New Research Proposal to Jefferson Lab PAC 21

Coherent Vector Meson Production off the Deuteron

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Abstract

Coherent production of vector mesons off the deuterium using a 6 GeV electron beam and the CLAS detector at Jefferson Lab will be used to investigate hard exclusive processes.

The large acceptance offered by the CLAS detector and its capability of detecting multi-particle final states will allow a simultaneous measurement of the electroproduction of ρ, ω, and ϕ mesons over a large kinematic range: $1 < Q^2 < 4.5$ $(\mathrm{GeV/c})^2$, $0.1 < x < 0.5$, and $0.1 < -t < 1$ $(\mathrm{GeV/c})^2$.

The production of the $q\bar{q}$ and its evolution into the final hadronic state will be studied in the range where the vector meson dominance describes the process to the regime where QCD degrees of freedom become important. This measurement, together with CLAS data on the vector meson electroproduction off a proton target at 6 GeV, will provide important information on the production of small size configurations of quarks and gluons in hard exclusive processes, and on the interaction of these objects with nuclear matter. The reduced interaction of small-size objects is known as the *Color Transparency* (CT) phenomenon.

This experiment will form the basis of a broad program, ultimately including polarization observables and photoproduction experiments, that will lead to investigations with the proposed CEBAF 12 GeV upgrade. For the proposed measurement we request a total of 66 days of beam time, of which 16 days will be concurrently with the approved E6 run with CLAS in the standard configuration. The remaining 50 days are new beam time at 6 GeV with a modified CLAS configuration.

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1 Introduction

One of the fundamental properties of QCD is the decreased interaction between quarks and gluons at short distances due to the phenomenon of asymptotic freedom. Small size configurations (also called point-like configurations, PLCs) of quarks and gluons produced in hard scattering reactions [1] will interact weakly with nuclear matter. This leads to the fundamental prediction of QCD, the existence of *color transparency* (CT), *i.e.* nuclear matter becomes transparent to a small color singlet object (see e.g. [2, 3] and references therein).

One important feature of hard reactions is the possibility to separate the perturbative and non-perturbative parts of the interaction, known as the *factorization property.* Qualitatively, the presence of a hard probe allows one to create small size quark-gluon configurations whose interactions can be described in pQCD. The recently developed formalism of a QCD description of deep exclusive reactions [4, 5, 6] opens a new avenue for studying the structure of hadrons in terms of interacting quarks and gluons through the *Generalized Parton Distributions* (GPDs). Here the interaction is factorized into a hard scattering part (exactly calculable in pQCD) and a non-perturbative nucleon structure part (parametrized via GPDs).

While theoretical guidance is available, experiments ultimately define the kinematic range where quark-gluon degrees-of-freedom dominate the description of hard exclusive reactions. Experimentally establishing the existence of CT is crucial for understanding the dynamics of hard reactions. By embedding a hard process inside nuclei one can effectively study the production, and the transition of the produced quark-gluon configuration into the final hadronic state. Using spectator nucleons to study the interaction of the produced object over a wide range of transferred momentum will establish the kinematical domain where pQCD becomes important.

Our goal is to study CT phenomena in the transition region from the $soft$ to the *hard* limit. The main emphasis in many color transparency studies has been nucleon electro-knockout processes, although it is widely expected that one should observe the onset of color coherence in meson electroproduction earlier than for the case of nucleon knockout. The simple argument here is that it is easier to bring the $q\bar{q}$ quarks of a meson close together to form a PLC, than the qqq of the baryon. Existing and proposed experiments studying CT with meson production are concentrated on semi-inclusive reactions. In these measurements one is not able to control the interaction process in the initial and final state separately.

We propose to study color transparency phenomena in fully exclusive measurements of coherent vector meson production off deuterium, $e + d \rightarrow e' + V + d'$. These reactions offer the most promising channel for studying color coherent effects. Vector meson production has a large cross section at high energies, and the deuteron is the best understood and simplest nuclear system. The detection of the nuclear response in coincidence with the produced final state hadron will be used as a method to investigate the space-time picture of high energy two-body reactions. Exclusivity allows the kinematics of both initial and final state to be controlled separately.

Measurements will be carried out using the CLAS detector in Hall B and a 6 GeV electron beam at Jefferson Lab. CLAS is well suited for the detection and identification of multi-particle final states. The large acceptance will allow measurements of vector meson production spanning the range where vector meson dominance describes the process to the regime where pQCD becomes important. We will also analyze the decay angular distributions of the vector meson decay products to isolate the longitudinal part of the production cross section, where the effect is expected to be largest. The main goal of the experiment will be map out the x, Q^2, and t dependences of vector meson production in the reaction $\gamma_L^* + d \rightarrow V + d'$. For that a total of 66 days of beam time is required. 16 days are concurrent with the E6 run, and 50 days are new beam time.

2 Physics Motivation

Color transparency is one of the fundamental predictions of QCD. It is a novel QCD effect, where a point like configuration of quarks and gluons, produced in a hard scattering reaction, can escape the nucleus without interaction due to the reduced color field. The existence of point-like color singlet quark-gluon configurations is another fundamental property of QCD. Studying the CT effect is an important issue for understanding the dynamics of hard reactions.

With the availability of high energy and high intensity electron beams a new possibility in the experimental investigation of CT phenomena opens up, namely exclusive reactions. Electroproduction of vector mesons off a deuteron in fully exclusive reactions is one of them:

$$e + d \rightarrow e' + V + d' \tag{1}$$

where "V" is the ρ, ω, or ϕ vector meson. The decay products of the vector meson, as well as the scattered electron and the recoiling deuteron, will be detected in the final state. The detection of the nuclear response in coincidence with the produced final hadron state is the key element in the investigation of the space-time picture of hard exclusive reactions.

The proposed reaction is the most favorable channel for studying CT for the following reasons:

- Due to the large $photon-vector\ meson$ coupling the cross section of the process is large, and at high energies and low momentum transfer is well understood in the framework of the vector meson dominance (VMD) model;
- The deuteron is the best understood nucleus, and the distance scales (coherence length and formation length) reachable at JLAB are comparable to the inter-nucleon distance in the deuteron.

In diffractive vector meson production, different interaction mechanisms become important at different kinematics. The process is described in terms of the four-momentum of the exchanged virtual photon $q^\mu = (\nu, \vec{q})$, with $Q^2 \equiv -q^2$, the energy transfer ν, the momentum fraction of the struck quark, $x = Q^2/2p \cdot q$, and the momentum transfer t. (For a nucleon at rest, x becomes $x_B = Q^2/2m\nu$). The experiment will cover regions including:

- *Region of large $\nu \geq 3GeV$ and $Q^2 \ll 1GeV^2$ - "soft" limit:* Thorough experimental and theoretical studies in this region have established the validity of the vector meson dominance model (for a review see *e.g.*[7]). Within the VMD picture the vector meson, as seen in the lab frame, is formed prior to the interaction with the target, with a subsequent diffractive interaction of vector meson with the nucleons in the target.

- *Region of $x \ll 0.1$ and $Q^2 \geq 5-10\ GeV^2$ - "hard" limit:* This limit is presently under intensive theoretical and experimental investigation (for a review see *e.g.*[8]). In this kinematical region one finds that small $q\bar{q}$ configurations are produced in longitudinally polarized virtual photon - nucleon interactions. The vector meson is then formed at a much later stage than in the soft process characterized by a distance $z \approx t \gg R$, where R is the radius of the target. In this region exclusive meson production is calculable in the framework of perturbative QCD.

- *Transition region* between the soft and hard limits. In spite of intensive theoretical activities to understand the dynamics of vector meson electroproduction in the transition (nonperturbative) region (for some of the recent publications see [9, 10, 11, 12, 13, 14, 15, 16]), this region remains practically unexplored experimentally, with very scarce experimental data [17, 18].

The theoretical expectation in the transition region is that at $Q^2 \geq 1\ GeV^2$ and $x \geq 0.1$, the VMD picture will break down, and the process will be dominated by two-gluon or quark-antiquark exchange in the t-channel. The transverse distances between the $q\bar{q}$ pair, in the case of a longitudinally polarized photon, remain small in the limit of large Q^2. Calculations of vector meson production at pre-asymptotic Q^2 for longitudinally polarized photons [19, 20] produce a reasonable description of the data already at $Q^2 \geq 2GeV^2$ (for a recent review, see [21]). This indicates that already at $Q^2 \sim 2 - 3\ (GeV/c)^2$ a wave packet should be produced in a state with smaller than average hadronic size.

