# Study of Color Transparency in Exclusive Vector Meson Electroproduction off Nuclei

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A **CLAS COLLABORATION PROPOSAL**

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# Study of Color Transparency in Exclusive Vector Meson Electroproduction off Nuclei

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Measurements of exclusive incoherent electroproduction of $\rho^0(770)$ meson from $^2$H, C, Fe and Sn targets up to $Q^2$ = 5.5 GeV$^2$ are proposed using the CLAS12 detector. The objective of these measurements is to study the color transparency phenomenon by measuring the $Q^2$ dependence of the nuclear transparency ratio for three nuclear targets: C, Fe, and Sn at fixed coherence length of quark-antiquark fluctuations of the virtual photon. A sizeable rise of the nuclear transparency is predicted due to color transparency and can be measured in this experiment.

# Introduction

The nature of the strong interaction is known to the extent that Quantum Chromo-Dynamics (QCD) is a solid theoretical reference. The microscopic processes correspond to the exchange of gluons between the quarks; the elementary constituents of the nucleon. Quarks and gluons are not observed as free particles (asymptotic), they are confined in hadrons. While the interaction between quarks at short distances and for very short times can be described by perturbative QCD, the non perturbative processes such as quark confinement, spontaneous chiral symmetry breaking, or color neutralization processes (hadronization) are still largely unknown. At the moment and for the near future, lattice QCD is far from providing the solution to these problems. Therefore one has to rely on models. This situation is unsatisfactory since a realistic theory of matter cannot emerge without decisive progress of the field. We believe that JLab 12 GeV upgrade will offer a unique opportunity to study in great details many of these important questions.

Nearly two decades of experiments convinced us that the nucleus can be successfully used as a unique laboratory to study quark dynamics. Indeed, the nucleus can be used as a revealing medium of the evolution in time of elementary configurations in the hadron wave function. The time necessary for a quark to cross distances typical of the confined systems is of the order of 1 fm. By taking into account the relativistic time dilatation factor, the time scale characteristic becomes of the order of a few fm. The only medium available at this scale is the nucleus offering to us a new generation of experiments where the nucleus functions as bubble chamber!

In this proposal, we are interested in studying a fascinating phenomenon closely connected to the dynamics of confinement, called Color Transparency (CT). The notion of CT is more than two decades old although it did emerge from successive observations starting in 1955! At the time of the study of ultra-fast pion decay $\pi^0 \rightarrow e^+ e^- \gamma$ in an emulsion [1], the ionization rate in the medium was found to increase with the distance traveled by the ($e^+ e^-$) pair: near the creation point, the pair didn't interact with the medium! This surprising observation was quickly interpreted in the context of QED [2]: a pair of oppositely charged particles interacts with the medium with a dipole cross section, e.g., proportional to the distance between the two particles of the pair. Therefore, it vanishes near the creation point.

In 1982, Brodsky and Mueller [3] were the first to introduce CT to QCD and to the color charge. According to QCD, point like colorless systems, such as those produced in exclusive processes at high $Q^2$ have quite small transverse sizes, therefore and by analogy to QED, they are expected to travel through nuclear matter experiencing very little attenuation.

Experimentally, we would like to understand this spectacular phenomenon by studying the hadron attenuation as it propagates through the nuclear medium.

The $\rho^0$ meson is our hadron of choice because it offers many advantages. It is believed that the onset of CT is expected at lower $Q^2$ in the $q\bar{q}$ system than in the $qqq$ one as it is much more probable to produce a small size system of two quarks than one of three quarks [4]. In addition, the $\rho^0$ is a vector meson similar to the virtual photon. Therefore its production mechanism is fairly well understood because the virtual photon fluctuates into a $(q\bar{q})$ pair which then materializes into the $\rho^0$ meson. The size of the produced $(q\bar{q})$ can be directly connected to the virtuality of the photon. Therefore, smaller sizes can be reached at larger $Q^2$.

# Physics Motivations

The color transparency phenomenon illustrates the power of exclusive reactions to isolate simple elementary quark configurations. For a hard exclusive reaction such as vector meson electroproduction on the nucleon, the scattering amplitude at large momentum transfer is suppressed by powers of $Q^2$ if the hadron (vector meson in this case) contains more than the minimal number of constituents. This is derived from the QCD based quark counting rules. Therefore, the hadron containing valence quarks only, participates in the scattering. Moreover, each quark, connected to another one by hard gluon exchange carrying momentum of order $Q$, should be found within a distance of order $1/Q$. Therefore, at large $Q^2$ one selects a very special configuration of the hadron wave function where all connected quarks are close together, forming a small size color neutral configuration called Point Like Configuration (PLC). Such an object is unable to emit or absorb soft gluons. Therefore, its strong interaction with the other nucleons becomes significantly reduced, and then the nuclear medium becomes more transparent.

In a hadronic basis, the PLC is described as a coherent superposition of a large number of resonances, with specific weights; the smaller the configuration size, the larger the number of resonances in the hadron admixture. In this language CT is understood as coherent rescattering of all those resonances with the nucleons of the medium. During a formation time $\tau_f = 2\nu/(M_{v'}^2 - M_v^2)$, where $M_v$ is the mass of the vector meson in its ground state, $M_{v'}$ is its first orbital excitation mass and $\nu$ is the energy of the virtual photon, the PLC evolves to a normal hadron. While the hadronic picture is useful in determining, in a quite realistic way, the scales involved in the process, it does not allow us to access in a straightforward way the dynamic of the elementary degrees of freedom at this scale: the quarks and gluons.

In the hadronic picture, one has to include all excited hadron states, which makes it extremely hard for any theoretical prediction. Therefore the quark gluon picture offers a more natural way to describe CT. In this basis, the wave function of the hadron can be decomposed in a schematic way as:

$$|h> = \alpha\,|q\bar{q}> + \beta\,|q\bar{q}\;q\bar{q}> + \cdots$$

By definition, CT selects the first component of the hadron wave function. The second one is suppressed by a factor $\alpha_s$, while $\alpha_s$ goes to zero at small distances. The first component corresponds to the valence quarks.

The proposed experiment, which is part of the larger physics program build around the ideas of Color Transparency and Hadronization, will allow us to not only access the special configuration of the hadron wave function, but also to study how this configuration dresses with time to form the fully complex asymptotic wave function of the hadron. This puts us in the heart of the dynamics of confinement. Furthermore, the onset of CT is related to the onset of factorization, which is an important requirement for accessing Generalized Parton Distributions (GPDs) in deep exclusive meson production.

## Previous Measurements

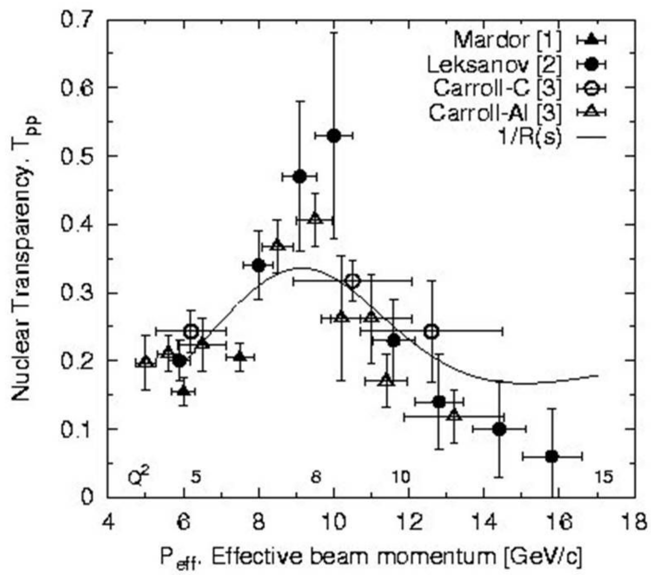


Figure 1: Nuclear Transparency of (p, 2p) experiments at Brookhaven National Laboratory (see text for details)

To summarize the previous discussion, the arguments leading to Color Transparency (CT) involve three ingredients. First, at the time of interaction, the hadron has to fluctuate to a small size configuration (or Point Like Configuration (PLC)). Second, the PLC experiences a reduced interaction with the nucleus. Third, the hadrons remain small while they propagate out of the nucleus. Consequently, the signature of CT is an increase in the nuclear transparency $T_A$ with increasing hardness of the reaction. $T_A$ is defined as the ratio of the measured exclusive cross section to the cross section in absence of initial and final state interactions. It can be measured by taking the ratio of the nuclear per nucleon ($\sigma_A$/A) to the free nucleon cross section: $T_A = \sigma_A/(A\sigma_N)$. Tremendous experimental efforts went into looking for the onset of CT. One can organize these searches into two categories. The first category focuses on studying baryon (proton) transparency, and the second one studies meson (pions and $\rho^0$-meson) transparency.

