where E_{dep} is the energy deposited in EC and constant f is the sampling fraction. However, the formula $E = \frac{E_{dep}}{A} + B$ results in less dependence on photon energy and sector. To obtain the A and B values two different processes were considered:

- Then the π^0 mass was reconstructed from two photons detected in EC. The energy of photon is calculated using the fixed value of $A = 0.3$. The mass peak position shows the least dependence with $B = 0.06$ GeV.

- The inclusive electrons are used to determine A as a mean value of $E_{tot}/(P - 0.06)$, where 0.06 GeV is B value and accounts for the average energy loss by electrons before they enter EC.

Figure 4.6: The A values for inclusive electrons versus run number. Sectors 1 to 6 are represented by black, blue, green, red, magenta and cyan colors. The rapid variations occur in the few runs after the EC HV was turned on, after being off for some period of time.

This method allows sampling fraction A to vary for each of six sectors from run to run accounting for the different gains in EC sectors and runs that were collected after the EC HV trips.

4.4.5 IC photon pulse-height correction

Due to the "hot" blocks in IC near the beam line, the IC timing variable plays an important role in background rejection. The resolution of the timing system is affected by the variations in the amplitude and/or risetime of the signals. To account for this effect the pulse-height correction is developed. The timing dependence on

signal amplitude, i.e. photon energy, comes from the signal processing in discriminator. Fig. 4.7 shows two signals coincident in time but with different pulse height. They reach the discriminator threshold at different times due to the difference in amplitudes.

Figure 4.7: Signal amplitude impact on the timing measurements.

In eg1dvcs experiment the IC timing peak is shifted from zero for three distinct run groups: part A, few runs at the beginning of part B and majority of part B. The linear dependence of timing peak position on photon energy is fitted and the IC photon time is corrected based on the fit results. The parameters are obtained for individual run and show no variation for a large group of runs (see Fig. 4.8), see values in Table 4.3.

$$t_{\gamma}^{corr} = t_{\gamma}^{meas} - p_0 - p_1 E_{\gamma} \quad (4.3)$$

Run period	p_0	p_1
part A	-0.4	-0.22
part B (59221-59484)	-0.076	-0.22
part B (59485-60223)	0.536	-0.22

Table 4.3: Parameters values for pulse height correction.

Significant improvement is observed after application of the pulse-height correction as shown of Fig. 4.9. The correct peak position allows to place more stringent

Figure 4.8: Offset(left) and pulse-height coefficient(right) used to correct the IC photon time

cut on timing variable resulting in better background rejection, explained in details in next section.

Figure 4.9: IC time distribution before(red) and after(blue) pulse height correction.

4.5 Particle identification

In this experiment the event of interest is identified if four final state particles (electron, proton and two photons from π^0 decay) are detected. The particle identification technique is described in details below for each of the detected particle. Since we select the exclusive final state with all particles detected we intentionally loosen or remove the "standard" CLAS PID cuts, in order to maximize the number of good events. The assumption is that exclusive cuts placed on kinematic constraints would filter the good signal events from the background. The effect of exclusive cuts on PID variables is shown for each distribution.

4.5.1 Electron

- Negative charge.
- Energy deposited in EC divided by momentum P (with 0.12 GeV offset) greater than 0.2: $\frac{E_{EC}}{p-0.12} > 0.2$ (see Fig. 4.10, 4.11, 4.12). The offset in 0.12 GeV roughly accounts for the energy lost by electron in target, drift chambers, scintillation counters and in entrance window of electromagnetic calorimeters before it is detected in EC.

Figure 4.10: Electron cut (red line) on energy deposited in EC: $\frac{E_{EC}}{p-0.12}$ after other electron PID cuts

Figure 4.11: Electron cut (red line) on energy deposited in EC: $\frac{E_{EC}}{p-0.12}$ vs p after other electron PID cuts

Figure 4.12: Electron cut (red line) on energy deposited in EC: $\frac{E_{EC}}{p-0.12}$ vs p after exclusive cuts

- Cherenkov signal time agrees with EC signal within ± 4 ns (see Fig. 4.13).

(a) after other electron PID cuts

(b) after exclusive cuts

Figure 4.13: Electron cut (red line) on CC and EC timing $t_{CC} - t_{EC}$

- Cut on the vertex position along beam line (z), to eliminate the events originated from the material outside the target: $|v_z - v_{nom}| < 4$ cm (see Fig. 4.14).

(a) after other electron PID cuts

(b) after exclusive cuts

Figure 4.14: Electron cut (red line) on vertex position $v_z - v_{znom}$

4.5.2 Proton

- Positive charge.
- Cut of variable $\Delta\beta = \beta_1 - \beta_2$, where β_1 is calculated using the SC time and β_2 is calculated using the particle momentum under assumption that this particle is a proton. The resolution of $\Delta\beta$ is shown to be dependent on proton momentum in Fig. 4.15, 4.16, 4.17 with error bars increasing after 2 GeV due to π^+ contamination. The final cut was chosen relatively loosely to ignore the momentum dependence and was set to be constant $|\Delta\beta| < 0.05$.

Figure 4.15: Proton identification cut (red line) on β variable: β after proton PID cuts

- Cut on the vertex position along beam line (z), to eliminate the events originated from the material outside the target: $|v_z - v_{nom}| < 4$ cm.

Figure 4.16: Proton identification cut (red line) on β variable: β after exclusivity cuts

Figure 4.17: Proton identification cut (red line) on β variable: $\Delta\beta$ resolution vs p

4.5.3 Neutral pion

Neutral pions decay into two photons and are reconstructed using their invariant mass. The photons can be detected in Electromagnetic Calorimeter and Inner Calorimeter. The photon selection is described below. Due to this detector combination π^0 s can be reconstructed with both photons in EC, both in IC or one photon in EC and another in IC. All three cases have different resolution that affect further analysis.

4.5.4 Photons in IC

- Photons from the IC are contaminated by low energy Moller electrons at low angles. A triangular cut on IC photon position and momentum was chosen to eliminate Moller background: $E_\gamma > 1.2 - \frac{1}{6.2}r_\gamma$. The "hot" blocks are clearly visible on Fig. 4.18, 4.19, 4.20 as well as effect of this cut on invariant mass.

Figure 4.18: Distribution of photon's energy vs IC radius (red line shows the Moller cut): before exclusive cuts

Figure 4.19: Distribution of photon's energy vs IC radius (red line shows the Moller cut): after exclusive cuts

Figure 4.20: The invariant mass with good photons (black) and at least one of the being from Moller region (red).

- The accidental photons also can introduce significant background. The IC timing cut $|\Delta t| < 2$ ns requires the deviation of the photon detection time from time expected to be within 2 ns (see Fig. 4.21). This cut reduces the background under invariant mass peak of two photons, eliminating the events with accidental photons (see Fig. 4.22).

Figure 4.21: IC photon time. The corner picture shows the same distribution on wider scale. Red lines indicate the cuts used.

Figure 4.22: Invariant mass of two photons (on the right) without IC timing cut(black), with $t \in [-2; 2]$ ns (red) and $t \notin [-2; 2]$ ns (blue).

4.5.5 Photons in EC

- Neutral charge.
- The low energy threshold 0.2 GeV.
- The time-of-flight from the target to EC allows us to separate photons from neutrons using the cut on variables $\beta > 0.8$ (see Fig. 4.23, 4.24).

Figure 4.23: β for neutral particles in EC: before exclusive cuts

Figure 4.24: β for neutral particles in EC: after exclusive cuts

4.6 Fiducial cuts

The CLAS detector has regions where acceptance efficiency and reconstruction process are not well known. These regions include the torus coils, dead wires in DC, broken PMTs in SC, edges of detectors in EC etc. Usually the fiducial cuts are used to exclude the events detected by the questionable parts of the detector from the analysis. The sets of cuts specific for IC and EC detectors ([43,44]) are discussed below.

4.6.1 IC fiducial cuts

Fiducial cuts on IC hit positions (see Fig. 4.25) remove the events detected at the Inner Calorimeter edges and might have leaked their energy outside.

Figure 4.25: IC hit position with red line showing IC fiducial cut

4.6.2 EC fiducial cuts

The same geometric cuts (in U,V,W) for electron and photon (see Fig. 4.26) are applied. They eliminate the particles that hit detector near its edge and can leak part

of their energy outside preventing proper reconstruction.

4.6.3 IC shadow fiducial cuts

Inner Calorimeter blocks the detection of low angle particles in EC. The cuts of particle position on IC face plane were developed [44] to remove the particles passing through the IC edges, material of its cooling system, etc. (see Fig. 4.27).

(a) after electron PID cuts

(b) after photon PID cuts

(c) electrons after exclusive cuts

(d) photons after exclusive cuts

(e) electrons after fiducial cuts

(f) photons after fiducial cuts

Figure 4.26: Fiducial cuts in EC for electrons (left column) and photons (right column).