2.1 Coherent vector meson production off deuterium

Coherent production of vector mesons off deuterium at momentum transfer $-t \leq 1.5\ (GeV/c)^2$ can be described by single and double scattering mechanisms. In Figure

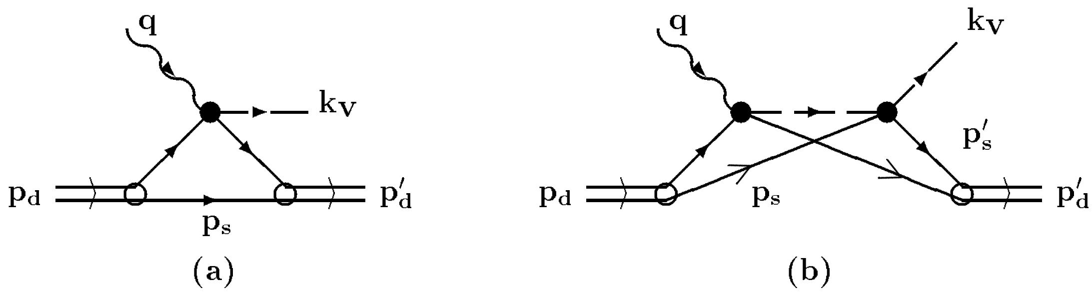

Figure 1: Single scattering (a) and double scattering contribution (b) to exclusive vector meson production in photon-deuteron collisions.

1, the schematic diagrams for these processes are shown. Figure 1.a corresponds to single scattering, where only one nucleon participates in the interaction and, therefore, the t dependence will follow the deuteron form factor. Figure 1.b corresponds to the rescattering mechanism, where the photon interacts with one of the nucleons inside the target, produces an intermediate hadronic state which subsequently rescatters from the second nucleon before forming the final state vector meson. This process has a harder t dependence than the first one, and this is where evidence of CT will manifest itself.

Coherent production is well established experimentally in the photoproduction of the ρ meson off the deuteron [22, 23]. In Figure 2, results of a SLAC experiment are shown together with calculations in the framework of VMD, where the amplitude for vector meson production from the deuteron can be split into two pieces: a single scattering term, F_1, and a double scattering contribution F_2. The (virtual) photon-deuteron cross section then reads:

$$\frac{d\sigma_{\gamma^{(*)}d}}{dt} = \frac{1}{16\pi}\left(|F_1|^2 + 2Re\left(F_1^* F_2\right) + |F_2|^2\right), \tag{2}$$

For a photon momentum along the z direction one obtains for the single scattering or Born amplitude [9]:

$$F_1 \quad = \quad f^{\gamma^* p\to Vp}(\vec{l})\, S_d\left(-\frac{\vec{l}_\perp}{2}, \frac{l_-}{2}\right) \quad + \quad f^{\gamma^* n\to Vn}(\vec{l})\, S_d\left(\frac{\vec{l}_\perp}{2}, -\frac{l_-}{2}\right), \tag{3}$$

where $l_\perp$ is the transverse component of the transferred momentum, and $l_- = l_0 - l_z$, l_0 is the transferred energy. The Born amplitude is determined by the vector meson production amplitude $f^{\gamma^* p(n)\to Vp(n)}$ off a proton or neutron, respectively, and the deuteron form factor S_d. The double scattering contribution is given in the eikonal approximation by [9]:

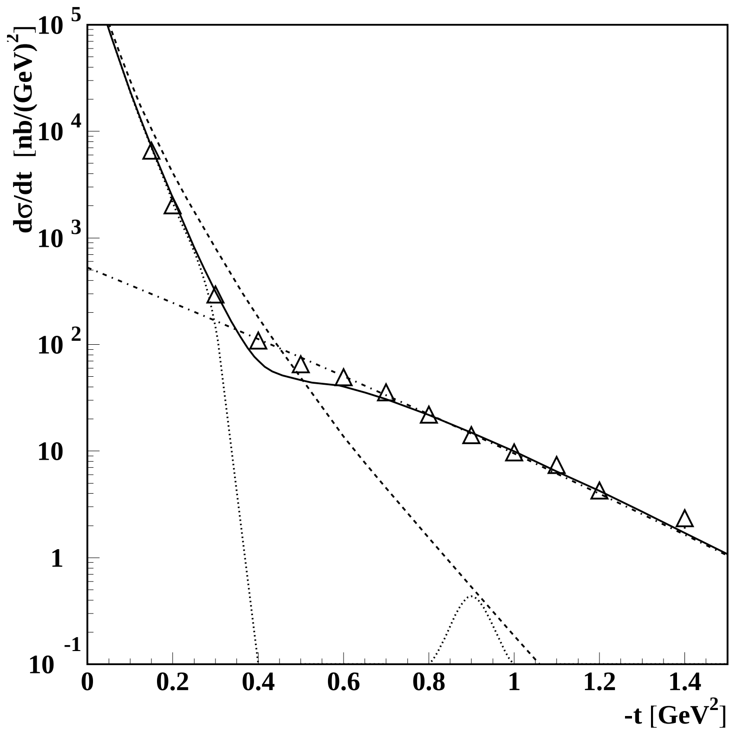

Figure 2: The cross section $d\sigma_{\gamma d\to\rho^0 d}/dt$ for the photoproduction of ρ-mesons off unpolarized deuterium. The dashed, dotted, and dash-dotted curves correspond to the single, single-double interference, and double scattering terms calculated within the VMD model. The solid curve is the sum all of these terms. The experimental data are from Ref.[22, 23].

$$F_2 \approx \frac{i}{2}\sum_h \int \frac{d^2k_\perp}{(2\pi)^2}\, S_d(\vec{k}_\perp, -\Delta_h) f^{\gamma^* N\to hN}\left(\frac{\vec{l}_\perp}{2}-\vec{k}_\perp\right) f^{hN\to VN}\left(\frac{\vec{l}_\perp}{2}+\vec{k}_\perp\right). \quad (4)$$

Here $\Delta_h = (Q^2+2m_h^2-m_V^2+t)/(4\nu)$, with the invariant mass m_h of the intermediate hadronic state. (The isospin dependence of the nucleon amplitudes and the deuteron spin variables are omitted here). In double scattering the transferred momentum is shared between both nucleons. As a consequence it dominates the production cross section at large values of $-t$.

A similar picture of the coherent production is expected to hold in the case of electroproduction as well. The key issue in the investigation of CT phenomena is measuring the re-interaction process. The reduction of the transverse size of the produced wave packet with increased Q^2 will be detected through diminished re-interaction[9, 10].

2.1.1 Vector meson production mechanism.

At high energies and low momentum transfer the photoproduction of vector mesons is well understood in the framework of VMD, where the photon fluctuates into an intermediate vector meson, and then the vector meson elastically scatters off the nucleon. The scattering process is described in terms of the t-channel exchange of the Pomeron, or meson Regge trajectories. (For ϕ production, meson exchange is practically absent).

The diffractive process is characterized by the *coherence length*, l_c, which is defined as:

$$l_c = \frac{2\nu}{m_V^2 + Q^2} \quad (at \;\; Q^2 \to \infty \;\; l_c = \frac{1}{2xm_N}). \tag{5}$$

Here m_V is the mass of the vector meson, and m_N is the nucleon mass. l_c defines a distance over which the photon fluctuates into a vector meson.

At high Q^2, the process can be described using partonic degrees-of-freedom. Now a virtual photon will turn into a $q\bar{q}$, and the relevant mechanisms for scattering of a quark-antiquark pair will be the exchange of two gluons, or quark interchange. In addition, diagrams where a virtual photon scatters directly off the quark in the nucleon forming a $q\bar{q}$ pair (hand-bag approximation) are becoming important as well. At large Q^2 another scale becomes important, the transverse size of the produced quark-antiquark configuration, that is [1, 24]:

$$b_{q\bar{q}} \propto \frac{1}{Q}. \tag{6}$$

2.1.2 Rescattering mechanism.

Measuring the rescattering process gives the unique possibility to study the structure of the produced intermediate state. In addition to the two scales mentioned above, a new important scale comes into play, namely the so-called formation length l_f. It is defined as:

$$l_f = 2\frac{\sqrt{Q^2 + \nu^2}}{\Delta m^2} \tag{7}$$

where Δm^2 ($\sim 0.7 - 1.0$ GeV^2) is the typical squared mass difference between the vector meson ground state and the first excited states. The formation length l_f describes the distance over which the intermediate hadronic ($q\bar{q}$) states will expand and attain a normal hadronic size. If l_f is comparable to the target size, then nuclear effects become important for studying the characteristics of the initially produced state.

At the kinematics of the proposed measurements, l_f is in the range of $1fm$ to $2.5fm$, while l_c will be in the range from $0.4fm$ to $1fm$ (x from 0.1 to 0.4). In a fully exclusive measurement we will be able to control the production and propagation processes by controlling Q^2, l_f, l_c (x), and t. This is important for the separation of the different stages of the reactions.

3 Proposed Measurements

Measurements of t, l_c (x), and Q^2 (and/or l_f) dependences of ρ^0, ω, and ϕ meson production with separation of longitudinal and transverse photon polarizations will be used to study several aspects of vector meson electroproduction. The t dependence of the differential cross section will be studied for a wide range in Q^2 and l_c for transferred momentum squared, $-t$, up to 1 (GeV/c)^2.