The first experiment to investigate CT was performed by Carroll et al. [5] at Brookhaven National Laboratory. Quasi-elastic (p, 2p) scattering from each of several nuclei was compared to pp elastic scattering in hydrogen at incident proton momenta of 6, 10, and 12 GeV/c. Its results do not support a monotonic increase in transparency with $Q^2$ as predicted by CT: the transparency increases for $Q^2$ from 3 to 8 GeV$^2$ but then decreases for higher $Q^2$, up to 11 GeV$^2$. This subsequent decrease was explained as a consequence of soft processes that interfere with perturbative QCD in free pp scattering but are suppressed in the nuclear medium [6]. As shown in Figure 1, new measurements [7] did confirm the earlier results of the Brookhaven experiment. Due to the simplicity of the elementary electron-proton interaction compared to the proton-proton one, the quasi-free A(e, e'p) reaction was suggested as an alternative [8]. Unfortunately, all experiments (Bates [9], SLAC [10] and JLab [11]) failed to produce evidence of CT even for $Q^2$ values as large as 8 GeV$^2$, as shown in Figure 2. The experimental data is qualitatively compatible with Glauber type model by Pandharipande and Pieper [12].

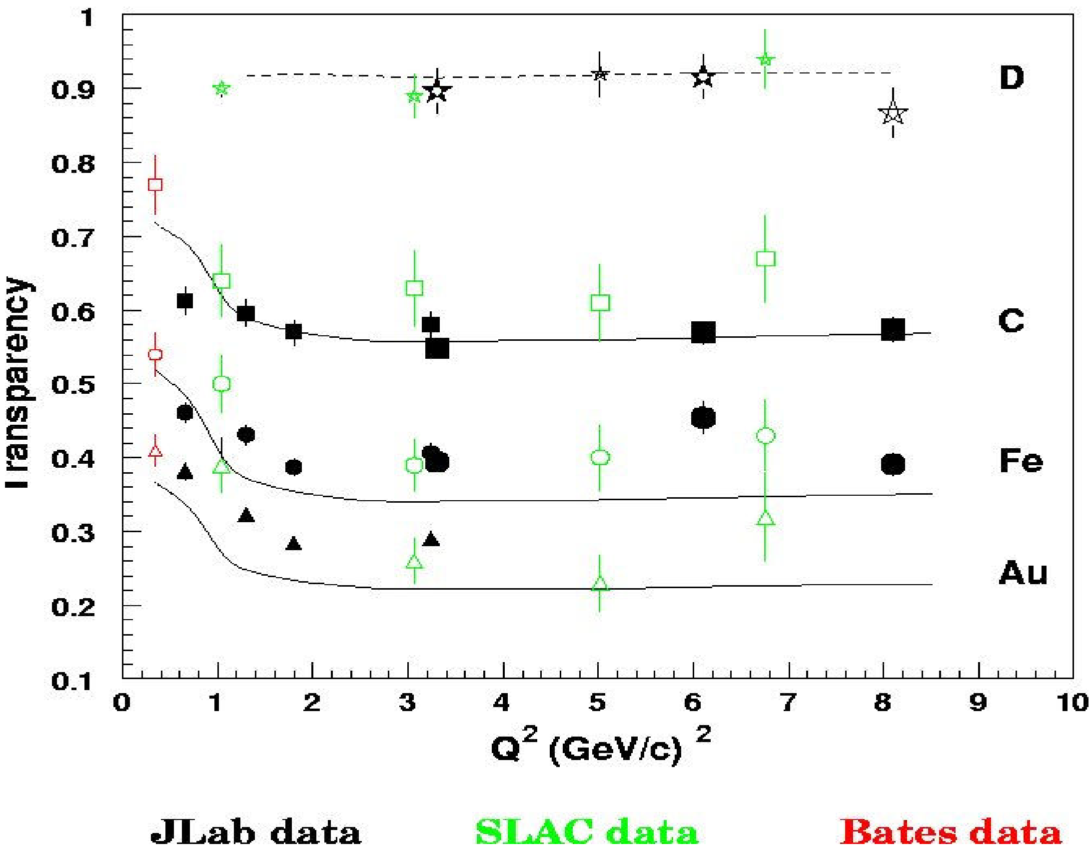


Figure 2: The nuclear transparency as a function of $Q^2$. The red open symbols are the Bates measurements [9]. The open green symbols are from SLAC experiments [10]. The black solid symbols are the JLab measurements [11]. The solid curve for carbon target represents a model by Pandharipande et al [12]. The curves for iron and gold are scaled from carbon calculations. The dashed curve is a linear fit to deuterium data.

Studying CT through meson production offers many advantages compared to the baryon sector. Naively, we would expect that a small size is more probable in a two quarks system such as pions and ρs than in protons. In addition the onset of CT is expected at lower $Q^2$ in the meson sector. Furthermore, the onset of CT is related to the onset of factorization required for access to GPDs in deep exclusive meson production. Until now, the clearest signal of CT was observed in the E791 experiment [13] at Fermilab. The A-dependence of the diffractive dissociation into di-jets of 500 GeV/c pions scattering coherently from carbon and platinum targets was measured. It was found that the cross section can be parameterized as $\sigma = \sigma_0 \mathbf{A}^{\alpha}$ , with α= 1.6. This result is quite consistent with theoretical calculations [14] including CT and obviously inconsistent with a cross section proportional to $A^{2/3}$ which is typical of inclusive pion-nucleus interactions. A more recent experiment [15] to look for CT was performed in Hall C at JLab, where the (e, e'π) process on $^{1}H$, $^{2}H$, $^{12}C$, $^{27}Al$, $^{64}Cu$ and $^{197}Au$ was used to measure the pion transparency over a $Q^2$ range from 1 to 5 $GeV^2$. The results are expected soon.

Exclusive diffractive $\rho^0$ electro-production of vector mesons off nuclei has also been suggested [16] as a sensitive way to detect CT. In these processes, a fluctuation of the virtual photon gives rise to a $q\bar{q}$ pair that travels through the nuclear medium evolving from the initial state, with $Q^2$ dependent size (the transverse size of hadronic fluctuation is $r_\perp \sim 1/Q$), to develop the vector meson in the final state. Therefore increasing the photon virtuality $Q^2$ one can squeeze the size of the produced $q\bar{q}$ wave packet. The hadronic structure of high energy photons was realized [17] back in the 1960's. In the laboratory frame, the photon fluctuation can propagate over a distance $l_c$ known as the coherence length.

The coherence length can be estimated relying on the uncertainty principle and Lorentz time dilatation as $l_c = 2\nu/(Q^2 + M_{q\bar{q}}^2)$, where ν is the energy of the virtual photon in the laboratory frame; ($-Q^2$ ) is its squared mass and $M_{q\bar{q}}$ is the mass of the $q\bar{q}$ pair. In the case of exclusive $\rho^0$ electro-production, the mass of $q\bar{q}$ is dominated by the $\rho^0$ mass. The produced small size colorless hadronic system will then propagate through the nuclear medium with reduced attenuation because its cross section is proportional to its size ($\sigma(r) \propto r^2$). The effect of the nuclear medium on the particles in the initial and final states can be characterized by the nuclear transparency. The experiment E665 [18] at Fermilab used the same process to look for CT using 470 GeV/c muon beam. As shown in Figure 3, the increase of the nuclear transparency with $Q^2$ was only suggestive of CT because the statistical precision of the data was not sufficient. The HERMES experiment [19] measured the nuclear transparency as a function of $l_c$.