(a) after electron PID cuts

(b) after exclusive cuts

(c) after proton PID cuts

(d) after exclusive cuts

(e) after EC photon PID cuts

(f) after exclusive cuts

Figure 4.27: Fiducial cuts removing IC shadow for electrons (top), protons (middle) and EC photons (bottom)

Chapter 5

Data analysis

5.1 Deeply virtual π^0 production selection

After the four particles composing the final state have been identified through the PID cuts, the actual channel selection can be performed. Because of the different source of background it is possible that the number of particles in the event is bigger than four. Then all possible combinations of electron, proton and two photons are checked with exclusivity cuts and the events is subject to asymmetry calculation if one is successful. The kinematic constraints calculated using the all four final state particles were studied in order to maximize background rejection without losing any good event. The exclusive variables used in this analysis are the following:

- The angle $\theta_{X\pi^0}$ between the reconstructed π^0 and missing momentum $e\vec{p} \rightarrow epX$ should be zero.
- The squared missing mass of electron and proton MM_{epX}^2 is expected to be equal to the squared π^0 mass.
- The invariant mass of two photons M_{π^0} is expected to be equal to π^0 mass.
- The missing energy $E_{ep\pi^0}$ should be zero.

Due to the detector resolution we obtain Gaussian distributions near expectation values for all variables except the $\theta_{X\pi^0}$ angle. Unfortunately considering that we

used NH_3 target the number of events from polarized protons in hydrogen is significantly smaller than from nucleon in nitrogen. The nuclear effect is clearly seen on Fig. 5.1.

Figure 5.1: Square missing mass of epX for NH_3 (black) and carbon (red) targets. The very preliminary cut on $\theta_{X\pi^0} < 10^\circ$ was applied to make the peak distinguishable.

In order to be in the kinematic region of interest in this analysis the very preliminary cuts were applied to dataset to eliminate the most obvious contamination:

- $Q^2 > 1 \text{ GeV}^2$, $W > 2 \text{ GeV}$ - to ensure that the event is in the DIS region.
- $\left| MM^2_{epX} \right| < 0.3 \text{ GeV}^2$ - to remove most of the background from different channels.

5.1.1 Invariant mass of the two photons $M_{\gamma\gamma}$

The photons from π^0 decay can be detected in two detectors EC and IC resulting in three configurations different in resolution and kinematic coverage. The invariant mass of two photons was reconstructed for each case and fitted with Gaussian and polynomial accounting for the background under the peak. Results of fitting procedures for each configuration are shown on Fig. 5.2. The standard deviations σ are extracted from the fits, and $\pm 3\sigma$ cuts were used for final selection of exclusive events.

Figure 5.2: Invariant mass of two photons M_{π^0} .

5.1.2 Missing energy $E_{e\gamma\gamma}$

Missing energy cut account for the events where electron radiates the photon along the way. Again, the resolution is different for three cases because the resolutions for reconstructed energies of both photons are significantly different in IC and EC.

Figure 5.3: Missing energy $E_{e\gamma\gamma}$

5.1.3 Missing mass squared MM_{epX}^2

The MM_{epX}^2 cut is one of the cuts that play a major role in nuclear background rejection. It is crucial to reject the background from η and ρ meson channels as well. As it is shown on Fig. 5.1, the NH_3 data has the clear signal near $M_{\pi^0}^2$ while the carbon data normalized to simulate the nitrogen in ammonia don't show any signs of peak due to the smearing from Fermi motion. So this variable allows us to separate events from polarized proton, removing events from nucleons in nitrogen and events from different channels. The standard fitting procedure was applied to determine the cut as shown of Fig. 5.4.

(a) after preliminary cuts

(b) after exclusive cuts

Figure 5.4: Squared missing mass MM_{epX}^2 . Plot (a) is produced with preliminary cut $\theta_{X\pi^0} < 10^\circ$ to make the polarized proton signal distinguishable from the nuclear background.

5.1.4 Cone angle between reconstructed and predicted π^0

For $\theta_{X\pi^0}$ cuts determination we deviated from the " 3σ " method. A different strategy is adopted in this case, since the variable $\theta_{X\pi^0}$ is not distributed following a Gaussian shape. So in order to define the best cut for background rejection the MM_{epX}^2 spectrum was analyzed from NH_3 and carbon targets. The carbon data were scaled using the negative tail of MM_{epX}^2 distribution to simulate the nitrogen background.

Figure 5.5: Angle between predicted and reconstructed π^0 (left column) and signal significance as a function of angle (right column). The "DIS" cuts and 3σ cut on MM_{epX}^2 were applied. Green lines indicate final cut values.

Looking for optimal $\theta_{X\pi^0}$ value the systematic linear search over the variable was performed (see Fig. 5.5). The signal significance $\frac{\sqrt{S+B}}{S}$ for MM_{epX}^2 distribution was analyzed for 50 cut values, and optimal cut was chosen with respect to its minimum. The signal significance is defined as follows:

$$\frac{\sqrt{S+B}}{S} = \frac{\sqrt{N_{NH_3} + sN_{C_{12}}}}{N_{NH_3} - sN_{C_{12}}} \quad (5.1)$$

where N_{NH_3} and $N_{C_{12}}$ are the number of events from NH_3 and carbon targets respectively, s is a normalization constant that scales carbon to nitrogen in ammonia.

5.1.5 $e\vec{p} \rightarrow ep\pi^0$ selection summary

The four-dimensional variable space was analyzed and conventional approach to separate signal from background in the form of set of rectangular cuts was used (see Fig. 5.6).

There are several factors that affect the resolution of deeply virtual π^0 events.

- The longitudinally polarized solid target was used and its magnetic shield should be accounted for during the particle tracking. It complicates the tracking, so that slight misalignments or incorrect knowledge of magnetic field cause uncertainties in reconstruction and require additional corrections, such as target field corrections.
- Another factor is nitrogen that introduces a huge nuclear background into the data. Some part of it is left even after the exclusive cuts application. So this contamination should be taken into consideration for further analysis.
- The resolutions of Inner Calorimeter and Electromagnetic Calorimeter are different. It is clearly visible from the cut values as the ICIC case always has a more narrow peak, ECEC - wider, and ECIC - being in the middle. To eliminate these effects, the kinematic variables used to define the reaction are calculated using the charged particles only, i.e. electron and proton. So the resolution of reconstructed photons affect only event statistics and not their kinematics.

(a) $E_{ep\gamma\gamma}$ vs MM_{epX}^2

(b) $\theta_{X\pi^0}$ vs $E_{ep\gamma\gamma}$

(c) MM_{epX}^2 vs $M_{\gamma\gamma}$

Figure 5.6: Projection of cuts on two dimensional variable distributions.

The final sets of cuts used for part A and B are given in Table 5.1 and 5.2.

Variable	ECEC	ICIC	ECIC
MM_{epX}^2 [GeV ²]	0.019 ± 0.13		
$E_{ep\gamma\gamma}$ [GeV]	-0.004 ± 0.65	-0.0139 ± 0.46	0.073 ± 0.5
M_{π^0} [GeV]	0.1329 ± 0.051	0.1363 ± 0.025	0.1341 ± 0.04
$\theta_{X\pi^0}$ [°]	< 1.8	< 1.2	< 1.6

Table 5.1: Part A summary cuts for $e\vec{p} \rightarrow ep\pi^0$ selection.

Variable	ECEC	ICIC	ECIC
MM_{epX}^2 [GeV ²]	0.0151 ± 0.13		
$E_{ep\gamma\gamma}$ [GeV]	-0.0269 ± 0.69	-0.044 ± 0.43	0.0586 ± 0.53
M_{π^0} [GeV]	0.1335 ± 0.051	0.1341 ± 0.025	0.136 ± 0.04
$\theta_{X\pi^0}$ [°]	< 1.8	< 1.2	< 1.6

Table 5.2: Part B summary cuts for $e\vec{p} \rightarrow ep\pi^0$ selection.

5.2 Beam and target polarizations

Target and beam polarizations were measured during the experiment using two independent systems: NMR system and Moller polarimeter. However, considering the systematic uncertainties associated with NMR measurements, a separate study was conducted using the exclusive elastic events. The product of beam and target polarizations was extracted in several Q^2 bins ranging from 2 to 5 GeV^2 as a ratio of experimental double spin asymmetry and expected asymmetry (Eq.5.2) from [45,46].

$$A_{||} = \frac{2\tau r \left[\frac{M}{E} + r \left(\tau \frac{M}{E} + (1 + \tau) \tan^2 \left(\frac{\theta}{2} \right) \right) \right]}{1 + \tau \frac{r^2}{\epsilon}} \quad (5.2)$$

where the ratio of form factors r was parameterized as $\frac{G_M}{G_E} = \frac{\mu_p}{1 - \frac{Q^2}{9}}$, given by [47]. The product of polarization is then given by:

$$P_b P_t = \frac{A_{exp}}{A_{||}} \quad (5.3)$$

The results showed no dependence on Q^2 and were averaged over the whole range for runs with the same polarization sign. Hence, the product was extracted separately for positively and negatively polarized targets (see Fig. 5.7, 5.8). The summary is given in Table 5.3 for each group of runs:

Part	$P_b P_t^+$	$P_b P_t^-$	P_b^{Moller}
Part A (5.887 GeV)	0.65 ± 0.02	-0.63 ± 0.02	0.868 ± 0.006
Part B (5.954 GeV)	0.67 ± 0.01	-0.63 ± 0.01	0.836 ± 0.006

Table 5.3: Summary on $P_b P_t$ values. The average beam polarization is obtained from Moller measurements.