The main focus of these studies will be the CT phenomenon in the coherent vector meson production off the deuteron. The change of the slope of the t dependence at high t, with an increase of Q^2 at fixed l_c (x), will indicate a change of the re-interaction cross section. The ratio of two differential cross sections at the same Q^2 and l_c but at different t, the first one in the double scattering region (t_1), Figure 1.b, and the second one in the single (t_2) scattering region, Figure 1.a, is particularly sensitive to this change while being insensitive to systematic uncertainties:

$$R_{(L)} = \frac{d\sigma_{(L)}(Q^2, l_c, t_1)/dt}{d\sigma_{(L)}(Q^2, l_c, t_2)/dt} \quad (8)$$

In Figure 3, a model calculation of the Q^2 dependence of the ratio R for $-t_1 = 0.8$ (GeV/c)^2 and $-t_2 = 0.4$ (GeV/c)^2 is presented for ρ electroproduction. The upper curve is calculated without CT. The lower band corresponds to calculations with different assumptions for CT [9, 25]. The coherence length is fixed at $l_c = 0.5\ fm$. As one can see, already at $Q^2 = 3.5$ (GeV/c)^2 the expected effect is in the 10% - 15% range. The effect will be bigger for the ratio of the longitudinal part of the cross sections, R_L. The Q^2 dependence of R_L at the same t_1 and t_2 is shown in Figure 4. In this case the expected CT effect is about 20%.

This ratio will be insensitive to the change of the t-behavior of the cross section that is due to the first (single) interaction. The Q^2 dependence of the t-slope in the single scattering range, $-t < 0.5$ (GeV/c)^2, can be studied by comparing vector meson electroproduction off deuteron and proton targets.

Our investigation will also determine:

- the limits of applicability of VMD, by measuring vector meson production in the region $Q^2 \sim 1$ (GeV/c)^2 and $x \leq 0.2$, and comparing to photoproduction data.

- coherence length effects in vector meson production, observed for incoherent reactions at HERMES [18] - measurements of l_c dependence of $d(e, e'V)d'$ differential cross section at fixed Q^2.

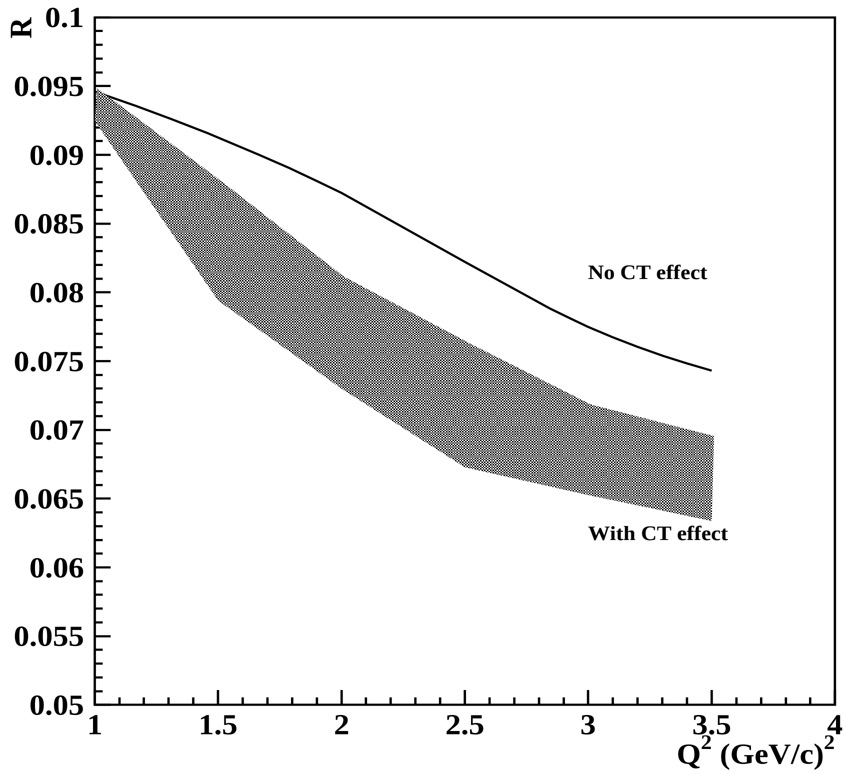

Figure 3: The ratio R of the ρ meson electroproduction cross sections, at transferred momenta $-t_1$=0.4 (GeV/c)^2, and $-t_2$=0.8 (GeV/c)^2, as a function of Q^2. The hatched part corresponds to model calculations with the assumption of color coherence. l_c is fixed at 0.5.

- the onset of the quark-interchange mechanism as compared with the diffractive production of vector mesons. Theoretical expectations are that the relative importance of the exchange of $q\bar{q}$ in the t-channel as compared to the two-gluon exchange will gradually increase with increasing x, and will dominate the cross section at $x \sim 0.2 - 0.3$. Comparison of ρ meson production with the coherent production of ϕ mesons (where the $q\bar{q}$ exchange mechanism is practically absent) will elucidate the dependence of the re-interaction on the vector meson production mechanism.

3.1 Relation to the studies of Generalized Parton Distributions

The proposed studies will be highly complementary to the emerging program of Generalized Parton Distributions (GPDs) studies at Jefferson Lab [26, 27]. The deuteron data, combined with the data from experiments on vector meson electroproduction off the proton [26], will provide important information on the dynamics

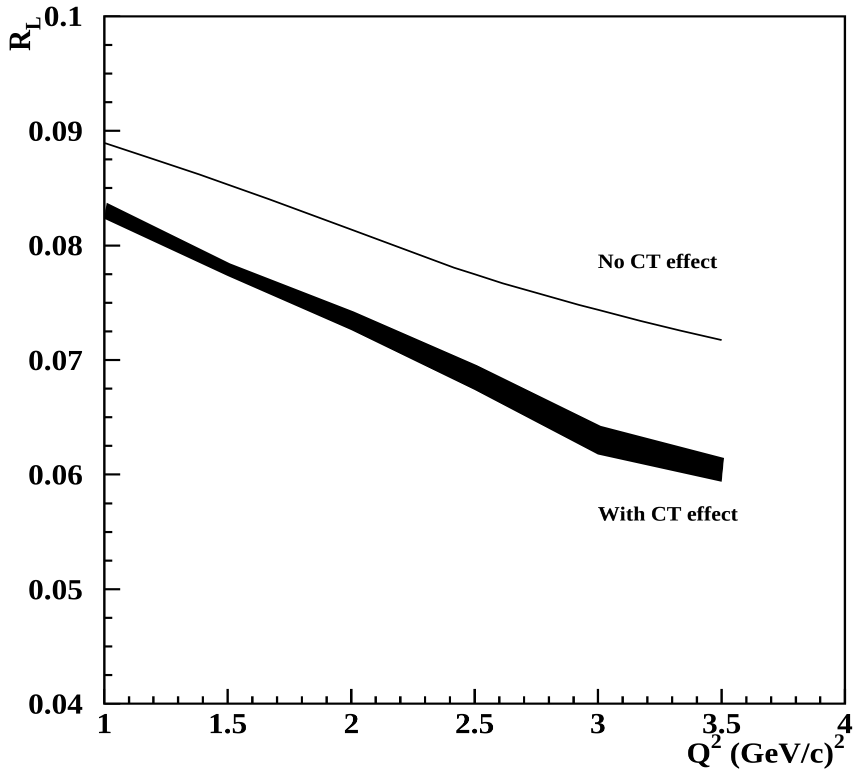

Figure 4: The Q^2 dependence of the ratio of ρ production cross sections with longitudinal photons, R_L, at transferred momenta $-t_1$=0.4 (GeV/c)^2, and $-t_2$=0.8 (GeV/c)^2. The hatched part corresponds to model calculations with the assumption of color coherence. l_c is fixed at 0.5.

of hard processes. Several aspects of these studies are highlighted:

- *Measurement of the isosinglet contribution of GDP's:* In analogy to the measurements of deep inelastic parton distributions, it is important to measure the GPD of isosinglet configurations (n+p) targets. For GPD physics this can be achieved by measuring coherent electro-production of vector mesons off deuterium at small $-t \ll 0.6\ GeV^2$. In this case, as follows from Figure 2 the differential cross section of the reaction is defined through the coherent sum of the single scattering (Figure 1.a) amplitudes, which will allow a direct measurement of the isosinglet GPD's. At low t the contribution of the spin-flip GPD's will be strongly suppressed compared to the proton case due to the small value of the magnetic form factor as compared to the electric form factor the deuteron.

- *Onset of the factorization regime:* The measurement of GPD's assumes the onset of the factorization in which case the high momentum and energy transfer (hard) part of the reaction (which can be calculated in pQCD) is factorized from the nonperturbative part of the reaction. (Only in this case can one directly measure the GPD's of the target). However, exploiting only nucleon targets in the transition kinematics makes the observation of the signature of the onset of factorization highly nontrivial. Coherent electroproduction of vector mesons off the deuteron at large $-t$ will allow a complementary test of factorization based on the observation of the Q^2 dependence of the rescattering contribution of Figure 1b. Indeed, in the kinematical limit in which a complete factorization is achieved the upper part of the handbag diagram at the final state is dominated by the minimal Fock component of the final vector mesons. As a result of color screening the re-interaction of this configuration with the spectator nucleon in the deuteron will be suppressed.