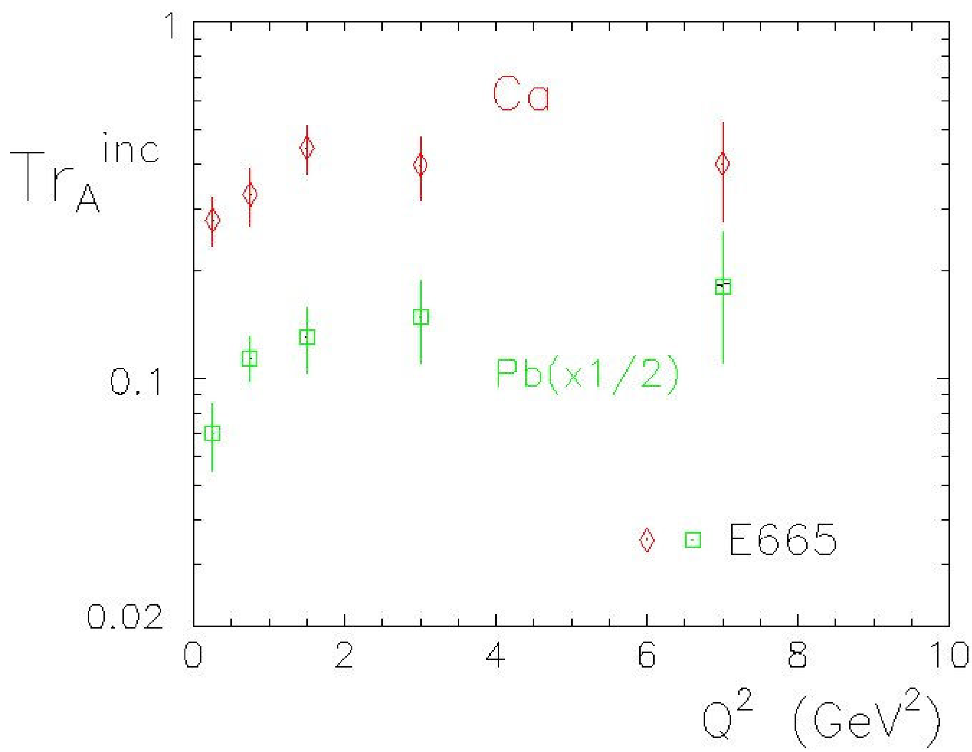


Figure 3: The nuclear transparency for incoherent $\rho^0$ muon-production as a function of $Q^2$. The data is from E665 experiment at Fermilab.

Figure 4 shows that the nuclear transparency increases when $l_c$ varies from long to short compared to the size of the nucleus. This is due to the fact that the nuclear medium seen by the $q\bar{q}$ fluctuation becomes shorter. Thus the $q\bar{q}$ pair interacts less. This situation occurs when $Q^2$ increases at fixed ν. This so called coherence length effect (CL) can mimic the CT signal. Therefore one should keep $l_c$ fixed while measuring the $Q^2$ dependence of the nuclear transparency.

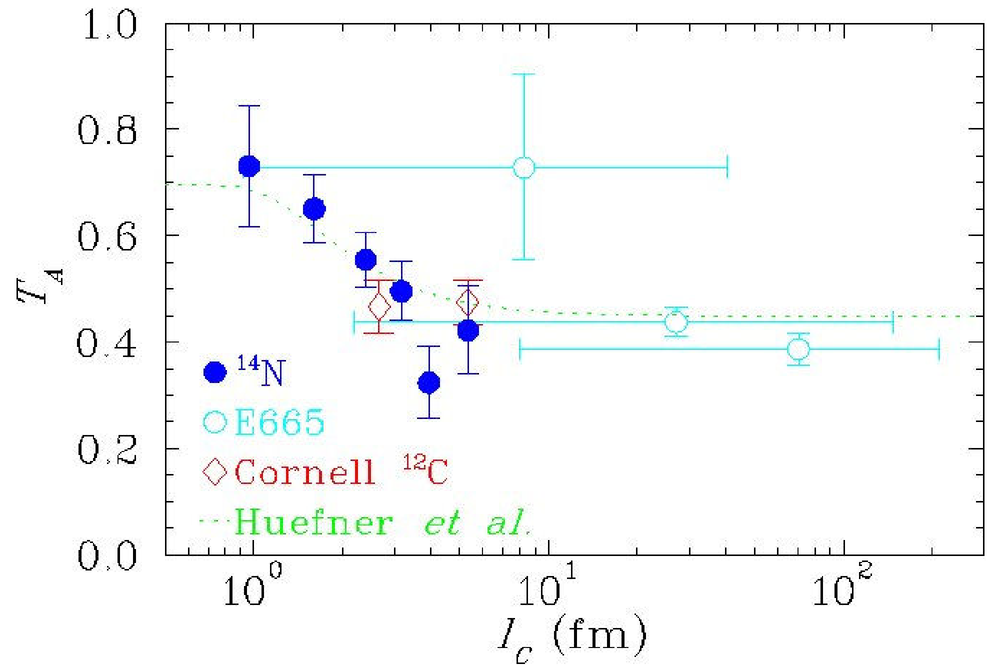


Figure 4: The nuclear transparency as a function of the coherence length. The dashed curve is a model calculation by Hufner et al [20].

HERMES measured the $Q^2$ dependence of the nuclear transparency for fixed Coherence Length. A simultaneous fit of the $Q^2$ dependence for different $l_c$ bins resulted in a $Q^2$ slope two sigma away from zero.

More recent measurements [21] were performed in Hall B using the CLAS detector. The beam energy was 5 GeV. The $Q^2$ range was from 0.7 to 2.7 GeV$^2$. The amount of data taken was not sufficient to allow for binning in $l_c$ , however the $l_c$ range measured is small enough (less than 1 fm) that no $l_c$ dependence is expected for $T_A$ (see Figure 4 and Figure 8). This assumption was checked by plotting $T_A$ versus $l_c$, which was indeed flat. The analysis of this data is still in progress with a number of corrections (radiative correction, pion absorption correction, acceptance correction) that still need to be applied before the results are finalized. The initial estimates are that these corrections will be small and predominantly shift all points up or down but do not affect the relative shape and slope of the points. These preliminary results are shown in Figure 5. The graph shows a clear rise with increasing $Q^2$.