The exclusive elastic events were chosen from events with electron and proton that passed our PID cuts using the following set of cuts:

- $0.84 < W < 1.02 \text{ GeV}$
- $|P_t| < 0.05 \text{ GeV}$ - missing transverse momentum

Figure 5.7: $P_b P_t$ extraction for positively and negatively polarized target: part A

Figure 5.8: $P_b P_t$ extraction for positively and negatively polarized target: part B

- $|E_{epX}| < 0.15$ GeV - missing energy
- $\theta_{pX} < 1.1^\circ$ - angle between reconstructed and predicted proton

The experimental asymmetry should be corrected for the quasi-elastic back-ground from the nucleons in nitrogen. After the exclusive cuts the nuclear back-ground was estimated to be less than 5%. It was determined using the exclusive elastic events from carbon target scaled accordingly to simulate the nitrogen back-

ground.

5.3 Dilution factor

In experiments with frozen ammonia target one should correct the measured asymmetries due to the contribution from the scattering on unpolarized nitrogen instead of polarized hydrogen. The so called "dilution factor" was measured using the data from NH_3 and Carbon target.

The description of target geometry used to determine the length of banjo and target beads packing fraction can be found in [34]. The Fig. 5.9 provide the schematic overview of targets geometries and their material properties.

Figure 5.9: Target schematic for eg1dvcs showing the targets used: loosely packed ammonia beads, an empty target cell, and a solid carbon target.

The dilution factor is the fraction of events from scattering on NH_3 target that corresponds to the scattering on polarized proton from hydrogen. It is calculated as:

$$f = 1 - s \frac{n_{C_{12}}}{n_{NH_3}} \quad (5.4)$$

where $n_{C_{12}}$ and n_{NH_3} are the number of events from carbon and NH_3 targets respectively normalized by corresponding Faraday-cup counts, the scaling constant s accounts for the difference between carbon and nitrogen that contribute to the nuclear background. This constant can be estimated with good precision as the ratio of number of nucleons in NH_3 target along the electron path to the number of nu-

cleons in carbon target. Since the number of nucleons is proportional to the mass the constant can be calculated as a ratio of areal densities of the materials along the beam path.

$$s = \frac{(L - l_{NH_3}) \rho_{He} + l_{Al} \rho_{AL} + l_K \rho_K + l_{NH_3} \rho_{NH_3} \frac{14}{17}}{(L - l_{C_{12}}) \rho_{He} + l_{Al} \rho_{AL} + l_K \rho_K + l_{C_{12}} \rho_{C_{12}}} = 0.726 \quad (5.5)$$

The statistics of data on carbon target doesn't allow us to perform the calculation of dilution factor for each of 4-dimensional kinematic bins individually. So the dilution dependence was tested along each of kinematic variables while integrating over the others. The results are shown on Fig. 5.10.

Figure 5.10: Dilution factor as a function of kinematic variables for exclusive π^0 electroproduction for part B.

An approximately flat behavior was observed for dilution factor along all 4 variables. Although the results slightly deviate along the ϕ . The further study showed that the cause of dilution ϕ dependence is in different acceptance of ECEC, ICIC

and ECIC detector configurations. The IC detector has better resolution over the EC, so, naturally, the exclusive cuts should be chosen tighter. The individual sets of cuts developed for each case to provide the best background to signal ratio led to the different rejection of nuclear background. Due to the ϕ acceptance we have less background near 0° and 360° and more near 180° as shown on Fig. 5.11.

Figure 5.11: ϕ dependence of dilution factor for ECEC (black) and ICIC (red) cases. The ECIC case represented by green points (part B only) is not fitted due to limited statistics.

For part A, however, the difference between dilution factors is much smaller presumably due to the change of target position. So the same dilution factor was adopted for the three cases in part A.

Part	f_{ECEC}	f_{ICIC}	f_{ECIC}
Part A (5.887 GeV)	0.908 ± 0.007	0.908 ± 0.007	0.908 ± 0.007
Part B (5.954 GeV)	0.903 ± 0.008	0.937 ± 0.005	0.912 ± 0.017

Table 5.4: Summary on dilution factor values.

5.4 Background subtraction

Despite the application of strict exclusivity cuts there are fraction of events that pass them without being a good exclusive π^0 production events. In order to account for them the distribution of two photons invariant mass $M_{\gamma\gamma}$ was studied. The

background under the invariant mass peak was assumed to be linear and fitted with Gaussian and first degree polynomial as shown on Fig. 5.12. The background diminishes drastically the further we move from π^0 mass, so the assumption of linear background persists only in 5σ region.

Figure 5.12: Invariant mass of two photons M_{π^0} . The 3σ cut used to select the good events (cyan) and 1.5σ wings were used to estimate background (red).

The ratio of the background to signal is defined as follows:

$$R = \frac{N_{bg}}{N_{3\sigma} - N_{bg}} \quad (5.6)$$

where $N_{3\sigma}$ is the number of events under the 3σ cut, N_{bg} is the number of events that belong to the wings $(-4.5\sigma, -3\sigma)$ and $(3\sigma, 4.5\sigma)$ and then multiplied by factor 2 to compensate the width difference.

The same sideband method was applied for each combination of target and beam polarization states in each of kinematic bins. This ratio distribution is plotted on Fig. 5.13. That way the possibility of polarized background is accounted for.

One should be careful using the sideband subtraction because the final invariant mass spectrum shows a slight ϕ -dependence due to the CLAS acceptance and resolution. The effect is negligible in signal counts but it would lead to significant overestimation of background if σ value averaged over ϕ is used. The average value will in principle be smaller than actual resolution for the worst bins and the π^0 events would be accounted as background.

To ensure that background is not overestimated the dataset was divided into several ϕ bins while integrated over all other kinematic variables due to the limited statistics. Then two photons mass distribution was fitted by a Gaussian plus a linear

Figure 5.13: Sideband background-to-signal ratio for all kinematic bins, polarization and detector configurations.

function to extract the corresponding mean and sigma values for each ϕ bin. The ϕ dependence of invariant mass resolution is shown on Fig. 5.14 separately for three detector configuration.

Figure 5.14: Top row shows $M_{\gamma\gamma}$ vs ϕ distribution. Bottom row shows resolution (σ) of invariant mass distribution as a function of ϕ . Dashed line for ECEC case indicates the "worst" resolution.

The ECEC detector configuration shows definite ϕ dependence confirmed by χ^2 values from zero-degree and second-degree polynomials used as fitting functions. Other cases can be safely assumed as ϕ independent.

In order not to introduce the ϕ dependence into the $M_{\gamma\gamma}$ cut the final value was chosen a little bigger than the highest sigma which corresponds to $\phi = 180^\circ$. Thus

we will not overestimate background by including signal events to the sidebands for the "worst" bins, while the only drawback would be a negligible increase of background to signal ratio and, therefore, final errors for other kinematic bins.

5.5 Radiative corrections

The radiative corrections for exclusive π^0 electroproduction on the proton were studied for the case where the final electron, proton and pion are detected [48]. According to this the inelasticity cut defined as:

$$v_{cut} = MM_{e p X}^2 - M_{\pi^0}^2 \quad (5.7)$$

plays a particularly important role since it restricts the maximum energy of the radiated photon. So the use of experimental cuts results in maximal possible energy of unobserved photon comparable with the resolution in the experiment. The hard-photon emission contribution decreases and the radiative correction is determined by loop effects and soft photon emission. In this case the radiative correction to spin average and spin dependent parts of the cross section is almost the same, leading to a negligible correction to polarization asymmetries. It has been listed under the systematic uncertainties and estimated to be less than 1 per cent.

5.6 Role of acceptance

The asymmetries are defined as ratios of counts for different helicity/polarization combinations. So the expectation is that acceptance enters the numerator as well as denominator and therefore cancels out. However, it is true only if the data analysis is performed in the small kinematic bins where the acceptance can be considered constant. In case of the data integrated over wide kinematic range of Q^2 , x_B , t and ϕ the measured asymmetry is related to the ratio of cross section and acceptance products:

$$A \sim \frac{\int \sigma_{pol}(Q^2, x_B, t, \phi) \eta(Q^2, x_B, t, \phi)}{\int \sigma_{unp}(Q^2, x_B, t, \phi) \eta(Q^2, x_B, t, \phi)} \quad (5.8)$$

Since the acceptance can differ within the non-zero kinematic bin it could, in principle, affect the asymmetries measurements.

However, the acceptance effect on the measured asymmetries was thoroughly examined in the study of the double polarization asymmetries for $\Delta(1232)$ by A. Biselli [49]. Although the physics is not related to the current analysis the technique and methods used to extract the polarized observables are similar. With the assumption on detector efficiency being 100% within strict fiducial regions, the CLAS detector acceptance is defined by its geometry. So the method based on calculation of geometrical acceptance was applied in [49].