3.2 Foundation for future studies

These measurements will form the basis for a broad experimental program. We plan on a complementary set of photoproduction measurements on coherent vector meson production. Studies utilizing a polarized target will produce more sensitivity to formation time effects in coherent photoproduction. Double scattering is most sensitive to the tensor polarization of the deuteron. This leads to greater sensitivity to smaller internucleon distances at the same t when compared to unpolarized scattering. Ultimately, the program will extend to 12 GeV. Coherent vector meson production off the deuteron is described in the Report of the Hadrons in the Nuclear Medium Working Group [28] and in the Jefferson Lab 12 GeV White Paper [29] as a fundamental measurement, and contributes to the physics justification of the Jefferson Lab upgrade. However, before more advanced studies can be carried out, the current experimental program must be in place.

These studies will lead to other interesting directions, including:

1. Comparing the break-up and coherent channels - this will provide a better handle on the relative phases of the amplitudes of scattering off protons and neutrons.

2. Other double scattering processes in the channels like $\gamma^* + d \rightarrow V + \Delta^0$+recoil proton.

3. Looking at the processes of DVCS, and π^0 and η coherent production. Similar to the vector meson case, this would provide information complementary to the proton case (isosinglet and non-spin flip). Also in the π^0 and η cases one expects drastic differences for the production rates from the case of the free proton and neutron as these amplitudes tend to have opposite sign, at least in the leading twist limit [30].

4. Study of the di-pion production below the ρ meson mass is also interesting as the mechanism of the di-pion production changes with t and with Q^2. It appears that two mechanisms compete - one produces two pions with subsequent rescattering of one or two pions off the target nucleon (nucleons), another produces a $q\bar{q}$ pair of the same size as for the ρ-meson case.

4 Experimental Situation

The proposed experiment will be part of a broad effort to establish the existence of color transparency in QCD which includes several other previous and ongoing experimental efforts. The recent experiment at Fermilab on diffractive dissociation into di-jets of 500 GeV/c pions scattering coherently from nuclear targets[31] unambiguously demonstrated the existence of color transparency. Also the measurement of the Q^2 dependence of σ_L/σ_T ratio for vector meson electroproduction off a proton at HERA [32, 33] demonstrated that the transverse size of the $q\bar{q}$ component of the virtual photon that produced the final vector meson decreased with increasing Q^2. The analysis of these data [20] indicate that at $Q^2 \geq 5\ GeV^2$ the transverse size of the $q\bar{q}$ wave packet amounts to less than a third of the typical diameter of a ρ meson. However, the direct observation of the diminished final state interaction in the electroproduction of vector mesons from a nuclear target has yet to be observed. Data from Fermilab experiment E665 [34] and the New Muon Collaboration (NMC) [35] preclude the separation of color transparency from finite longitudinal interaction length effects since the coherence length l_c varied with Q^2 in both experiments.

Both E665 and NMC used muon beams to extend the kinematical range at the cost of limited statistics. NMC carried out incoherent exclusive ρ^0 production off deuterium, carbon, and calcium, covering $2 < Q^2 < 25$ GeV^2, and 1 fm $< l_c <$ 30 fm [35]. NMC extracted coherent contributions by fitting the transverse momentum distribution. E665 had a higher energy muon beam than NMC and, thus, a larger kinematical range. They published incoherent exclusive ρ^0 production off ^{1}H, ^{2}H, ^{12}C, ^{20}Ca, and

^{208}Pb, covering Q^2 from 0.1 (GeV/c)^2 to over 5 (GeV/c)^2 [34] and $1 < l_c < 200$ fm [34]. They also extracted incoherent contributions by fitting their data. They found increases in transparency with increasing Q^2, in general agreement with CT predictions, but were limited by statistics. Again, the measured transparency did not exclude possible coherence length effects, since l_c was not fixed.

The COMPASS experiment at CERN will also investigate both incoherent and coherent exclusive ρ^0 production off nuclear targets [36]. Their goal is to measure the production on carbon and lead in the $2 < Q^2 < 20$ (GeV/c)^2 and $35 < \nu < 170$ GeV range with high statistics. Their plans are to investigate color transparency on heavier targets; hydrogen and deuterium targets are included with lower priority. As with the other experiments, COMPASS will separate coherent and incoherent contributions by fitting to $-t'$ (or p_t^2) distributions. This experiment will allow to obtain a definitive answer on the existence of CT in the high Q^2 domain where pQCD is expected to be valid.

The experimental situation in the domain of non-perturbative QCD is rather controversial. Although many non-perturbative models of hadrons predict the production of small-size wave packets in the intermediate region of $Q^2 \geq 2-3GeV^2$, the high rate of expansion of these wave packets significantly complicates the observation of the CT. That the expansion plays a dominant role in the non-perturbative domain of QCD follows from several recent experiments performed at BNL [37] (see also [38]), SLAC [39] and Jefferson Lab [40]. The BNL experiment studied the color transparency in the high momentum transfer $A(p,2p)X$ reaction while at SLAC and Jefferson Lab the nuclear transparency was studied in quasi-elastic $A(e,e'p)X$ reaction. Both experiments covered a similar range of Q^2; however, the BNL data correspond to higher energies of protons propagating in the nuclear medium, thus providing smaller expansion effects than the SLAC and Jefferson Lab experiments. The BNL experiment observed the energy dependence of the transparency indicating the filtration of the small-size component of the pp amplitude through the nuclear medium. On the other hand, the SLAC and Jefferson Lab experiments did not find a substantial energy dependence. Both observations indicate the crucial role which expansion plays at intermediate energies as well as the difficulty of producing small-size qqq configurations at intermediate Q^2.

Studies of color transparency involving meson production in the intermediate energy region will substantially complement the above investigations which used proton probes. It is more feasible to produce small-sized $q\bar{q}$ than qqq configurations at intermediate Q^2. Presently, only at HERMES and at Jefferson Lab can such studies be performed.

HERMES has published results for exclusive incoherent electroproduction of ρ^0 mesons off ^{1}H, ^{2}D, ^{3}He, and ^{14}N [18]. Their covered kinematical range is $0.4 < \mathrm{Q}^2 < 5.5$ (GeV/c)^2, $9 < \nu < 20$ GeV, and $0.6 < l_c < 8$ fm. To date HERMES has only extracted the incoherent scattering contribution by fitting the t' distribution with incoherent slope parameters. In this experiment the coherent length was not fixed at different Q^2 values. HERMES found that the nitrogen transparency decreased with l_c, in agreement with the finite longitudinal interaction length effects. Their data support the hypothesis that absorption of the $q\bar{q}$ component of the photon contributes to the shadowing effects seen in real and virtual photo-nuclear cross sections. Future plans for HERMES include extracting the coherent contributions from their current data set, and a detector upgrade to measure recoil particles in coincidence.

Jefferson Lab has an evolving program for studies of color transparency in meson production reactions [41, 42]. Our experiment will exclusively concentrate on vector meson production. The proposed measurements are meant to bridge the region between VMD and pQCD, and focus on light nuclei. We will also be uniquely able to directly identify and measure coherent vector meson production by measuring deuterons in coincidence. The other experiments can only infer coherent and incoherent contributions by fitting their data as a function of $-t'$ (or p_t^2). The proposed measurement will be the only fully exclusive measurement which will be able to measure the Q^2 dependence of the cross section at fixed l_c. The ability to measure in a wide range t allows us to vary the internucleon distances involved in the production of vector mesons [9] thus enhancing the effects of the interaction of $q\bar{q}$ configurations with the spectator nucleon.

5 Experimental Objectives

In this experiment we will measure the cross section of coherent electroproduction of vector mesons in the reactions:

$$e + d = e' + d' + \rho^0 \tag{9}$$

$$e + d = e' + d' + \phi \tag{10}$$

$$e + d = e' + d' + \omega\ . \tag{11}$$

CLAS is an ideal tool for conducting such experiments. With a single setting one can simultaneously measure all of the above reactions in a broad range of kinematics as seen in Figure 5. The longitudinal part of the cross sections will be extracted through an analysis of the vector meson decay angular distribution. The t dependence of the coherent vector meson electroproduction cross section will be measured in fixed Q^2 and l_c bins. At this kinematics the formation length, l_f, varies from 1 fm to 2 fm (cf. Figure 6), which is comparable to the inter-nucleon distance in the deuteron.

The CLAS collaboration has already published data on ρ [43] and ϕ [44, 45] electro- and photoproduction off the proton. These papers show that CLAS is well suited to handling multi-particle final states, and that the cross section of these processes can be measured with less than 10% systematic uncertainties.