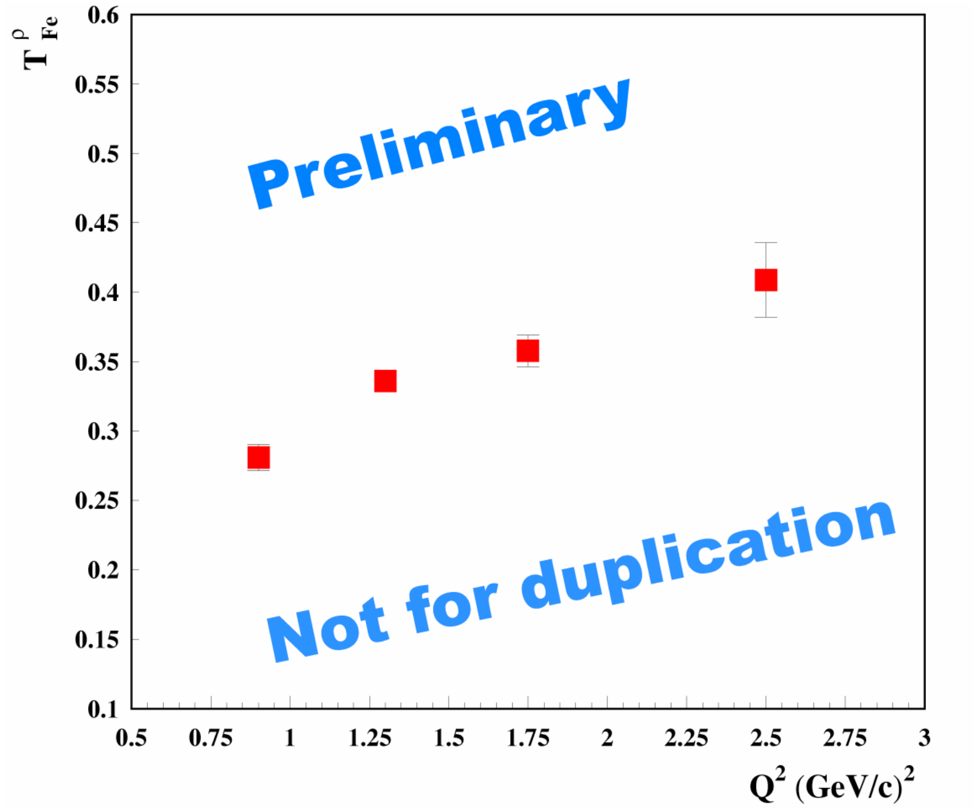


Figure 5: Preliminary results for the nuclear transparency $T_A$ for $\rho^0$ production on Fe versus $Q^2$ for the 5 GeV data from experiment E02-110. Corrections for acceptance, pion absorption and radiative effects are not yet included. See Figure 8 for the kinematical coverage in $l_c$ and $Q^2$.

# Theoretical Efforts

The concept of Color Transparency (CT) has attracted much attention since the 1980s because it is a frontier problem of QCD. Theorists continued developing models to describe the strong interaction of color singlet small object. In calculating the effect of CT, the general approach has been to use a reduced value of pre-hadron-nucleon cross section. The physics content of the CT models is in the $Q^2$ and time dependence of the reduced cross section. Although many models were developed to describe CT in baryon sector, there is only one model that is relevant to our measurements. Kopeliovich and collaborators [22] used a light cone QCD formalism for a comprehensive description of exclusive electro-production of vector mesons off nuclei at medium energies. Their model incorporates both CT and coherence length effects. The amplitude of a diffractive process is treated as elastic scattering of a $q\bar{q}$ fluctuation of the incident particle. The elastic amplitude $M_{\gamma^* N \to VN}(x, Q^2) = \langle V | \sigma^N_{q\bar{q}} | \gamma^* \rangle$ is obtained by a convolution of the universal flavor-independent dipole cross section for the $q\bar{q}$ interaction with a nucleon $\sigma_{q\bar{q}}$ and the initial and final wave functions. The dipole cross section cannot be reliably evaluated theoretically and is fitted to the data of the proton structure function in a wide range of $x_B$ and $Q^2$. As a rigorous test of the model, the cross sections of elastic electro-production of ρ and ϕ off a nucleon target were calculated with no free parameters. These calculations reproduce remarkably well both the energy and $Q^2$ dependence including the absolute normalization. In order to describe incoherent production of vector mesons off nuclei, a modified Green's function was used to describe the propagation of the $q\bar{q}$ in the medium taking into account absorption. This is done by introducing an imaginary part of the potential into the two dimensional light cone Schrödinger equations for the Green's function. This model has succeeded in describing the coherence length dependence of the nuclear transparency and is in good agreement with FNAL measurements. The predicted nuclear transparency as a function of $Q^2$ for incoherent $\rho^0$ on nitrogen and krypton at fixed coherence length is shown in Figure 6.

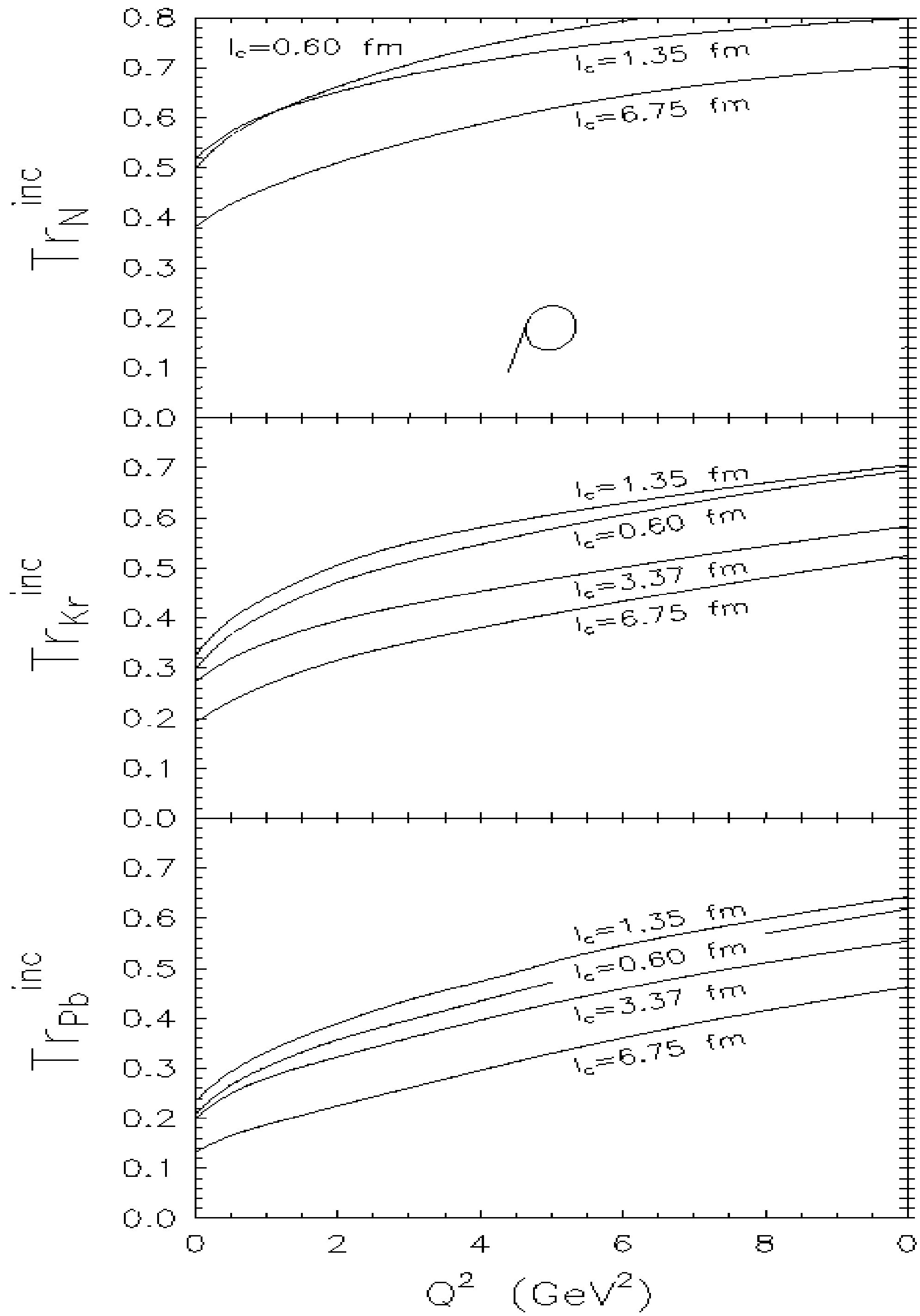


Figure 6: $Q^2$ dependence of the nuclear transparency for exclusive $\rho^0$ electroproduction on nuclear targets $^{14}$N, $^{84}$Kr and $^{208}$Pb for fixed coherence lengths.