It was found that even though the acceptance corrections strongly affect the numerator and denominator, the asymmetries themselves are almost unchanged. It is especially reassuring since this observation was made for the kinematic regions where acceptance have a much higher variations than expected in the current analysis. The expectation on less variations follows from the fact that asymmetry in [49] is defined using the partial integration over the half ϕ ranges: $0 < \phi < 180^\circ$ and $180 < \phi < 360^\circ$, while in current analysis we perform the fit using 11 ϕ bins. So the acceptance corrections to single and double spin asymmetry measurements in this study is recognized to be negligible within our statistical error bars.

5.7 Kinematic binning

The following set of independent kinematic variables is used to describe the final state of $e\vec{p} \rightarrow ep\pi^0$ reaction:

- Q^2 - virtual photon's 4-momentum squared
- x_B - Bjorken scaling variable
- t - momentum transfer to the proton
- ϕ - angle between lepton and hadron plane

In order to extract dependence of the asymmetries the rectangular four dimensional bins were defined. Unfortunately considering the limited statistics of experiment the number of bins is extremely limited. The priority was given to the ϕ and $-t$ variables because the dependence on ϕ allows us extraction of the moments and dependence on $-t$ provides insight on relative contributions of the nucleon helicity-flip and non-flip processes.

Two independent variables Q^2 and x_B are kinematically correlated because of the CLAS acceptance as shown on Fig. 5.15.

Figure 5.15: Q^2 vs x_B coverage.

The dataset left after the application of all PID and exclusivity cuts contains:

part A

14000 exclusive π^0 events

part B

29000 exclusive π^0 events

We divide all the events in two (Q^2, x_B) bins in Q^2 and x_B , then each bin is split into 5 bins in $-t$ with 11 bins in ϕ . The total number of kinematic bins is $2 \times 5 \times 11 = 110$. The projections of 4-dimensional binning are shown on Fig. 5.16.

Please note, that the $-t$ bin definitions are different for two $Q^2 - x_B$ bins due to the correlations between $-t$ and x_B that come from the CLAS acceptance. The ϕ bins are almost equidistant with two boundary bins being a little wider to account the smaller statistics on the edges of ϕ distribution.

Figure 5.16: Rectangular kinematic binning (red-ICIC, blue-ECEC, green-ECIC).

#	x_B bin	$\langle x_B \rangle$	$\langle Q^2 \rangle$ GeV ²
1	$x_B < 0.32$	0.250	1.91
2	$x_B > 0.32$	0.398	2.79

Table 5.5: Q^2 vs x_B bins definitions.

First Q^2 vs x_B bin ($x_B < 0.32$)			Second Q^2 vs x_B bin ($x_B > 0.32$)		
#	$-t$ bin	$\langle -t \rangle$ GeV ²	#	$-t$ bin	$\langle -t \rangle$ GeV ²
1	$0 < -t < 0.21$ GeV ²	0.155	1	$0 < -t < 0.41$ GeV ²	0.305
2	$0.21 < -t < 0.39$ GeV ²	0.289	2	$0.41 < -t < 0.63$ GeV ²	0.518
3	$0.39 < -t < 0.72$ GeV ²	0.541	3	$0.63 < -t < 0.91$ GeV ²	0.761
4	$0.72 < -t < 1.2$ GeV ²	0.951	4	$0.91 < -t < 1.3$ GeV ²	1.091
5	$1.2 < -t < 2$ GeV ²	1.520	5	$1.3 < -t < 2$ GeV ²	1.607

Table 5.6: $-t$ bins definitions.

5.7.1 Finite bin size

In every given individual bin the events are distributed with respect to the reaction cross section and experiment's acceptance. So to account for the effects due to finite bin size one has to compare the mean value of the fit function over the bin range to the value of the function in the evaluation point. To do so requires assumption of the fitting function shape and calculation of integral for each bin individually. Fortunately, to the first order the finite bin effects can be corrected for any general function, as shown in [50]. Therefore the weighted averages over the events in the

bin were used to define the values of the kinematic variables:

$$\langle Q^2 \rangle = \frac{1}{N} \sum_{i=1}^N Q_i^2, \quad \langle x_B \rangle = \frac{1}{N} \sum_{i=1}^N x_{Bi}, \quad \langle t \rangle = \frac{1}{N} \sum_{i=1}^N t_i, \quad \langle \phi \rangle = \frac{1}{N} \sum_{i=1}^N \phi_i \quad (5.9)$$

The mean values for Q^2 , x_B , $-t$ and ϕ are shown for each of 110 kinematic bins in part A and B on Fig. 5.17 and Fig. 5.18. They indicate that the kinematics from part A and B for each bin are statistically comparable.

(a) First Q^2 vs x_B bin (b) Second Q^2 vs x_B bin

Figure 5.17: 55 bins in $-t$ and ϕ and their average values. The error bars represent standard deviation inside the bin. The two markers correspond to part A and B in order to show similar kinematic coverages for both parts.

 (a) Second Q^2 vs x_B bin

 (b) Second Q^2 vs x_B bin

Figure 5.18: Average values of Q^2 and x_B for each of 55 bins in $-t$ and ϕ . Each cell is a Q^2 vs x_B frame with the same labels and ranges that are shown for bottom left cell. The error bars represent standard deviation inside the bin. The two markers correspond to part A and B in order to show similar kinematic coverages for both parts.

Chapter 6

Extraction of spin asymmetries

Due to the different dilution factor for different combinations of detectors, different values of negative and positive target polarizations and specific combination of beam and target helicities we use 12 independent variables obtained from the experiment in calculation of asymmetries. These variables are:

$$\begin{aligned} \{n_1^{++}, n_1^{+-}, n_1^{-+}, n_1^{--}\} &- ECEC \text{ combination of photons} \\ \{n_2^{++}, n_2^{+-}, n_2^{-+}, n_2^{--}\} &- ECIC \text{ combination of photons} \\ \{n_3^{++}, n_3^{+-}, n_3^{-+}, n_3^{--}\} &- ICIC \text{ combination of photons} \end{aligned} \quad (6.1)$$

where $n = \frac{N}{FC}$ - number of specific events normalized by Faraday Cup information.

The statistical error for asymmetry in particular kinematical bin is defined as:

$$dA_X = \sqrt{\sum_i \left(\frac{\partial A_X}{\partial n_i^{++}} dn_i^{++} \right)^2 + \sum_i \left(\frac{\partial A_X}{\partial n_i^{+-}} dn_i^{+-} \right)^2 + \sum_i \left(\frac{\partial A_X}{\partial n_i^{-+}} dn_i^{-+} \right)^2 + \sum_i \left(\frac{\partial A_X}{\partial n_i^{--}} dn_i^{--} \right)^2} \quad (6.2)$$

The index X represents target, beam or double spin asymmetry and can be UL , LU or LL . The i index denotes different detector combinations for π^0 photons and

can be *ECEC*, *ICIC*, *ECIC*.

6.1 Beam spin asymmetry

The beam spin asymmetry is defined in following equation:

$$A_{LU} = \frac{1}{P_b} \frac{P_t^- \sum_i f_i (n_i^{++} - n_i^{-+}) + P_t^+ \sum_i f_i (n_i^{+-} - n_i^{--})}{P_t^- \sum_i f_i (n_i^{++} + n_i^{-+}) + P_t^+ \sum_i f_i (n_i^{+-} + n_i^{--})} \quad (6.3)$$

6.2 Target spin asymmetry

The target spin asymmetry is defined in following equation:

$$A_{UL} = \frac{\sum_i (n_i^{++} + n_i^{-+}) - \sum_i (n_i^{+-} + n_i^{--})}{P_t^- \sum_i f_i (n_i^{++} + n_i^{-+}) + P_t^+ \sum_i f_i (n_i^{+-} + n_i^{--})} \quad (6.4)$$

6.3 Double spin asymmetry

The double spin asymmetry is defined in following equation:

$$A_{LL} = \frac{1}{P_b} \frac{\sum_i (n_i^{++} + n_i^{--}) - \sum_i (n_i^{+-} + n_i^{-+})}{P_t^- \sum_i f_i (n_i^{++} + n_i^{-+}) + P_t^+ \sum_i f_i (n_i^{+-} + n_i^{--})} \quad (6.5)$$

6.4 Combination of part A and part B results

Following discussion from previous section the kinematic coverages of part A and B agree with each other, so the asymmetries from corresponding kinematic bins can be combined.