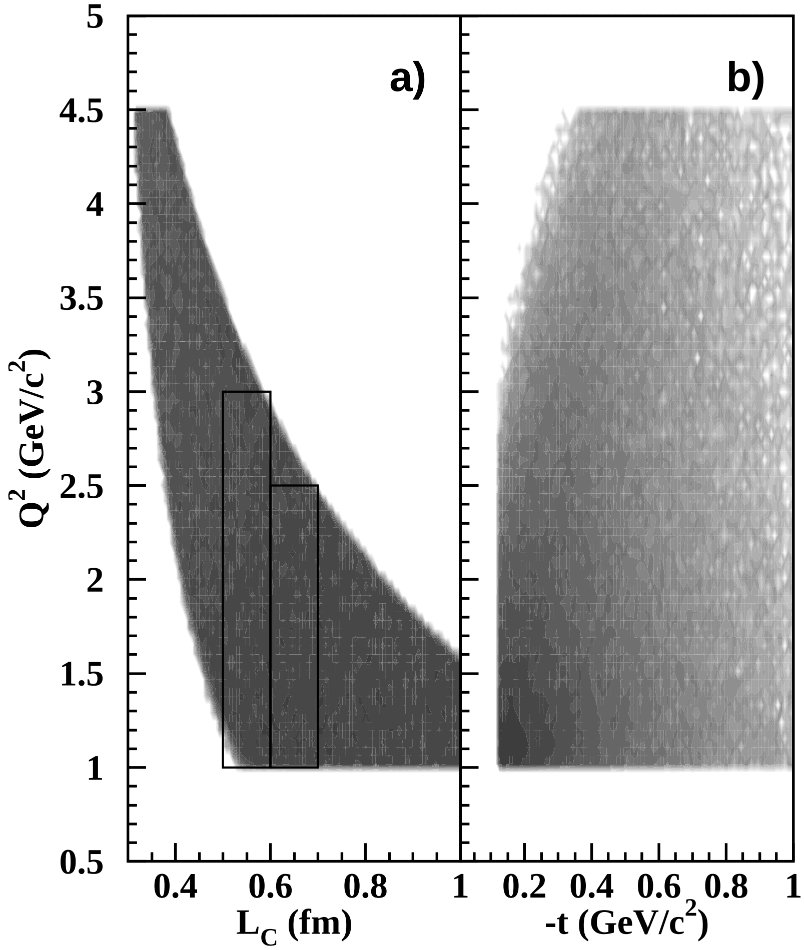

Figure 5: The accessible range of Q^2, l_c and t with CLAS at 6 GeV beam energy. Target position is at $Z = -60cm$.

5.1 CLAS configuration

We plan to use CLAS in its modified configuration (see Figure 7), similar to what has been proposed for the dedicated DVCS measurement [27]. We intend to move the target upstream of the CLAS center by $\sim 60cm$. This will significantly increase the detector acceptance for forward going charged particles. We also will use the solenoid magnetic field for reducing the Møller background. Studies of luminosity limitations at various electron scattering experiments showed that use of the Helmholtz configuration at the target location oriented parallel to the beam direction (CLAS/EG1 run) works better for shielding the Møller background than the standard mini-torus configuration. Although during the EG1 run the Helmholtz coils were not optimized for background reduction (the magnet was designed as a polarized target holding field), the luminosity achieved was a factor of 2 higher compared to regular electron runs with the mini-torus, see Figure 8. Studies also showed that an optimized solenoid field with a lead shielded downstream beam pipe will allow to run CLAS at

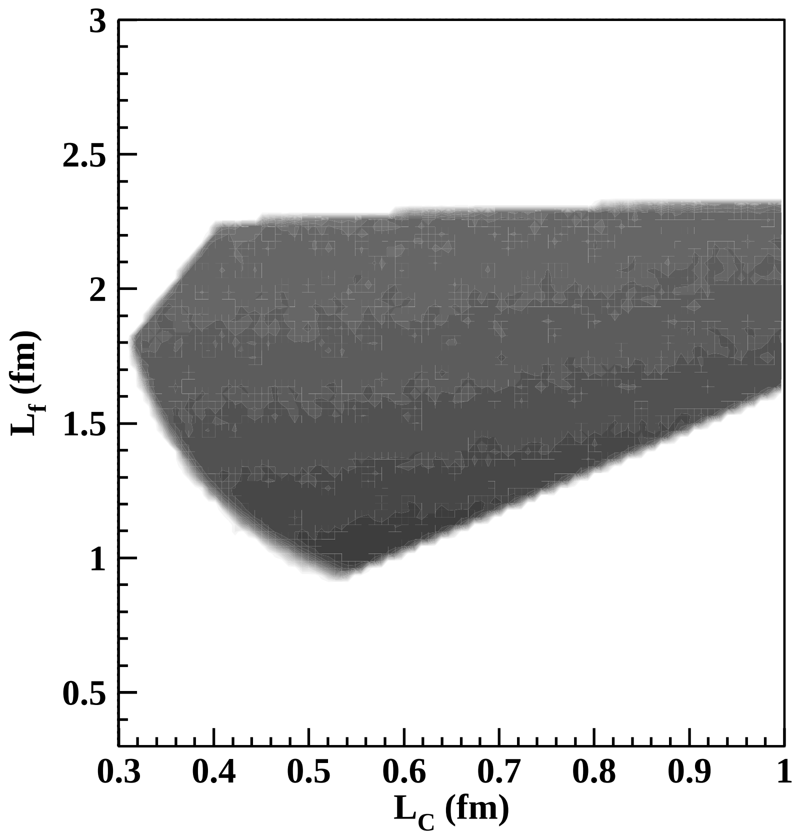

Figure 6: The accessible range of l_f vs l_c at 6 GeV beam energy.

$2 \times 10^{34} cm^{-2} s^{-1}$ luminosity.

We are planning to use the standard trigger, data acquisition, and online monitoring system of CLAS. The signal amplitude and time information will be read out using the standard Fastbus ADC and TDC boards currently in use in CLAS. We plan to use the standard CLAS level 1 trigger to select scattered electrons. No changes to the trigger hardware are anticipated.

5.2 Event identification and acceptances

Final states will be identified using the CLAS standard particle identification techniques. Vector mesons will be reconstructed after detection of their decay products. Analysis of decay angular distributions will allow separation of the longitudinal and transverse parts of the cross section.

Current analysis of CLAS data shows close to 100% reconstruction efficiency for electrons, and reliable identification of pions, kaons, and protons with momenta up to 3 GeV/c. In our measurements the detection of the recoiling deuteron is required. In Figure 9a, the distribution of β vs. momentum for positively charged particles is plotted for the recent CLAS/EG1 run with 5.67 GeV electrons. During this run the

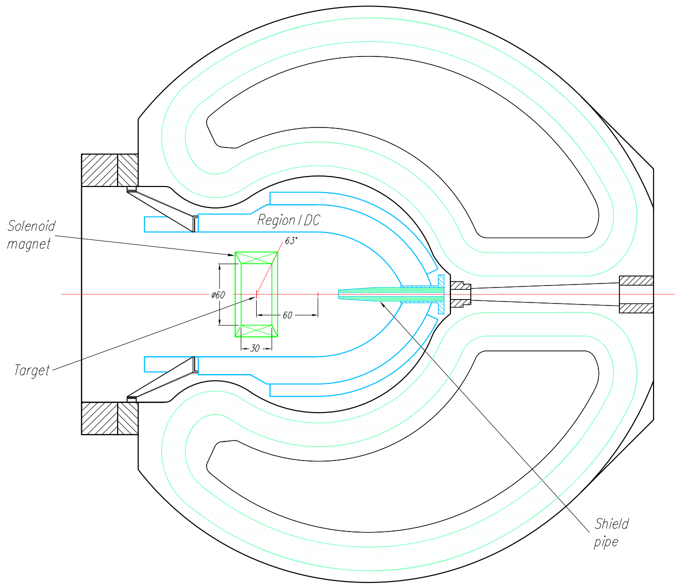

Figure 7: CLAS arrangement proposed for these studies. The target has been moved upstream by 60 cm to increase the forward acceptance. A solenoid magnet and an upgraded shield pipe are added to reduce the Møller background, allowing a factor of 2 increase in luminosity.

CLAS configuration was very close to the one described above: retracted target, $Z = -55cm$, and $5T$ longitudinal magnetic field in the target region. One can see a clean separation of π^+s, protons, and deuterons (knocked out from the nuclear part of the target material). In Figure 9b, the kinetic energy distribution of identified deuterons is presented. Deuterons are detected starting from $30 - 40MeV$ kinetic energy, which means that measurements can be done starting from transferred momentum squared of 0.15 (GeV/c)^2 ($-t = 2 \cdot m_d \cdot T_d$).