# Proposed Measurements

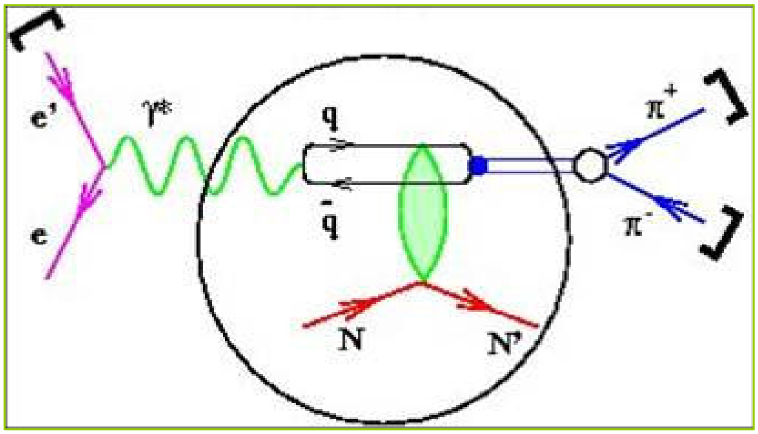


Figure 7: Exclusive lepto-production of the $\rho^0$ meson.

We propose to measure the nuclear transparency ($T_A$) for exclusive incoherent $\rho^0$ electro-production on $^1H$, $^2H$, C, Fe and Sn targets up to $Q^2$ = 5.5 GeV$^2$ and for fixed $l_c$ values from 0.4 to 2 fm. Binning the data in a way which keeps $l_c$ constant represents a simple prescription to eliminate the Coherence Length effect from the $Q^2$ dependence of the nuclear transparency. Moreover, because the chosen values of $l_c$ are shorter than the mean free path of the vector meson in the nuclear medium, it is obvious that there is no shadowing in the initial state. By isolating the Coherence Length effect, the Glauber model predicts no variation of $T_A$ with $Q^2$. The schematic of the reaction is given in Figure 7: the incident electron scatters off the target nucleus and exchanges a virtual photon. The photon interacts with one of the nucleons inside the nucleus and eventually produces a $\rho^0$ meson. The $\rho^0$ meson decays into two pions. We propose to perform these measurements at Hall B using the CLAS12 detector with an electron beam of 11 GeV at maximum luminosity of $10^{35}$ cm$^{-2}$s$^{-1}$. The nuclear transparency for three targets will be determined: carbon, iron and thin. The scattered electron will be detected to determine $Q^2$ and $l_c$. The coincident detection of the two pions will allow the identification of $\rho^0$ particles using their reconstructed invariant mass. We propose to make this measurement with two targets simultaneously in the beam to reduce systematic errors in calculating the $T_A$ ratio.

## Kinematics

Since the Coherence Length effect can imitate the Color Transparency effect, we will study the $Q^2$ dependence of $T_A$ at fixed $l_c$ values. Although our measurements will cover a coherence length range from 0.4 to 2.1 fm, for simplicity we will only illustrate the $l_c$ bin from 0.4 to 0.5 fm where the whole $Q^2$ range is covered as shown in Figure 8. This figure also shows the much more limited range of the 5 GeV data with the black and red contour lines.

In order to identify the process of interest, these kinematical cuts will be applied:

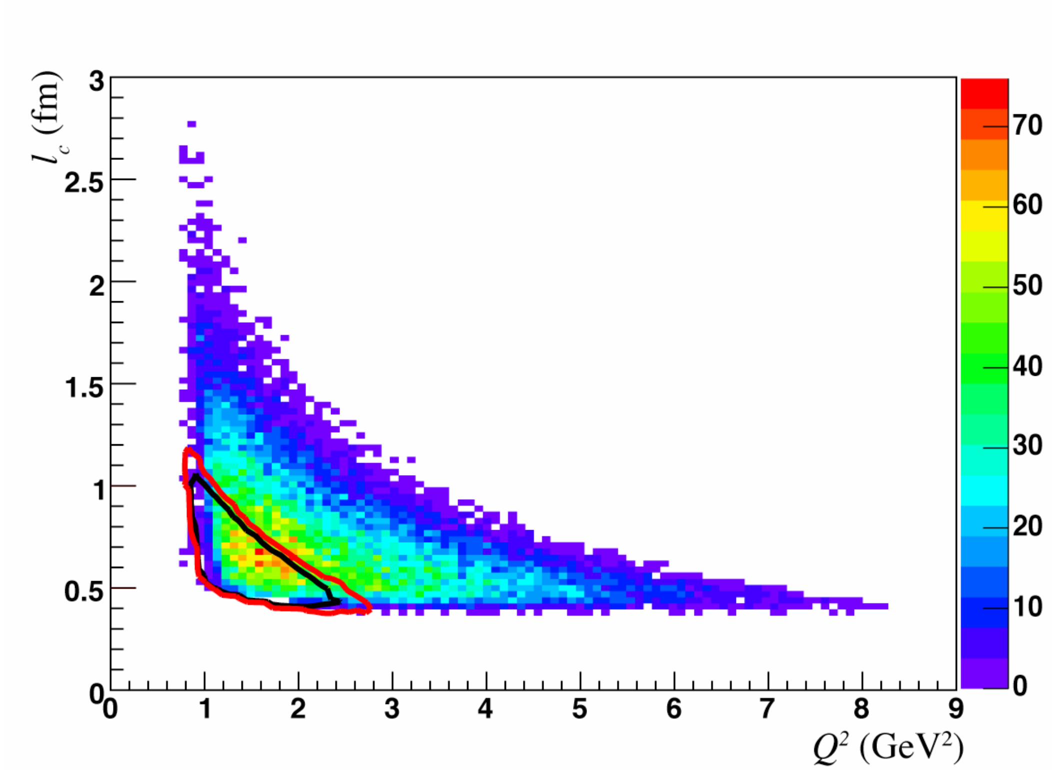


Figure 8: $l_c$ vs. $Q^2$ correlation for the proposed experiment with an 11 GeV electron beam. The detector response was simulated with the CLAS12 FastMC. The black and red contour lines indicate the area covered by the 5 GeV data.

- W > 2 GeV, to avoid the resonance region,
- $Z = E_\rho/\nu > 0.8$, to select the elastic process,
- $|\Delta E| < 0.2$ to reduce the contamination from non-exclusive events,
- $-t > 0.1$ GeV$^2$ to exclude coherent production,
- $-t < 0.5$ GeV$^2$ to select the diffractive process.

$\Delta E$ is the energy missing from the $\pi^+ \pi^-$ pair due to the creation of any additional final state particles (excitations of the recoil nucleus don't affect $\Delta E$ within the resolution). The cut on $\Delta E$ is closely related to the cut $z \cong 1$ but has the advantage that it includes the correction for the kinetic energy $-t/2M_p$ of the recoil nucleon and that the inelastic threshold $\Delta E = m_\pi + m_\pi^2/2M_p$ is independent of the photon energy $\nu$.

### Count Rates

A new event generator of $\rho^0$ electroproduction from both protons and nuclear targets has been implemented. The three independent kinematical variables: $W$, $Q^2$ and the momentum transfer $t$ are generated according to their experimental distributions. $W$ and $Q^2$ are generated according to the flux of the virtual photons $\Gamma(W, Q^2)$ exchanged between the incident electron and the target:

$$\Gamma(Q^2,W) = \frac{\alpha}{8\pi^2} \times \frac{W}{ME^2} \times \frac{W^2 - M^2}{MQ^2} \times \frac{1}{1-\varepsilon}$$

$M$ is the mass of the target. $E$ and $E'$ are respectively the energies of incident and scattered electron, $\nu = E - E'$ is the energy of the virtual photon, and the variable $\varepsilon = [1 + 2(Q^2 + \nu^2)/(4EE' - Q^2)]^{-1}$ is its polarization. The momentum transfer, $t$ is generated according to the experimental cross section $d\sigma/dt$ from Cassel et al [23]. In addition, Fermi momentum of nucleons inside the nucleus has been taken into account. The momentum of the struck nucleon is generated inside the corresponding Fermi momentum sphere of radius $P_F$ [24]. The generator considers also the decay of $\rho^0$ into a pair of pions $\pi^+ \pi^-$. Pion angles are generated assuming s-channel helicity conservation. Using the generator output as input to the fast simulation code of the CLAS12 detector, we have been able to study the acceptance of the three particles. The acceptance for different $l_c$ and $Q^2$ bins taking into account the different kinematical cuts mentioned above, is shown in Figure 9. Using the electroproduction cross sections, $\sigma(W, Q^2)$, measured on hydrogen, we have been able to estimate the count rates for the chosen bins in $l_c$ and $Q^2$.