The asymmetries from both parts were weighted by their statistical errors and combined to give an estimate with smaller error than either one separately.

$$A = A_A \frac{\sigma_B^2}{\sigma_A^2 + \sigma_B^2} + A_B \frac{\sigma_A^2}{\sigma_A^2 + \sigma_B^2} \quad (6.6)$$

The error on combined asymmetry is then given by:

$$\sigma^2 = \frac{\sigma_A^2 \sigma_B^2}{\sigma_A^2 + \sigma_B^2} \quad (6.7)$$

In order to verify that the results from two different parts are statistically compatible the differences between two resulting values for each kinematic bin were studied. Since the analysis was performed on two independent datasets, there is no correlation between their errors, so the error quadrature of their differences is simply defined as sum of corresponding error quadratures.

$$\Delta = A_A - A_B; \quad \sigma_\Delta^2 = \sigma_A^2 + \sigma_B^2 \quad (6.8)$$

The t -values were defined for each kinematic bin as $t = \frac{\Delta}{\sigma_\Delta}$ [42]. They are distributed as a Gaussian with mean of zero and a unit width (see Fig. 6.1) indicating the statistical compatibility of two datasets.

Figure 6.1: Results of the t -tests for each of the three asymmetries.

6.5 Extraction of asymmetry moments

Using the combined data from part A and B we can extract the different combination of structure function ratios from its ϕ dependence. The cross section for exclusive π^0 electroproduction in one-photon exchange approximation is defined as [20]:

$$\begin{aligned} \frac{2\pi}{\Gamma(Q^2, x_B, E)} \frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = & \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{UU}^{\cos 2\phi} \cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{UU}^{\cos \phi} \cos \phi \\ & + P_b \sqrt{2\epsilon(1-\epsilon)}\sigma_{LU}^{\sin \phi} \sin \phi \\ & + P_t \left(\sqrt{2\epsilon(1+\epsilon)}\sigma_{UL}^{\sin \phi} \sin \phi + \epsilon\sigma_{UL}^{\sin 2\phi} \sin 2\phi \right) \\ & + P_b P_t \left(\sqrt{1-\epsilon^2}\sigma_{LL}^{const} + \sqrt{\epsilon(1-\epsilon)}\sigma_{LL}^{\cos \phi} \cos \phi \right) \quad (6.9) \end{aligned}$$

where $\sigma_{UU}^{\cos \phi}$, $\sigma_{UU}^{\cos 2\phi}$, $\sigma_{LU}^{\sin \phi}$ are the same structure functions as σ_{LT} , σ_{TT} , $\sigma_{LT'}$ correspondingly. The new convention was applied in order to have the same style for all structure functions.

Then the differential cross sections can be rewritten in terms of asymmetries:

$$\begin{aligned} \frac{2\pi}{\Gamma(Q^2, x_B, E)} \frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = & \sigma_0 \left[1 + A_{UU}^{\cos 2\phi} \cos 2\phi + A_{UU}^{\cos \phi} \cos \phi \right. \\ & + P_b A_{LU}^{\sin \phi} \sin \phi \\ & + P_t \left(A_{UL}^{\sin \phi} \sin \phi + A_{UL}^{\sin 2\phi} \sin 2\phi \right) \\ & \left. + P_b P_t \left(A_{LL}^{const} + A_{LL}^{\cos \phi} \cos \phi \right) \right] \quad (6.10) \end{aligned}$$

where $A_{UU}^{\cos 2\phi}$, $A_{UU}^{\cos \phi}$, ... are proportional to the ratios of corresponding structure functions to unseparated unpolarized cross section $\sigma_0 = \sigma_T + \epsilon\sigma_L$.

The measured asymmetries are related to the moments from Eq.6.10:

$$A_{LU} = \frac{A_{LU}^{\sin \phi} \sin \phi}{1 + A_{UU}^{\cos 2\phi} \cos 2\phi + A_{UU}^{\cos \phi} \cos \phi} \quad (6.11)$$

$$A_{UL} = \frac{A_{UL}^{\sin\phi} \sin\phi + A_{UL}^{\sin 2\phi} \sin 2\phi}{1 + A_{UU}^{\cos 2\phi} \cos 2\phi + A_{UU}^{\cos\phi} \cos\phi} \quad (6.12)$$

$$A_{LL} = \frac{A_{LL}^{const} + A_{LL}^{\cos\phi} \cos\phi}{1 + A_{UU}^{\cos 2\phi} \cos 2\phi + A_{UU}^{\cos\phi} \cos\phi} \quad (6.13)$$

Thanks to CLAS full ϕ coverage, polarized electron beam, longitudinally polarized proton target and known ϕ dependence all polarization moments for exclusive π^0 electroproduction can be extracted for the first time.

6.5.1 Fitting procedure

For each kinematic bin in Q^2 , x_B and $-t$ space the asymmetry moments can be extracted from ϕ dependence of measured asymmetries. Usually each asymmetry is fitted separately because the moments are independent of each other. But it is clear from Eq.6.11-6.13 that all three variables share the same terms from unpolarized cross sections in their denominator. It allows us to perform a unique procedure to fit them all together improving the values and error bars of the moments.

Unfortunately, the number of free parameters in Eq.6.11-6.13 is too high even for simultaneous fit. So an assumption on $A_{UU}^{\cos\phi}$ was made to make the fit possible. There are two reasons why $A_{UU}^{\cos\phi}$ was chosen:

- The recent CLAS analysis [18] has shown that the corresponding structure function σ_{LT} is very small compared to unseparated σ_0 , so the $A_{UU}^{\cos\phi}$ can be neglected.
- This particular parameter is fully correlated with $A_{LL}^{\cos\phi}$ from double spin asymmetry making the fit values and errors unreliable.

So the final ϕ dependence is defined for asymmetries as:

$$A_{LU} = \frac{A_{LU}^{\sin\phi} \sin\phi}{1 + A_{UU}^{\cos 2\phi} \cos 2\phi} \quad (6.14)$$

$$A_{UL} = \frac{A_{UL}^{\sin\phi} \sin\phi + A_{UL}^{\sin 2\phi} \sin 2\phi}{1 + A_{UU}^{\cos 2\phi} \cos 2\phi} \quad (6.15)$$

$$A_{LL} = \frac{A_{LL}^{const} + A_{LL}^{\cos\phi} \cos\phi}{1 + A_{UU}^{\cos 2\phi} \cos 2\phi} \quad (6.16)$$

The same simultaneous fit procedure was applied for each of 10 bin in Q^2 , x_B and $-t$ space. The example is shown on Fig. 6.2 for the first bin.

Figure 6.2: Simultaneous ϕ fit for first bin in Q^2 , x_B and $-t$ space.

Figure 6.3: χ^2 distribution from simultaneous fits for 10 $\{Q^2, x_B, -t\}$ bins

In order to further evaluate fit results the correlations between parameters were tested. The beam, target and double spin asymmetries moments are fitted independently of each other to the different datasets and can not correlate. So it decreases the number of correlated pairs, as shown in the next sections.

6.5.2 Beam spin asymmetry

For the beam spin asymmetry in simultaneous fit the correlation is possible only for one pair of parameters: $A_{LU}^{\sin\phi}$ and $A_{UU}^{\cos 2\phi}$. The contour from MINUIT package is shown on Fig. 6.4. The contour represents the values of the parameters with minimization function $\chi^2 = \chi_0^2 + 1$ and shows the correlation between two parameters near found minimum. The third $-t$ bin in first Q^2 - x_B bin was chosen for demonstration purposes. From contour plot it is clear that correlation is negligible.

Figure 6.4: The contour representing the correlation between $A_{LU}^{\sin\phi}$ and $A_{UU}^{\cos 2\phi}$.

In order to test this result the different function $[f(\phi) = A_{LU}^{\sin\phi} \sin\phi]$ was used to fit the beam spin asymmetry only. It is similar to simultaneous fit but with common term $A_{UU}^{\cos 2\phi}$ fixed to zero. The comparison of the extracted moments $A_{LU}^{\sin\phi}$ are shown on Fig. 6.5.

Figure 6.5: Comparison of $-t$ dependence of $A_{LU}^{\sin\phi}$ moments from different fit functions.

The results confirm that correlation is negligible. The fit values though are sys-

tematically lower.

6.5.3 Target spin asymmetry

Figure 6.6: Correlations between target spin asymmetry moments.

The correlations for parameters related to target spin asymmetry are shown on Fig. 6.6. The correlations are higher than in case of beam spin asymmetry due to higher number of free parameters.

The same method as for the beam spin asymmetry was applied. The denominator term was fixed to zero $\left[f(\phi) = A_{UL}^{\sin \phi} \sin \phi + A_{UL}^{\sin 2\phi} \sin 2\phi \right]$ and fit was performed again to the target spin asymmetry only. The results are shown on Fig. 6.7. The results from simultaneous fit have very slightly higher error bars, and again systematically smaller values specifically for $A_{UL}^{\sin \phi}$.

6.5.4 Double spin asymmetry

The effect from correlations is even bigger for double spin asymmetry. It is clearly visible on Fig. 6.10, where the results from simultaneous fit and results from the fit to double spin asymmetry only using the function $\left[f(\phi) = A_{LL}^{const} + A_{LL}^{\cos \phi} \cos \phi \right]$ are presented. The advantage of simultaneous fit for double spin asymmetry is visible with naked eye even on the ϕ dependence plots, as shown on Fig. 6.9 for one of the kinematic bins in Q^2 - x_B space. Without the denominator term the fit fails to account for the small deviation from the flat behavior near $\phi = 180^\circ$.