Although all possible final state topologies for decaying mesons will be analyzed, the main focus will be on final states $(e'd'\pi^+)$ for $\rho^0 \to \pi^+\pi^-$ reconstruction, and $(e'd'K^+)$ for $\phi \to K^+K^-$. The missing π^- (K^-) will be reconstructed using a missing mass technique. ω mesons will be identified via their decay to $(\pi^+\pi^-\pi^0)$. In this case, at least one of the photons from the π^0 decay will be detected in addition to the π^+. Analysis of existing CLAS photoproduction data off the deuteron show that $\gamma d \to d\rho^0$, and $\gamma d \to d\phi$ reactions can be reliably identified. In Figure 10a the missing mass of the detected $(d\pi^+)$ system shows a missing π^- peak. The invariant mass of $(\pi^+\pi^-)$, presented in Figure 10b, shows the typical ρ^0 mass distribution. In Figure 11, similar distributions for the $(d\phi)$ channel are presented. Again, the missing mass distribution

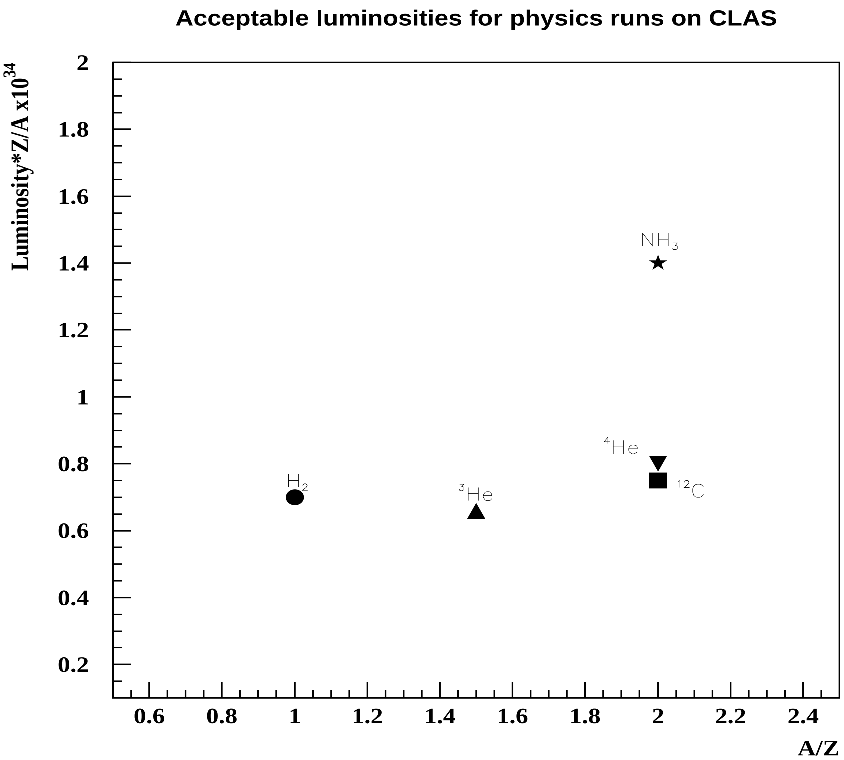

Figure 8: Maximum luminosities used during various electron scattering experiment. The data are multiplied by Z/A of the scattering target to obtain the hydrogen-equivalent luminosity. The point labeled NH_3 was obtained during operation with a longitudinal magnetic field during polarized target operation, thus illustrating the increased luminosity.

of (dK^+) has a peak in the range of the K^- mass, and the invariant mass distribution of two kaons shows a peak at the ϕ mass.

In order to calculate acceptances for the final states mentioned above, an event generator for t-channel meson production has been used. Events were generated in CLAS for a target position at $z = -60\ cm$. The reaction was identified using missing mass and missing energy cuts, as it will be done for real data. In Figures 12 and 13, the resulting acceptances for ρ electroproduction are presented. Figure 12.a shows the Q^2 dependence of the acceptance for different l_c, Figure 12.b shows the acceptance dependence on t for $2.5 \leq Q^2 \leq 3$ (GeV/c)^2 and $0.5 \leq l_c \leq 0.6$fm. In Figure 13, the acceptance dependence on $\cos\theta^*$ (angle of decay π^+ in the helicity frame) is shown for the same bin in Q^2 and l_c. As one can see at high Q^2 the average acceptance for the ρ^0 channel is about 0.4 and has a uniform distribution. Similar studies have been done for other channels as well.

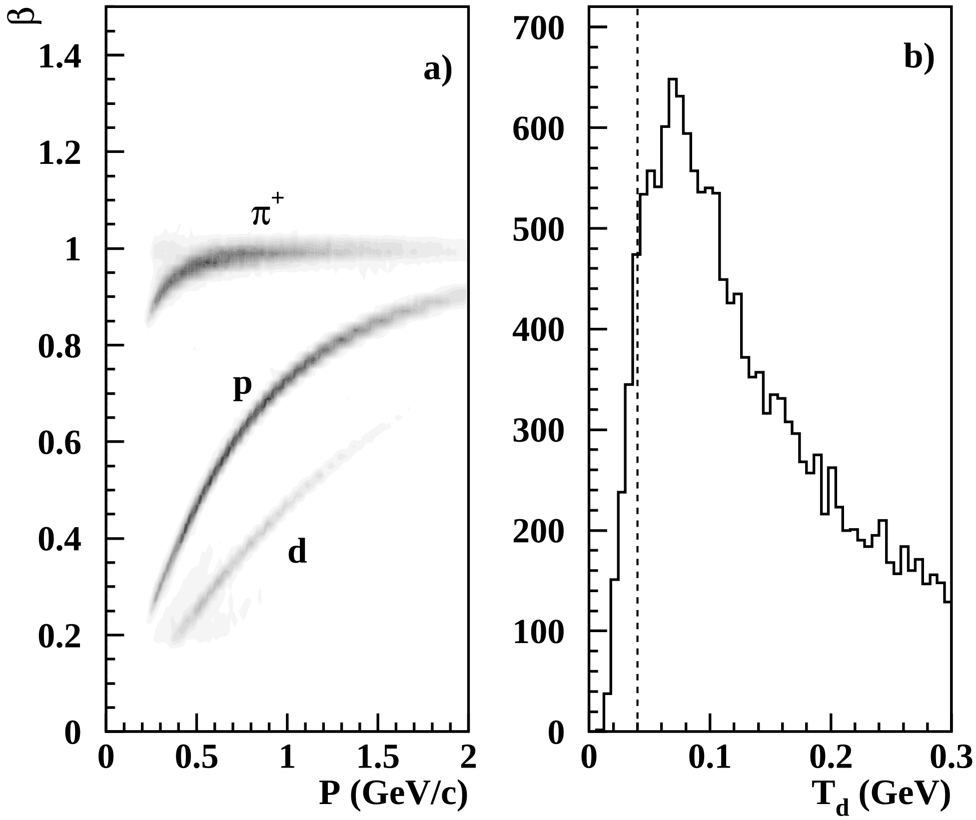

Figure 9: Analysis of CLAS/EG1b data at 5.67 GeV. a)β vs momentum distribution for positively charged particles. b) Kinetic energy distribution of identified deuterons. The vertical dashed line corresponds to $2 \cdot m_d \cdot T_d = 0.15(GeV/c)^2$.

5.3 Analysis of angular momenta

The separation of longitudinal and transverse polarization of the vector mesons will be performed by analyzing the decay angular distributions. Assuming s-channel helicity conservation (SCHC) the longitudinal cross section of the reactions $\gamma_L^* d \to d(\rho_L^0, \omega_L, \phi_L)$ can be extracted. The validity of the SCHC hypothesis can be checked by studying those decay density matrix elements that vanish in the case of SCHC.

When integrated over the azimuthal angle the decay angular distribution in the helicity frame is given by [46]

$$W(\cos\theta_{hel}) = \frac{3}{4}\{1 - r_{00}^{04} + (3r_{00}^{04} - 1)\cos^2\theta_{hel}\} \ . \quad (12)$$

The diagonal matrix element r_{00}^{04} depends on W, Q^2, and t. In case the vector meson is purely longitudinally polarized, $r_{00}^{04} = 1 (\equiv W(\cos\theta_{hel}) = \frac{3}{4}\cos^2\theta_{hel})$, for transverse polarization $r_{00}^{04} = 0$. Assuming SCHC the vector meson polarization is linked to the virtual photon polarization by

$$R = \frac{\sigma_L}{\sigma_T} = \frac{r_{00}^{04}}{\epsilon(1 - r_{00}^{04})} \ . \quad (13)$$