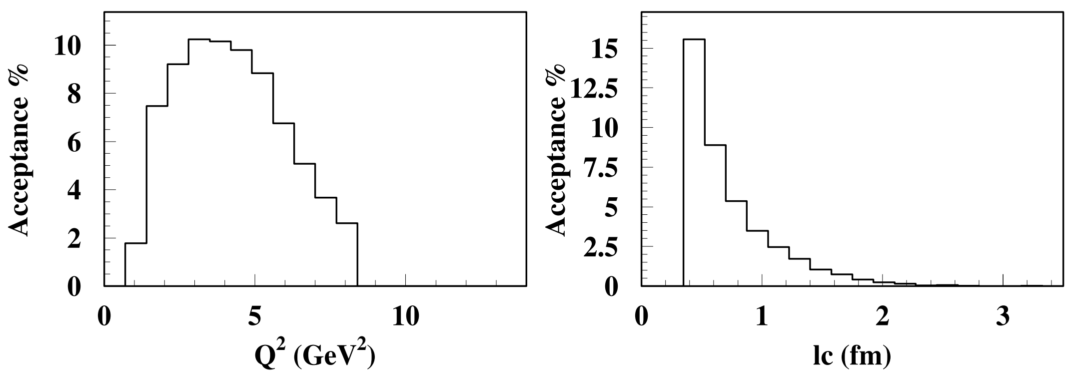


Figure 9: Acceptance for different bins in $l_c$ and $Q^2$.

According to our previous experience with 5 GeV data, running with both deuterium and the solid target simultaneously reduces the systematic errors significantly.

For carbon, we have used 8 days run time, for Fe, 12 days and for Sn, 16 days. The following table summarizes the expected statistical uncertainties on the nuclear transparency ratio for $l_c$ between 0.4 and 0.5 fm at different $Q^2$ bins for the three solid targets.

| Target\ $Q^2$ ( $GeV^2$ ) | 1.25±0.25 | 1.75±0.25 | 2.25±0.25 | 2.75±0.25 | 3.25±0.25 | 3.75±0.25 | 4.5±0.5 | 5.5±0.5 |
|---|---|---|---|---|---|---|---|---|
| C | 1.4% | 1.% | 1.2% | 1.7% | 2.4% | 3.5% | 4.3% | 7.5% |
| Fe | 1.7% | 1.1% | 1.4% | 1.8% | 2.6% | 4.1% | 4.5% | 7.8% |
| Sn | 1.6% | 1.1% | 1.3% | 1.8% | 2.6% | 4.% | 4.5% | 8% |

Table 1: Statistical errors expected for $l_c$ = 0.45 fm and different bins in $Q^2$.

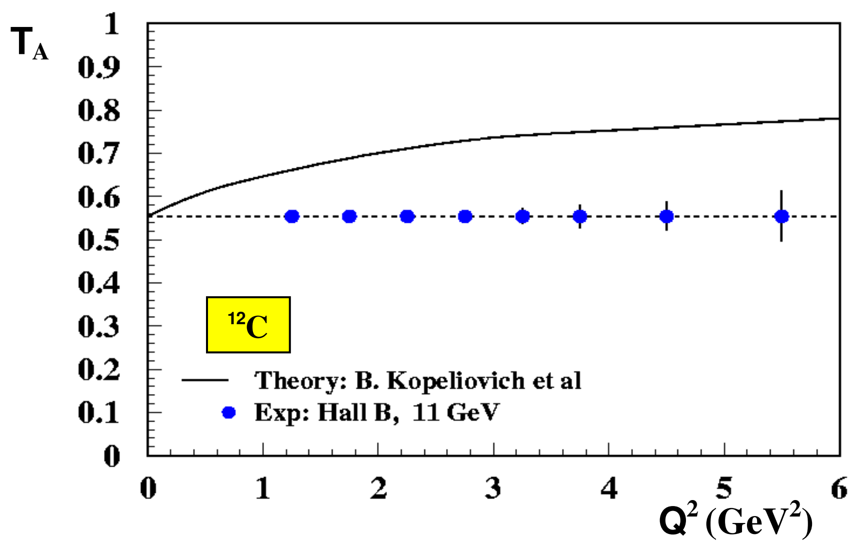


Figure 10: Expected error bars for the proposed nuclear transparency measurements for carbon and predictions of reference.

The projected measurements at the proposed values of $l_c$ are presented in Figure 10 for carbon, Figure 11 for Fe and Figure 12 for Sn.

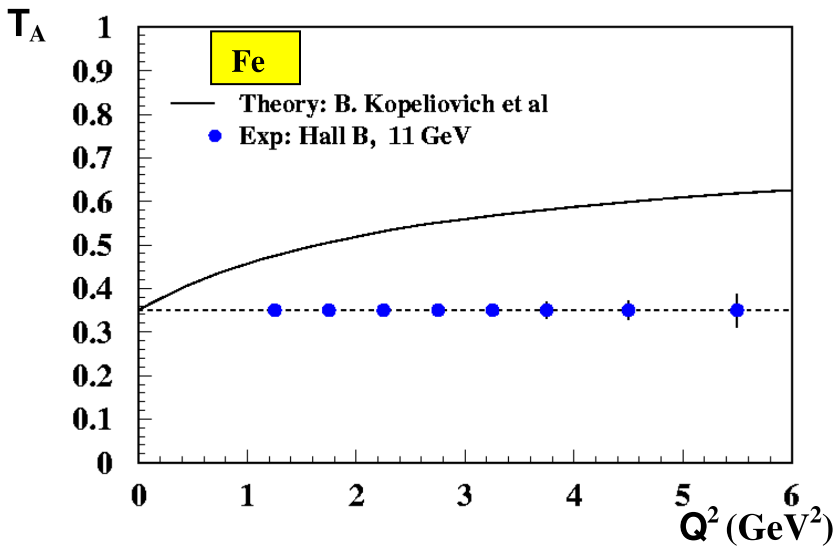


Figure 11: Expected error bars for the proposed nuclear transparency measurements for Fe target.

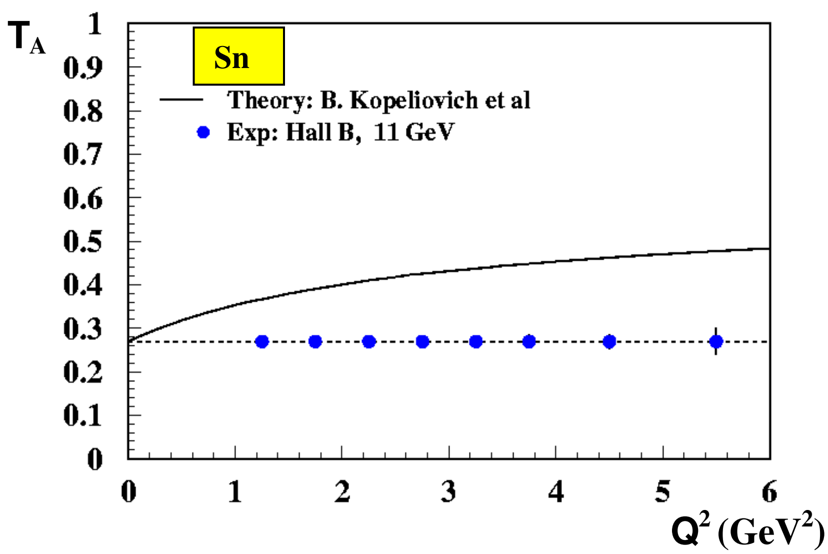


Figure 12: Expected error bars for the proposed nuclear transparency measurements for Sn target.

## Systematic uncertainties

In this section, various sources of systematic uncertainties will be discussed. These sources include the absorption of the decay pions inside the nucleus, the background subtraction and the radiative corrections.

## Background Contributions

Analysis of data from the experiment E02-110 [21] gave us a lot of experience dealing with different backgrounds contributing to the $\rho^0$ peak. The beam energy was 5 GeV. The invariant mass of the detected $\pi+\ \pi^-$ before and after kinematical cuts on *W, t* and *ΔE* for Fe target is presented in Figure 13.