Figure 6.7: Comparison of $-t$ dependence of target spin asymmetry moments from different fit functions.

Figure 6.8: Correlations between double spin asymmetry moments.

Generally the correlations in multiparameter fit always increase the errors of the free parameters. In that sense the results from the fit function without common denominator term have advantage of slightly smaller error bars due to the fix on parameter $A_{UU}^{\cos 2\phi}$, as if it is known to be zero. Unfortunately this approach leads to the underestimated errors and fit values due to the assumption on the unpolarized cross section value. If at some point one will use the ratio of structure functions in our kinematic bins from the recent CLAS measurement of exclusive π^0 electroproduction [18], that would very slightly increase the precision. However, at this level of the analysis the data from only eglvcs experiment are used in order not to introduce the systematic uncertainty associated with the data from another experiment.

Figure 6.9: Comparison of functions used to fit the ϕ dependence of double spin asymmetry.

(a) 2 bins on Q^2 vs x_B surface

(b) 2 bins on Q^2 vs x_B surface

Figure 6.10: Comparison of $-t$ dependence of double spin asymmetry moments from different fit functions.

Especially since it would provide very slight improvements only.

Chapter 7

Systematic uncertainties

There are many sources of systematic uncertainties that can affect the final values of asymmetries. The measured values depend on various parameters that correct the directly measured quantities to the desired asymmetries. So the errors of these parameters will be treated as one type of systematic uncertainties in this analysis. For example, dilution factors and polarization products were determined in the same experiment, but from separate measurements, and their statistical error will contribute to the asymmetries systematics.

The another type comes from the different assumptions and models that were used in order to select the exclusive π^0 events and affect the directly measured quantity, i.e. counts. It includes the exclusivity cuts values and sideband background subtraction.

While the first type of uncertainties is statistical by its nature their propagation is straightforward, and effect on final asymmetry can be evaluated analytically up to some point. The second type is more difficult to handle and require numerical approach. To estimate the uncertainties associated with selection procedure one needs to alter the cut values and run the data selection again to obtain the different dataset. One of the methods involves the composition of second dataset selected with adjusted cuts, e.g. $3\sigma \rightarrow 2\sigma$ for any variable used in exclusive cuts. However, this method doesn't account for the statistical fluctuations of the measured quantity. It is particularly important for the current analysis since the number of counts is

low, and statistical errors are dominant.

To suppress the contribution from statistical fluctuation a considerably high number of datasets was selected altering the exclusive cuts by smaller steps, e.g (3σ , 2.95σ , 2.9σ , ..., 2σ). Then the obtained values for asymmetries were plotted vs the altered cuts to deduce whether there is any systematic trend associated with corresponding cut. The assumption was made that any systematic tendency on this range can be described as linear. So the values from different datasets were fitted with first degree polynomial and the difference between two boundary values was taken as a systematic uncertainty.

7.1 Angle between reconstructed and predicted π^0

The $\theta_{X\pi^0}$ cut has been altered from 85% of $\theta_{X\pi^0}$ to 100% with 1% step size. Obtained 16 data subsets were analyzed using the same procedure to measure the beam, target and double spin asymmetries for each kinematic bin. Following the discussion from previous section the asymmetries were fitted to get the value of systematic uncertainty for each bin. The example for the first $\{Q^2, x_B, -t, \phi\}$ bin is shown of Fig. 7.1

Figure 7.1: Asymmetries measured with angular cut values from 85% of $\theta_{X\pi^0}$ to 100% with 1% step size.

The distribution of systematic errors for 110 bins is shown on Fig. 7.2. To estimate the systematic effect to the asymmetry moments extracted from the simultaneous fit the same procedure was applied to them, and their errors are plotted on Fig. 7.3 for 10 $\{Q^2, x_B, -t\}$ kinematic bins. Only $A_{LU}^{\sin\phi}$, $A_{UL}^{\sin\phi}$ and A_{LL}^{const} are shown as they are roughly proportional to the values of spin asymmetries near 90° .

Figure 7.2: Asymmetries systematic errors (blue) associated with angular cut. Red color shows the distribution of statistical errors to demonstrate their dominance.

Figure 7.3: Systematic errors (blue) of asymmetry moments associated with angular cut.

7.2 Missing mass squared

The MM_{epX}^2 cut value has been altered from 80% to 100% with 2% step corresponding to 2.4σ , 3σ and 0.06σ respectively. Distribution of systematic errors is shown on Fig. 7.4

(a) Systematic (blue) and statistical (red) errors of asymmetries

(b) Systematic errors of asymmetry moments

Figure 7.4: Systematic errors associated with MM_{epX}^2 cut.

7.3 Invariant mass of two photons

The $M_{\gamma\gamma}$ cut has been altered from 66% to 100% with 2% step corresponding to 2σ , 3σ and 0.06σ respectively. Distribution of systematic errors is shown on Fig. 7.5

Figure 7.5: Systematic errors associated with invariant mass of two photons cut.

7.4 Background subtraction

To test the systematic effect of sideband background subtraction method the width of sideband has been altered from 1σ to 1.5σ with step size 0.03σ . The wider range can not be tested due to the limited statistics. The distribution of errors is shown on Fig. 7.6.

7.5 Summary on systematic uncertainties

The systematic uncertainties associated with exclusivity cuts were discussed above. Please note that they are extremely correlated with each other and should not be put together. Usually decreasing the value of one exclusive cut leads to reduction of background in distribution of other exclusive variables. Also the dilution factor and sideband events should be recalculated every time the cut changes.

Figure 7.6: Systematic errors associated with MM^2_{epX} cut.

So in the worst-case scenario the conservative estimates do not exceed ± 0.007 , ± 0.01 and ± 0.011 for the beam, target and double spin asymmetry moments. These values correspond to about $\pm 9\%$, $\pm 5\%$ and $\pm 3\%$ relative systematic uncertainties. While the relative statistical errors are in average about $\pm 30\%$.

The systematic uncertainty from dilution factor was estimated from its statistical error. The almost analytical approach is possible for this type of systematic uncertainty. So from Table 5.4 we can conclude that uncertainty associated with dilution is less than 1%.

Similar to dilution factor uncertainty on target polarization that was extracted from elastic measurements affect the final correction and doesn't change the directly measured quantities. So from Table 5.3 the systematic uncertainty from $P_b P_t$ value is estimated to be less than 3%.

Chapter 8

Results

The $-t$ dependence of the polarized asymmetry moments are shown in the next sections with the perspective from theoretical model used to describe the exclusive π^0 electroproduction. The model investigates the exclusive π^0 electroproduction within the framework of modified perturbative approach.

Although the GK model showed good agreement with unpolarized structure functions [18], the prediction of asymmetries involves calculations of polarized structure functions. And they are more difficult to calculate due to the interferences between transverse and longitudinal GPDs. One should not only estimate the modulus of helicity amplitudes but also the relative phases between them.

More details on GPDs parameterization and comparison as well as calculation of polarized asymmetries can be found in [23]. The results of GPD-based model are shown on the same plots with data as curves.

The eg1dvcs is the first experiment to measure the beam, target and double spin asymmetries together from exclusive π^0 electroproduction. But the recent CLAS analyses include the measurements of unpolarized structure functions and beam spin asymmetries in a wide kinematic range. So the comparisons between our and previous measurements can be done for some of the measured quantities.

8.1 Unpolarized structure functions

From Eq.6.14-6.16 one can see that the only term related to the unpolarized structure functions is the denominator term:

$$A_{UU}^{\cos 2\phi} = \frac{\varepsilon \sigma_{UU}^{\cos 2\phi}}{\sigma_0} \quad (8.1)$$

The unpolarized structure functions were taken from e1dvcs experiment [18] as close as possible to the kinematic bins of current analysis. Then their ratios scaled with average kinematic coefficient ε were plotted on Fig. 8.1 together with $A_{UU}^{\cos 2\phi}$ parameters obtained from simultaneous fit.

Figure 8.1: Comparison of unpolarized term with previous experiment measurements.

The unpolarized term is not a variable of main interest in current analysis. There are much better suited experiments to extract the unpolarized structure functions using unpolarized proton target without nuclear background involved. These data were obtained as a by-product and were used to cross check the analysis with the recent dedicated π^0 electroproduction measurements.

8.2 Beam spin asymmetry

The beam spin asymmetry moment is proportional to the ratio of structure functions:

$$A_{LU}^{\sin\phi} = \sqrt{2\varepsilon(1-\varepsilon)} \frac{\sigma_{LU}^{\sin\phi}}{\sigma_0} \quad (8.2)$$

The comparison with previously measured beam spin asymmetries can be made. The beam spin asymmetry data from e1dvcs experiment [30] were taken in similar kinematic bins as shown on Fig. 8.2.

Figure 8.2: Beam spin asymmetry moments for eg1dvcs (red) and e1dvcs (blue) experiments.