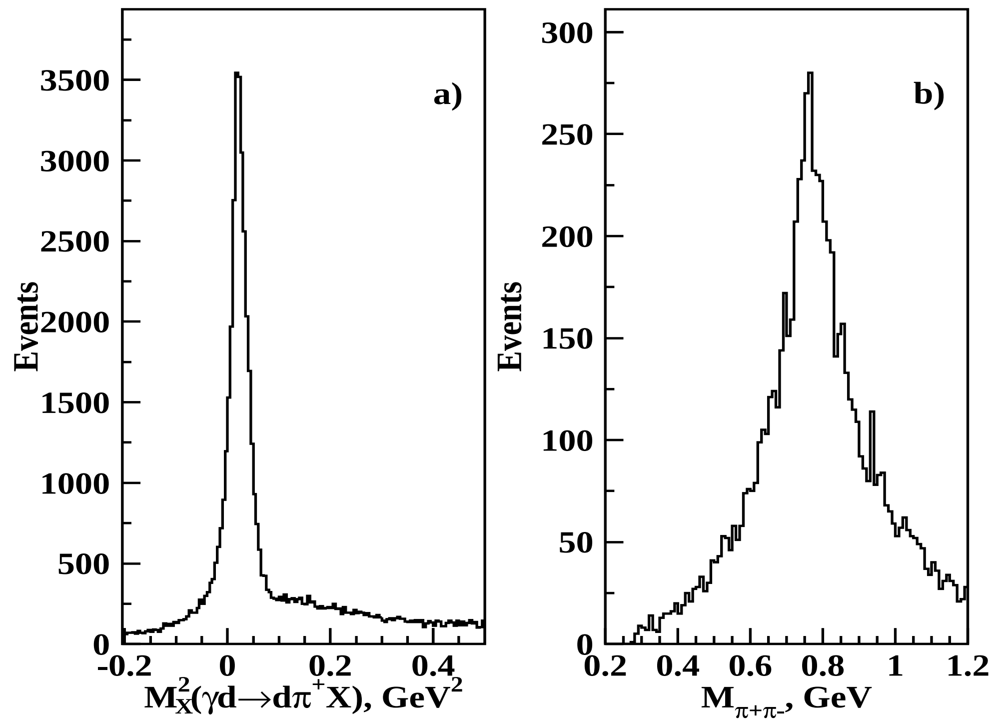

Figure 10: Reconstruction of $(\pi^+\pi^-)$ final state in the reaction $\gamma + d \to d' + \pi^+ + X$. a) the missing mass squared distribution. b) the invariant mass of the $(\pi^+\pi^-)$.

The assumption can easily be tested by an analysis of out-of-plane events. With Φ being the angle between the leptonic and hadronic scattering planes the Φ distribution can be written in the form (for unpolarized electron beam):

$$\bar{\sigma}(\Phi) = 1 - \epsilon \cos(2\Phi) \bar{R}_{TT} + \sqrt{2\epsilon(1+\epsilon)} \cos(\Phi) \bar{R}_{TL} \ . \tag{14}$$

where the normalized interference response functions are given by

$$\bar{R}_{TT} = \frac{R_{TT}}{R_T + \epsilon R_L} \ , \ \bar{R}_{TL} = \frac{R_{TL}}{R_T + \epsilon R_L} \ .$$

In case of SCHC the response functions R_{TT} and R_{TL} vanish, resulting in a flat Φ angular distribution.

The sensitivity which is required to obtain a significant check of SCHC and to extract the correct L/T ratio is being determined via MC studies.

6 Count rates

The beam time requested reflects the statistical accuracy that is required to measure the differential cross section of vector meson production with longitudinally polarized photons to have reasonable sensitivity to the model predictions with and without CT.

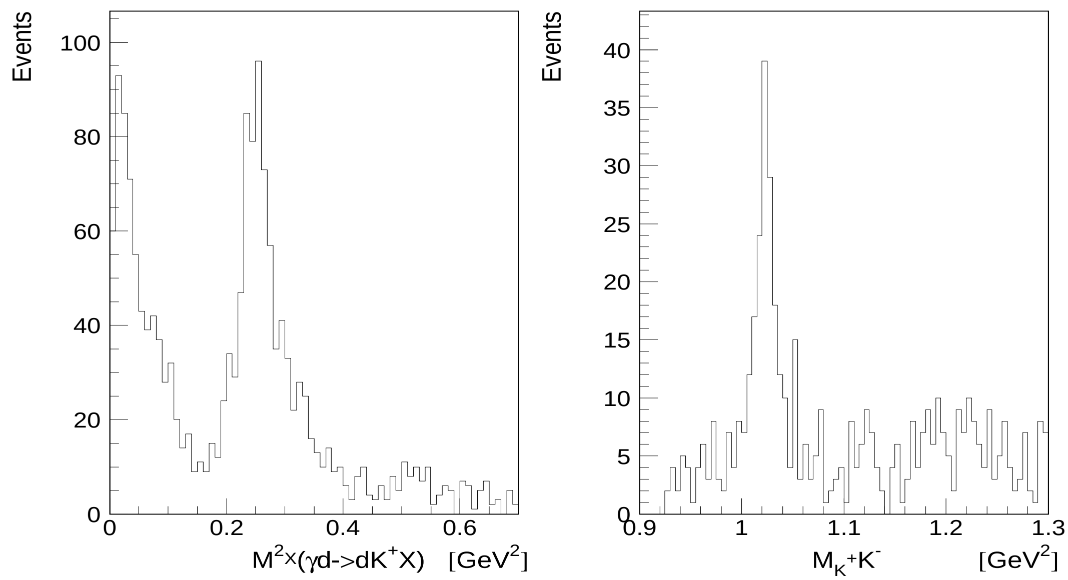

Figure 11: Reconstruction of (K^+K^-) final state in the reaction $\gamma+d \to d'+K^++X$. a) the missing mass squared distribution. b) the invariant mass of the (K^+K^-).

Count rates are estimated using the cross sections from [10, 25] and the acceptances from simulations presented above. The calculated cross section of coherent ρ electroproduction at $Q^2 = 4$ (GeV/c)^2, $l_c = 0.45$, and $-t = 0.8$ (GeV/c)^2 is:

$$\frac{d\sigma}{dl_c dQ^2 dt} = 2 \; pb \; GeV^{-4} \; fm^{-1} \qquad (15)$$

The estimated rate in the bins $\Delta Q^2 = 0.4$ (GeV/c)^2, $\Delta l_c = 0.1$, and $\Delta t = 0.2$ (GeV/c)^2, assuming 50 days of running with $2 \times 10^{34} cm^{-2} s^{-1}$ luminosity, will be 483 counts.

In the data analysis an important part will be the separation of the longitudinal portion of the cross section by analyzing the angular distributions of the vector meson decay products. To estimate the accuracy of extraction of $R = \frac{\sigma_L}{\sigma_T}$, the angular distribution of pions from ρ^0 decay was simulated according to Eq.12. The value of $R = 1.8$ is taken from [8]. Figure 14 shows the angular distribution of the decay pion with projected data (using the statistics from above estimates). The curves on the plots are the results of the fit to the function in Eq.12. The extracted value for R is 1.84 ± 0.017 (1.8 ± 0.007) for $-t = 0.8$ (GeV/c)^2 ($-t = 0.4$ (GeV/c)^2).

From these studies we conclude that 50 days of running CLAS at $2 \times 10^{34} cm^{-2} s^{-1}$ luminosity will allow us to measure differential cross section for ρ^0 production with

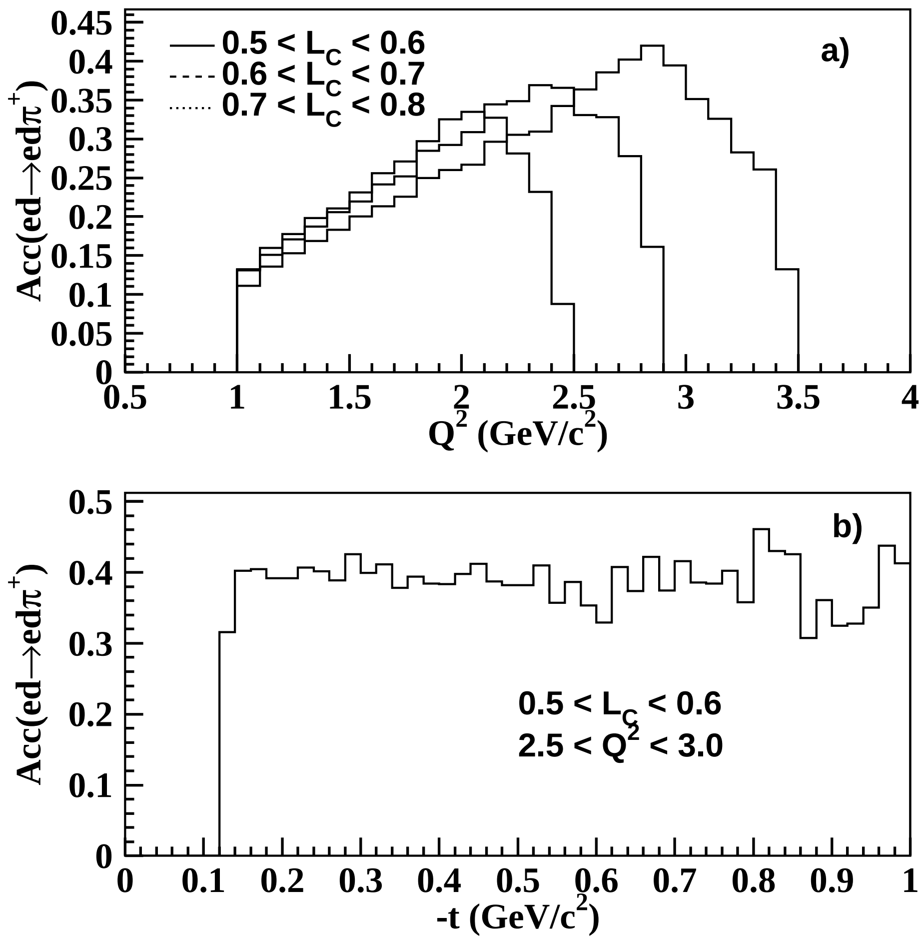

Figure 12: Simulated CLAS acceptances for the reaction $e + d = e' + d' + \rho^0$ with target position at $Z = -60cm$. Detected final state is $e'd'\pi^+$. a) Q^2 dependence of acceptance for different l_c bins. b) t dependence of acceptance for fixed l_c and Q^2 bin.

longitudinally polarized photons with a statistical accuracy of 8% (including the fit error in the determination of R). This accuracy is necessary to distinguish between models with and without CT. (One should note that systematic errors will not play any significant role in the ratio of Eq.8.)