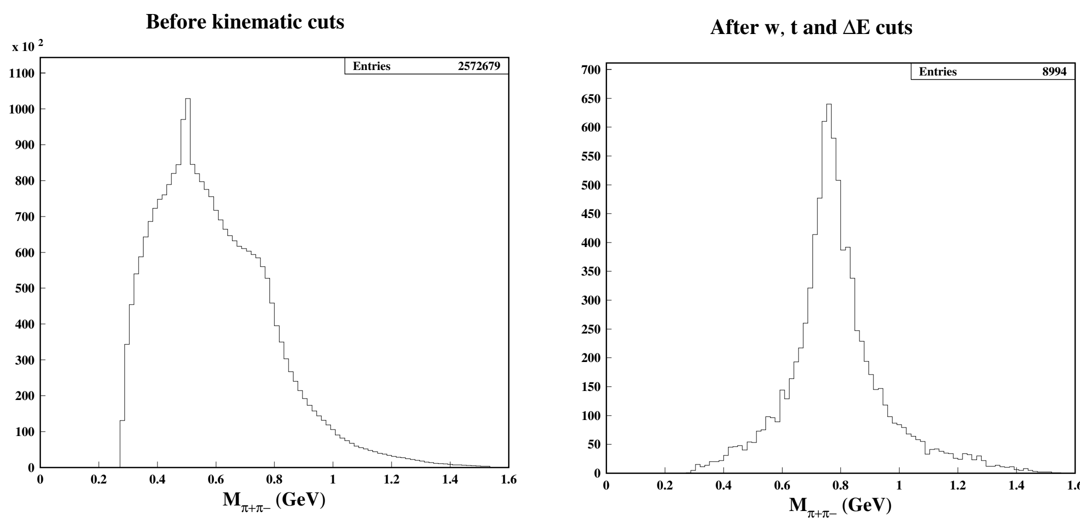


Figure 13: The $\pi^+\ \pi^-$ invariant mass before (left) and after (right) the kinematical cuts for Fe target.

The invariant mass of the two pions before the kinematical cuts only shows a nice peak for $K_s$. When we select the diffractive region, the $\rho^0$ peak emerges from the data and it cleans up as we apply cuts on W and ΔE. The main channels that can produce a $\pi^+\pi^-$ pair in the final state and could contribute to the background are $\Delta^0$, $\Delta^{++}$ and $\pi^+\pi^-$ non-resonant background. Shapes of these processes were taken from Genova Monte Carlo and their magnitudes were fitted to the data. The result is shown in Figure 14. The $\pi^+\pi^-$ from ω(782) meson decay could in principle contribute to the background when the $\pi^0$ is not detected but the invariant mass of the two pions is centered about 0.45 GeV with a width of 0.075 GeV (using the Dalitz plot for ω decay to $\pi^+$, $\pi^-$ and $\pi^0$). This means that the majority of these events are outside the relevant $\rho^0$ mass window. We estimated the residual contamination to be about 2%.

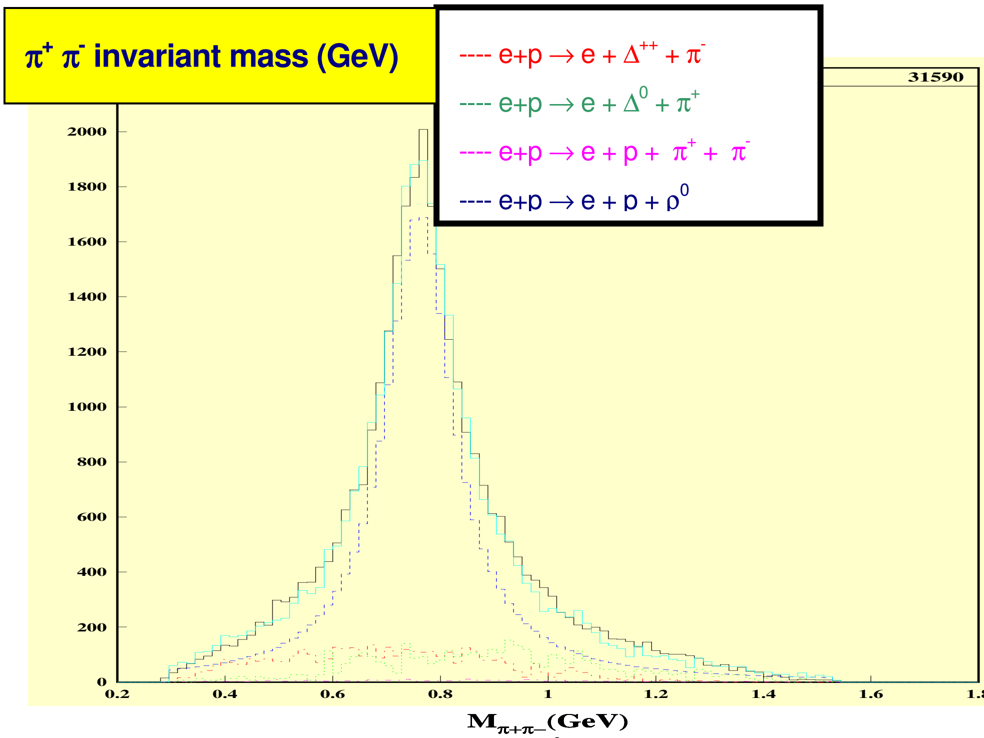


Figure 14: Reconstructed invariant mass of the $\rho^0$ decay pions using CLAS data of 5 GeV off Fe. The black line is the data; the cyan line is the sum of all the separate processes listed in the box.

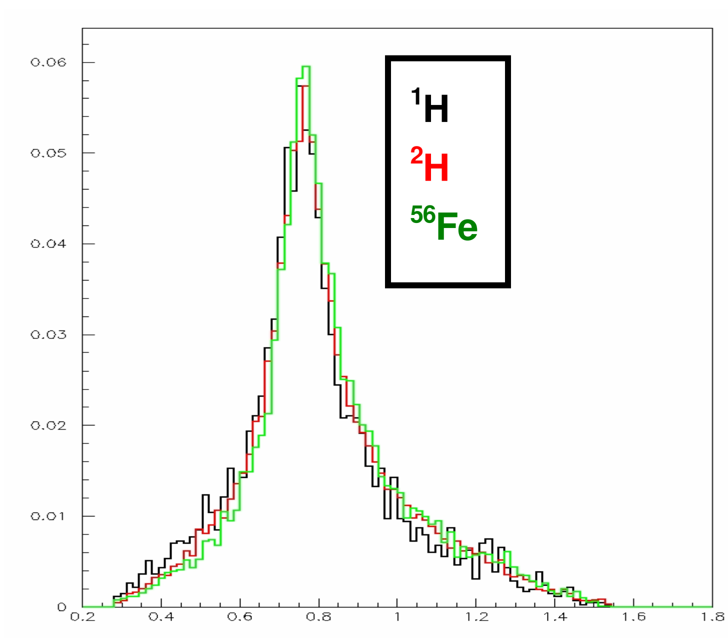


Figure 15: Reconstructed invariant mass of the $\rho^0$ decay pions using CLAS data of 5 GeV off H, $^2$H and Fe.

Because we are interested in the nuclear ratio, many of the background contributions cancel. This shows in the 5 GeV data as we have super-imposed the two pions invariant mass from hydrogen, deuterium and iron in Figure 15. A more efficient way to better control the background is to take data on hydrogen where one can identify exclusive $\rho^0$ production and study all the other channels, determine their relative contributions with the missing mass technique and then use them in a Monte Carlo to fix their magnitudes. To this end we have proposed to take 4 days on hydrogen target. This data is also useful in studying tracking efficiency, acceptance, and momentum smearing.