Please note that $-t$ binning are different in both experiments with e1dvcs bins being wider. The combination of a few data points for high $-t$ bins from eg1dvcs experiment would bring the result to even better agreement especially for second $\{Q^2 - x_B\}$ bin.

To check the beam spin asymmetry behavior for $-t$ between 0.5 GeV^2 and 1 GeV^2 the bigger kinematic bin was analyzed. This bin $0.2 < x_B < 0.4$ combines most of the statistics from two current bins and allow us to make different $-t$ binning as shown on Fig. 8.3. From this plot the $-t$ behavior is analyzed more closely and reveals gradual decrease of beam spin asymmetry amplitude.

So the beam spin asymmetry slowly decreases at higher $-t$ values. But second $\{Q^2, x_B\}$ bin shows the sudden increase after $-t > 1.5 \text{ GeV}^2$.

Figure 8.3: Beam spin asymmetry moments for one combined bin.

8.3 Target spin asymmetry

The target spin asymmetry is defined as a ratio of structure functions:

$$A_{UL}^{\sin\phi} = \sqrt{2\varepsilon(1+\varepsilon)} \frac{\sigma_{UL}^{\sin\phi}}{\sigma_0} \quad (8.3)$$

The $\sin\phi$ component of target spin asymmetry seems to dominate $\sin 2\phi$ component at small $-t'$ region. But as $-t'$ grows the $\sin 2\phi$ component starts to increase.

Note, that $A_{UL}^{\sin 2\phi}$ is approximately zero in GK model. It follows from the assumption on hierarchy of helicity amplitudes used to calculate the target spin asymmetry. Its deviation from zero especially at higher $-t$ values could be an indication of incorrect treatment of higher-twist contribution or uncertainties in the transversity GPDs parameterization.

Figure 8.4: Target spin asymmetry moments. The axis on top shows the target asymmetry moments as a function of t' . The axes on the right show the ratio of structure functions to represent the data independently of the experiment setup and beam energy.

8.4 Double spin asymmetry

The double spin asymmetry moments are written as:

$$A_{LL}^{const} = \sqrt{1 - \varepsilon^2} \frac{\sigma_{LL}^{const}}{\sigma_0} \quad (8.4)$$

$$A_{LL}^{\cos\phi} = \sqrt{\varepsilon(1 - \varepsilon)} \frac{\sigma_{LL}^{\cos\phi}}{\sigma_0} \quad (8.5)$$

Figure 8.5: Double spin asymmetry moments. The axes on top shows the double asymmetry moments as a function of t' . The axes on the right shows the ratio of structure functions to represent the data independently of the experiment setup and beam energy. Please note the dashed lines on top plots, they represent theoretical predictions from GL model available for A_{LL}^{const} only at this moment.

8.5 Transverse photons contribution

The Goloskokov-Kroll model utilizes the transversity GPDs in the calculation of π^0 electroproduction. Within their modified perturbative approach the polarized observables can be expressed in terms of helicity amplitudes as shown in Section 2.2.3. There are few mild assumptions then made on hierarchy of helicity amplitudes which simplify the calculations and provide model-dependent expressions of asymmetries. From these formulae expanded in details in Appendix C one is in the position to perform the separation of longitudinal and transverse photons contributions to unpolarized cross section, i.e. σ_L and σ_T , within the framework of Goloskokov-Kroll model. The ratio of σ_L over σ_T is shown on Fig. 8.6.

Figure 8.6: The ratio of σ_L over σ_T within the GK model.

From the interpretation of these results it is evident that the contribution of σ_L is of a small fraction to unseparated cross section. The ratio is less than 15% for almost all bins identifying the π^0 electroproduction as a uniquely sensitive process to access the transversity GPDs.

Chapter 9

Conclusion

The longitudinally polarized beam and longitudinally polarized proton target in eg1dvcs experiment allowed measurements of three polarization observables for deeply virtual exclusive π^0 electroproduction in wide kinematic range at CLAS. The target and double spin asymmetries were measured for the first time in DIS region, while the beam spin asymmetries served as a cross check and showed good agreement with previous CLAS experiments.

The first interpretation of newly obtained data from Goloskokov-Kroll model perspective was done. Unfortunately the precise calculation of all details of π^0 electroproduction is not possible at present. The current model predictions of single and double spin asymmetries do not agree with eg1dvcs measurements due to the lack of data to constrain the parameterization of transverse GPDs and their relative phases corresponding to the polarized structure functions. The exact treatment of the twist-3 contribution is also uncertain.

The contributions from transverse photons are dominant in the π^0 production. The behavior of the asymmetries as a functions of t is defined by relation between two primarily contributing GPDs, H_T and $\bar{E}_T$. The calculations from GK model shows the dominance of $\bar{E}_T$ over H_T and agree rather well with recent CLAS measurement of unpolarized cross sections of π^0 electroproduction. However, the correct parameterization of non-dominant H_T is required to describe the polarized observables. It is clear from data and model disagreement that the relative H_T contri-

bution is underestimated.

The fact that we can access 5 polarized moments from eg1dvcs data presented the opportunity to perform the amplitude analysis in GK model framework. With a few mild assumptions the dominance of transverse photons was confirmed.

The double spin asymmetry A_{LL}^{const} was compared to the Goldstein-Liuti model prediction. The more extensive data-driven determination (from EM form factors, PDFs, DVCS and some lattice gauge parameters) of the chiral-even helicity amplitudes and GPDs leads to better agreement with measured observables especially in the high- t region. The interplay between $\bar{E}_T$ and H_T GPDs as well as $\tilde{E}_T$ defines the model behavior. The calculations from GL model, in which E_T dominates at high- t values, agree with our experimental results. However, at low- t region the parameterizations of H_T and $\tilde{E}_T$ and their contributions relative to $\bar{E}_T$ seem to be underestimated.

The contribution of transverse photons is decreasing as Q^2 grows. So fortunately the Jefferson Lab upgrade program will provide data at the region where twist-2 contributions are dominant. It is not yet clear what value of Q^2 is required. However, future measurements of polarized observables may test model independent features of the reaction mechanism and supply further constraints for GPDs.

Appendix A Asymmetries from part A and B

Figure 9.1: Part A and B beam spin asymmetries plotted together. Left and right columns are two Q^2 and x_B kinematic bins with 5 $-t$ bins in corresponding rows.

Figure 9.2: Part A and B target spin asymmetries plotted together. Left and right columns are two Q^2 and x_B kinematic bins with 5 $-t$ bins in corresponding rows.

Figure 9.3: Part A and B double spin asymmetries plotted together. Left and right columns are two Q^2 and x_B kinematic bins with 5 $-t$ bins in corresponding rows.

Appendix B Simultaneous fit at different kinematics

Figure 9.4: Simultaneous fit for 1st-2nd $-t$ bins in first Q^2 - x_B bin.

B. SIMULTANEOUS FIT AT DIFFERENT KINEMATICS

Figure 9.5: Simultaneous fit for 3rd-5th $-t$ bins in first Q^2 - x_B bin.

B. SIMULTANEOUS FIT AT DIFFERENT KINEMATICS

Figure 9.6: Simultaneous fit for 1st-2nd $-t$ bins in second Q^2 - x_B bin.

B. SIMULTANEOUS FIT AT DIFFERENT KINEMATICS

Figure 9.7: Simultaneous fit for 3rd-5th $-t$ bins in second Q^2 - x_B bin.

Appendix C Amplitude analysis

Within Goloskokov-Kroll model the polarized structure functions are expressed in terms of the helicity amplitudes combinations. Then in the handbag approach with allowance of contributions from the transversity GPDs the helicity amplitudes are related to the convolutions of hard scattering amplitude and GPDs. The relations between polarized structure functions and GPDs are given below:

$$\sigma_L = \frac{4\pi\alpha}{k} \frac{1}{Q^2} \left\{ (1 - \xi^2) |\langle \tilde{H} \rangle|^2 - 2\xi^2 \text{Re} [\langle \tilde{H} \rangle^* \langle \tilde{E} \rangle] - \frac{t'}{4m^2} \xi^2 |\langle \tilde{E} \rangle|^2 \right\} \quad (9.1)$$

$$\sigma_T = \frac{4\pi\alpha}{2k} \frac{\mu_\pi^2}{Q^4} \left[(1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8m^2} |\langle \bar{E}_T \rangle|^2 \right] \quad (9.2)$$

$$\sigma_{UU}^{\cos\phi} = \sigma_{LT} = \frac{4\pi\alpha}{\sqrt{2}k} \frac{\mu_\pi}{Q^3} \xi \sqrt{1 - \xi^2} \frac{\sqrt{-t'}}{2m} \text{Re} [\langle H_T \rangle^* \langle \tilde{E} \rangle] \quad (9.3)$$

$$\sigma_{UU}^{\cos 2\phi} = \sigma_{TT} = \frac{4\pi\alpha}{k} \frac{\mu_\pi^2}{Q^4} \frac{t'}{16m^2} |\langle \bar{E}_T \rangle|^2 \quad (9.4)$$