6.1 Data taking during the CLAS E6 run period

For the initial phase of the program we propose to run concurrently during the E6 run period. This allows us to take approximately 10% of our data without additional beam time. More importantly, this will help us to establish run conditions for the dedicated 6 GeV run with the modified CLAS. It will allow us to ensure that the remainder of our data will be of high quality by diagnosing problems before the new beam time. The E6 run period covers Experiments E94-019[47] and E94-102[48]. The

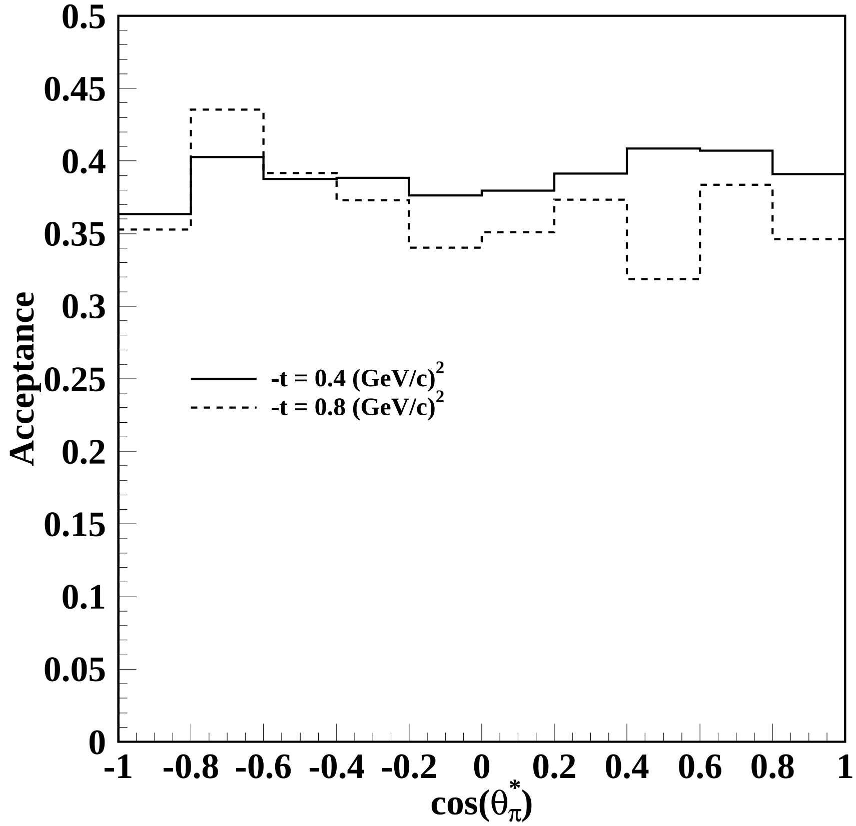

Figure 13: Simulated CLAS acceptance for the $e'd'\pi^+$ final state as a function of the pion angle in the helicity frame for the two bins of t, and for $0.5 < l_c < 0.6 fm$ and $2.5 < Q^2 < 3.0 (GeV/c)^2$.

16 days of beam time that are allocated to that run period are currently scheduled for January 2002.

The E6 run period will utilize the standard detector setup and target. The target is a cryogenic deuterium target, located at the nominal position. Both polarities of the torus field will be used. The setting with negative particles bent outward will allow measurements at Q^2 starting at 0.6 (GeV/c)^2. The low Q^2 part is particularly interesting for testing the limits of the validity of VMD.

The maximum luminosity for this run is expected to be $\sim 10^{34} cm^{-2} s^{-1}$. We require no changes in this setup, since a single electron trigger that will be used in the experiment permits recording data in all channels simultaneously.

7 Summary and beam time request

In the proposed experiment, coherent electroproduction of vector mesons off deuterium will used to study color transparency. Measurements of the differential cross sections of ρ, ω, and ϕ mesons will be performed in a wide range of kinematics: $0.6 \leq Q^2 \leq 4 (GeV/c)^2$, $0.4 \leq l_c \leq 1 fm$, and $0.15 \leq -t \leq 1.2 (GeV/c)^2$.

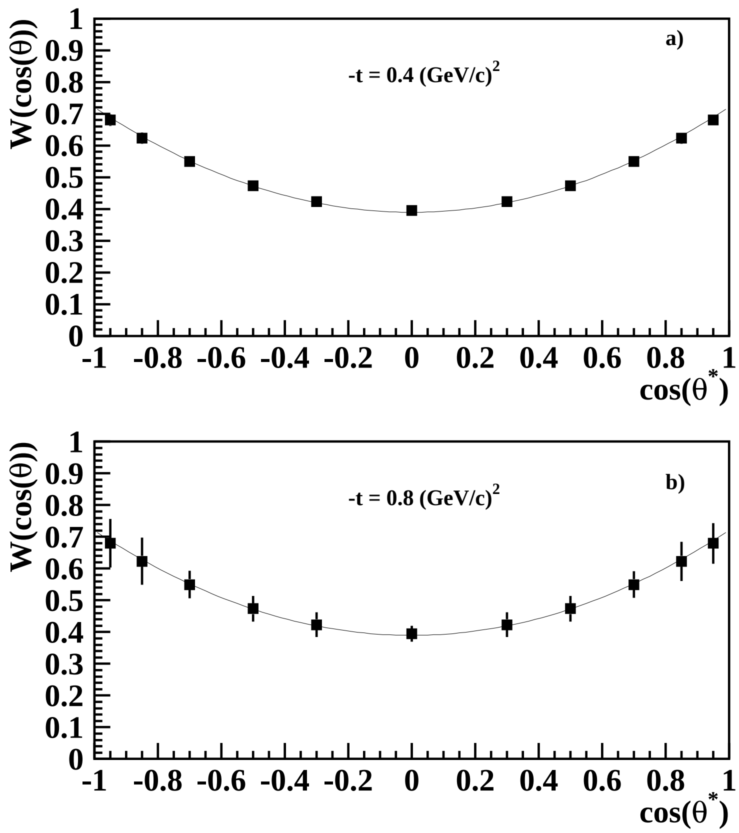

Figure 14: Simulated decay angular distribution of π^+ from ρ decay. Virtual photon kinematics is fixed at $Q^2 = 4$ (GeV/c)^2, $l_c = 0.5$. a) -t = 0.4 (GeV/c)^2, b) -t = 0.8 (GeV/c)^2. The curves are the results of the fit with the function in Eq.12.

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The combined analysis of CLAS electroproduction and photoproduction data off proton and deuterium targets will allow systematic and complete studies of the production and propagation of the $q\bar{q}$ in the nuclear medium. These studies are important for understanding QCD in the transition region.

Since we intend to use a single electron trigger, all possible reaction channels will be recorded as well. This will allow, in addition, study of breakup channels, and pseudo-scalar meson production reactions. One should note that the deuteron is the standard source for neutron data, and this measurement will add a large volume of data on the electron-neutron scattering at 6 GeV. This is in the interest of studying, for example, the isosinglet contributions to GPDs.

We request a total of 66 days of beam time, 16 of which are concurrent with the E6 run period. The remaining 50 days are new beam time.

The E6 run period is tentatively scheduled for 16 days starting January 2002. During that run CLAS will be in its nominal configuration. We will be able to collect 10% of our data with E6. Of particular interest are measurements at low Q^2 (data taking with negative particles bent outward). The data obtained will also help to optimize the setup for the dedicated run. No changes to the present E6 configuration are required.

The dedicated 50 days of new beam time will be used to run CLAS in the configuration proposed for the DVCS measurements [27]: the target will be 60 cm upstream of CLAS center, and a solenoid field for Møller background shielding will be used. (The inner calorimeter proposed for DVCS will not be used). CLAS will operate with the standard cryogenic deuterium target. This request is based on an operating luminosity of $2 \times 10^{34} cm^{-2} s^{-1}$.

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