## Pion Absorption

In order to estimate the correction of the measured $\rho^0$ nuclear transparency due to the pion absorption effect, we have implemented a Monte Carlo (MC) model to calculate the $\rho^0$ transparency. The model uses experimentally measured cross sections for the $\rho^0$ production and $\pi$N interactions. A MC event starts by generating a virtual photon according to the corresponding flux in (W, $Q^2$) for the given electron energy. A target nucleon is selected inside the nucleus and its momentum generated within the corresponding Fermi sphere. A $\rho^0$ is produced according to the experimental cross section in (W, $Q^2$) measured by Cassel et al[23]. The $\rho^0$ production point is randomly generated within the target nucleus sphere of radius $R_A = r_0 A^{1/3}$, with $r_0 \sim 1.2$ fm. The transfer momentum $t = (P_\gamma - P_\rho)^2$ is generated according to the exponential distribution $A\exp(-b\,t)$ measured by Cassel et al[23] for different bins in (W, $Q^2$). The $\rho^0$ Lab momentum $P_\rho$ and angle $\theta_\rho$ are determined from t and the kinematics in the $\gamma$N center of mass by a Lorentz transformation. The azimuthal angle $\phi_\rho$ is uniformly generated. The $\rho^0$ decay time $t_\rho$ is generated according to the decay law $\exp(-t/\tau)$ where $\tau$ is the $\rho^0$ lifetime in the Lab (rest-frame of the target nucleus): $\tau = \gamma\tau_0$, where $\tau_0$ is the $\rho^0$ lifetime in its rest-frame and $\gamma$ is the relativistic factor. Considering the $\rho^0$ momentum $P_\rho$, the decay survival length $L_\rho$ is calculated from $t_\rho$. $L_\rho$ is then compared to the distance $D_\rho$ from the production point to the nucleus boundary along the direction of $\rho^0$. If $L_\rho$ is shorter than $D_\rho$, the $\rho^0$ meson decays inside the nucleus, if not the decay should happen outside. In the case where the $\rho^0$ decays outside the nucleus, the absorption is considered for a distance or thickness $D_\rho$ with the nuclear density of the target $\rho_A$ and the $\rho$N cross section [17] taken at the same momentum. If the $\rho^0$ decays inside the nucleus, its absorption before decay is considered for a distance or thickness $L_\rho$ inside the nucleus. The decay into ($\pi^+$,$\pi^-$) is calculated only for the non absorbed $\rho^0$. The decay is performed in the $\rho^0$ rest frame and the pions angles are generated assuming s-channel helicity conservation (SCHC). The pions momenta and angles are then boosted back to the Lab frame (rest frame of the target nucleus). For each pion the distance $D_\pi$ to the nucleus boundary is calculated and the corresponding absorption is considered using the experimental $\pi$N cross section parameterized as a function of momentum. In the case where one of the decay pions is absorbed, the $\rho^0$ is considered absorbed.

By generating a large number of events for given kinematics (typically one million), we can determine the fraction of transmitted $\rho^0$ meson which is nothing but the $\rho^0$ nuclear transparency: $T_A = N_\rho(\text{transmitted})/N_\rho(\text{generated})$. This ratio can of course be calculated for any bin in kinematical variables (W, $Q^2$, etc...) by generating only events inside the considered kinematics region. By calculating the nuclear transparency when considering the $\rho^0$ decay inside the nucleus, $\mathbf{T_{dec}(A)}$, and when ignoring it, $\mathbf{T_{ndec}(A)}$, considering pure $\rho^0$ absorption we can estimate the correction to the measured transparency for the pion absorption effect. This correction is simply the difference between the two calculated transparencies $\mathbf{(T_{ndec}(A) - T_{dec}(A))}$ to be added to the measured transparency. The estimated systematic uncertainties are shown in Table 2.

| Target | $\rho^0$ decaying inside | $\pi$ absorbed | Error |
|---|---|---|---|
| C | 13 – 22 % | 9 – 15 % | 1 – 3 % |
| Fe | 16 – 26 % | 13 – 21 % | 1 – 3 % |
| Sn | 17 – 27 % | 14 – 23 % | 2 – 4 % |

Table 2: Systematic errors due to the pion absorption inside the nucleus

### Radiative Corrections

Radiative effect in electron scattering can be separated into two categories. The most straightforward to deal with are the so-called external corrections in which incoming or outgoing electrons radiates a real photon due to the interaction with the fields of nuclei other than the target. Those effects are pretty well understood [25] and can be corrected for with great precision. One of the consequences of external radiative corrections is the modification of the incoming and the outgoing electron energies differently for each target. The second category and the more difficult to handle is the internal radiative corrections. The latter is target independent since we are interested in incoherent $\rho^0$ electroproduction and is expected to cancel in the nuclear transparency ratio. This is not totally true because the electron bremsstrahlung modify differently the kinematics for each target. We use our Monte Carlo model to take into account the external radiative corrections and to get the modified kinematical variables $Q^2$, W and t for the considered ($l_c$, $Q^2$) bin. These variables are then used in the code DIFFRAD [26] written specifically for exclusive vector meson production. The correction to the cross section is found to vary from 5% to 15% while the correction to the nuclear transparency is 1 to 5%. Considering the cross section model dependence of the correction, we expect the corresponding systematic error to be less than 2%.

## Beam Request

Measurements of the nuclear transparency for C, Fe and Sn at 11 GeV electron beam have been proposed. The process in question is diffractive incoherent $\rho^0$ electroproduction. The total beam time requested for these measurements is 960 hours (40 days). The deuterium target is not included because it is used automatically with each solid target.

| Targets | Beam Time (hours) |
|---|---|
| $^1H$ | 96 |
| C | 192 |
| Fe | 288 |
| Sn | 384 |

Table 3: The electron beam time requested on each target

## Conclusion

This document proposes a measurement of the nuclear transparency for C, Fe, and Sn in diffractive incoherent $\rho^0$ electro-production with an 11 GeV beam and the CLAS12 detector. This measurement will be an important confirmation of the E02-110 experiment, with more accurate data that extends into the very important higher $Q^2$ region, up to 5.5 GeV. With a total requested beam time of 40 days, the experiment is expected to make a clear statement about the onset of the phenomenon of Color Transparency.

# Technical participation of research groups

## Argonne National Laboratory

Argonne National Laboratory Medium Energy group is actively involved in this proposal, as well as in the quark propagation proposal using CLAS12. Among CLAS12 baseline equipment, the group intends to take responsibility for the design, prototyping, construction and testing of the high threshold Cerenkov counter. Three research staff and two engineers are likely to work at least part time on this project in the next few years. Funding for the group is from DOE. Additional sources of funding will be sought as appropriate. Beyond the baseline equipment, the group is also interested in exploring the possibility of building a RICH detector for CLAS12.

## University of New Hampshire

The University of New Hampshire Nuclear Physics group is actively involved in this proposal, as well as in 3 other proposal using CLAS12. The UNH group is committed to significant contributions in the development of the CLAS12 software. Maurik Holtrop is currently chair of the CLAS12 GEANT4 simulation group to which our post-doc Hovanes Egiyan is also contributing. Since currently the main software efforts for CLAS12 are in the area of simulation we are also part of and contributing to the general CLAS12 Software group. Current man power commitments to this effort are 0.15 FTE of a faculty and 0.4 FTE of one post-doc. We expect to increase this effort as our CLAS activities wind down and our CLAS12 activities pick up and we expect to attract some talented undergraduate students to this project. Among CLAS12 baseline equipment, the group intends to take responsibility for the design, prototyping, construction and testing of the silicon vertex detector and perhaps the inner detector's silicon tracking detectors. Faculty member Maurik Holtrop is likely to work at least part time on this project in the next few years and is likely to be joined by Jim Connel, a cosmic ray experimentalist with a background in nuclear physics, who is very interested in joining the vertex detector project. He has considerable experience with silicon detectors for space observations. Funding for the group is from DOE and additional sources of funding will be sought for this project to bring aboard Prof. Connel. If funded we are likely to a post-doc, a graduate students and one or two undergraduate students to this project. Beyond the baseline equipment, the group is also interested in exploring an extended inner calorimeter for CLAS12.

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