$$\sigma_{LU}^{\sin\phi} = \sigma_{LT'} = \frac{4\pi\alpha}{\sqrt{2}k} \frac{\mu_\pi}{Q^3} \xi \sqrt{1 - \xi^2} \frac{\sqrt{-t'}}{2m} \text{Im} [\langle H_T \rangle^* \langle \tilde{E} \rangle] \quad (9.5)$$

$$\sigma_{UL}^{\sin\phi} = -\frac{4\pi\alpha}{\sqrt{2}k} \frac{\mu_\pi}{Q^3} \sqrt{1 - \xi^2} \frac{\sqrt{-t'}}{2m} \text{Im} [\langle \bar{E}_T \rangle^* \langle \tilde{H}_{eff} \rangle + \xi \langle H_T \rangle^* \langle \tilde{E} \rangle] \quad (9.6)$$

$$\sigma_{LL}^{const} = \frac{4\pi\alpha}{2k} (1 - \xi^2) |\langle H_T \rangle|^2 \quad (9.7)$$

$$\sigma_{LL}^{\cos\phi} = -\frac{4\pi\alpha}{\sqrt{2k}} \frac{\mu\pi}{Q^3} \sqrt{1 - \xi^2} \frac{\sqrt{-t'}}{2m} \operatorname{Re} [\langle \bar{E}_T \rangle^* \langle \tilde{H}_{eff} \rangle + \xi \langle H_T \rangle^* \langle \tilde{E} \rangle] \quad (9.8)$$

References

- [1] R. Hofstadter, *Rev. Mod. Phys.* **28**, 214 (1956).
- [2] G. Miller *et al.*, *Phys. Rev. D* **5**, 528 (1972).
- [3] M. Gell-Mann, *Physics Letters* **8**, 214 (1964).
- [4] M. Guidal, H. Moutarde, and M. Vanderhaeghen, *Rept.Prog.Phys.* **76**, 066202 (2013).
- [5] D. Mueller, D. Robaschik, B. Geyer, F. M. Dittes, and J. Horejsi, *Fortschr. Phys.* **42**, 101 (1994).
- [6] X. Ji, *Phys. Rev. Lett.* **78**, 610 (1997).
- [7] M. Burkardt, *Phys. Rev. D* **66**, 119903 (2002).
- [8] A. Radyushkin, *Physics Letters B* **380**, 417 (1996).
- [9] A. V. Belitsky, D. Mueller, and A. Kirchner, *Nucl. Phys.* **B629**, 323 (2002).
- [10] J. C. Collins, L. Frankfurt, and M. Strikman, *Phys. Rev. D* **56**, 2982 (1997).
- [11] X. Ji, *Phys. Rev.* **D55**, 7114 (1997).
- [12] A. V. Radyushkin, *Phys. Rev.* **D56**, 5524 (1997).
- [13] V. Kubarovsky, *Nuclear Physics B - Proceedings Supplements* **219-220**, 118 (2011).
- [14] M. Diehl, *Phys. Rept.* **388**, 41 (2003).

- [15] A. Belitsky and A. Radyushkin, *Physics Reports* **418**, 1 (2005).
- [16] K. Goeke, M. V. Polyakov, and M. Vanderhaeghen, *Prog. Part. Nucl. Phys.* **47**, 401 (2001).
- [17] M. Gockeler *et al.*, *Phys.Rev.Lett.* **98**, 222001 (2007).
- [18] I. Bedlinskiy *et al.*, *Phys. Rev. Lett.* **109**, 112001 (2012).
- [19] A. V. Belitsky, *AIP Conf.Proc.* **698**, 607 (2004).
- [20] M. Diehl and S. Sapeta, *Eur. Phys. J.* **C41**, 515 (2005).
- [21] S. Ahmad, G. R. Goldstein, and S. Liuti, *Phys. Rev.* **D79**, 054014 (2009).
- [22] S. V. Goloskokov and P. Kroll, *Eur. Phys. J.* **C65**, 137 (2010).
- [23] S. Goloskokov and P. Kroll, *Eur.Phys.J.* **A47**, 112 (2011).
- [24] G. Goldstein, J. O. G. Hernandez, and S. Liuti, *to be published* (2013).
- [25] G. R. Goldstein, S. Liuti, and J. O. G. Hernandez, *Proceedings of QCD Evolution Workshop III, Jefferson Lab* (2013).
- [26] G. R. Goldstein, J. O. Hernandez, and S. Liuti, *Phys.Rev.* **D84**, 034007 (2011).
- [27] M. Burkardt, *Phys. Rev.* **D72**, 094020 (2005).
- [28] M. Diehl, *Eur.Phys.J.* **C19**, 485 (2001).
- [29] S. V. Goloskokov and P. Kroll, *Eur. Phys. J.* **C53**, 367 (2008).
- [30] R. De Masi *et al.*, *Phys. Rev. C* **77**, 042201 (2008).
- [31] C. Leemann, D. Douglas, and G. Krafft, *Ann.Rev.Nucl.Part.Sci.* **51**, 413 (2001).
- [32] H. Liu, *Nucl.Instrum.Meth.* **A400**, 213 (1997).
- [33] B. Mecking *et al.*, *Nucl.Instrum.Meth.* **A503**, 513 (2003).

REFERENCES

- [34] C. Keith *et al.*, *Nucl.Instrum.Meth.* **A501**, 327 (2003).
- [35] M. Mestayer *et al.*, *Nucl.Instrum.Meth.* **A449**, 81 (2000).
- [36] G. Adams *et al.*, *Nucl.Instrum.Meth.* **A465**, 414 (2001).
- [37] E. Smith *et al.*, *Nucl.Instrum.Meth.* **A432**, 265 (1999).
- [38] M. Amarian *et al.*, *Nucl.Instrum.Meth.* **A460**, 239 (2001).
- [39] P. Bosted, S. Kuhn, and Y. Prok, *CLAS-NOTE* **03-008** (2003).
- [40] S. Niccolai, *Polarized target in gsim*, eg1-dvcs wiki.
- [41] S. Niccolai, *Gpp for eg1-dvcs simulation*, eg1-dvcs wiki.
- [42] S. Niccolai, S. Pisano, A. Biselli, G. Smith, and E. Seder, *Measurements of single- and double-spin asymmetries for deeply virtual compton scattering with a polarized electron beam and a longitudinally polarized proton target, private communication.*
- [43] F.-X. Girod, *Fiducial cuts*, e1-dvcs wiki.
- [44] P. Bosted, *Ic shadow cuts*, eg1-dvcs wiki.
- [45] B. Blankleider and R. M. Woloshyn, *Phys. Rev. C* **29**, 538 (1984).
- [46] T. Donnelly and A. Raskin, *Annals of Physics* **169**, 247 (1986).
- [47] P. E. Bosted, *Phys. Rev. C* **51**, 409 (1995).
- [48] A. Afanasev, I. Akushevich, V. Burkert, and K. Joo, *Phys.Rev.* **D66**, 074004 (2002).
- [49] A. S. Biselli *et al.*, *Phys. Rev. C* **78**, 045204 (2008).
- [50] F. X. Girod *et al.*, *Phys. Rev. Lett.* **100**, 162002 (2008).

CLAS를 이용한 세로방향의 편극양성자 과녁에 대한 심층가상 배타적 π^0
생성에서의 단일 및
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심층가상 배타적 과정들은 카이럴 짝수의 일반화된 쪽입자 분포 (Generalized Parton Distributions, GPDs)와 카이럴 홀수의 가로방향 GPDs에 민감한 구조함수와 그 비율들을 측정함으로써 핵자의 내부구조를 조사한다. GPDs는 세로방향의 운동량 공간 및 가로방향의 충격 파라미터 공간에서 쪽입자 분포들의 상관관계를 표시하며 중간자 생성의 x_B 와 t 에 대한 의존도를 측정함으로써 획득되어질 수 있다. CLAS 검출기의 넓은 운동학적 범위는 전체 방위각 범위에서 배타적 π^0 전자생성의 측정을 가능하게 한다. 심층가상 배타적 π^0 전자생성은 심층 비탄성 산란 영역에서 과녁과 이중스핀 비대칭성이 처음으로 측정되었다. 이 실험은 제퍼슨 가속기 연구소의 Hall B에서 최대 에너지 6 GeV의 세로방향 편극 전자빔과 빔 축 방향으로 정렬된 자유 양성자 스핀의 동역학적 편극 NH_3 과녁을 이용하여 실행되었다. 배타적 채널에서 나타난 4개의 최종상태 입자들, 즉, 전자, 양성자, π^0 붕괴에서 나온 2개의 광자들이 모두 확인되었다. 비대칭성들은 강입자 질량중심계에서 각도 조정에 따라 fitting 되고 모멘트들이 추출되었다. 카이럴 짝수와 카이럴 홀수 GPDs의 기여가 포함된 두 종류의 핸드백 기반의 계산과 실험 데이터와의 비교는 넓은 운동학적 영역에서 실행되었다. 수정된 섭동 접근 체제 내에서 일반화된 쪽입자 분포에 기반을 둔 수식체계의 적용 가능성이 논의되었다.