Jeopardy Update on E12-06-106: RG-D Experiment Study of Color Transparency in Exclusive Vector Meson Electroproduction off Nuclei

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Executive Summary

Experiment E12-06-106 (RG-D) aims to study the color transparency (CT) phenomenon in the exclusive diffractive ρ^0 electro-production off nuclei, using the CLAS-12 spectrometer in Hall-B. This experiment was endorsed by PAC30 back in 2006 and was reviewed by PAC36 in 2010 [1], at which time it was approved for 60 PAC days and granted the B$^+$ rating.

CT is one of the underlying properties of Quantum Chromo Dynamics (QCD) related to the presence of color degrees of freedom in the strongly interacting matter. It refers to the suppression of interactions of the colorless small size configuration in the nuclear medium at high momentum transfer. This compact configuration exhibits very small cross sections due to the cancellation of the color fields between its quarks, thus it is expected to travel through the nucleus experiencing reduced attenuation. Furthermore, the experimental signature of CT is the significant rise of the nuclear transparency, T_A, defined as the ratio of the cross section per nucleon on a bound nucleon to that on a free nucleon, with the four-momentum transfer squared (Q^2) involved in the reaction.

CT has previously been observed at high energies, and its onset was recently reported at lower Q^2 in both 6 GeV JLab experiments of pion [2] and ρ^0 [3] electro-production in Hall-C and Hall-B, respectively. Probing the CT effects in meson production is crucial for understanding the dynamical evolution from these exotic short-lived configurations into ordinary hadrons, and thus validates the QCD factorization theorem that is important for accessing Generalized Parton Distributions in deep exclusive meson processes.

The proposed measurements with an 11 GeV electron beam energy intend to study CT effects at fixed coherence length[1] and extend the Q^2 range up to 5.5 (GeV/c)^2, which will allow for significant increase in the momentum and energy transfer to produce smaller configurations that live longer and escape the nuclear medium intact. Therefore, we request 60 PAC days to study the Q^2-dependence of the nuclear transparency off the nuclei ^{12}C, ^{63}Cu, ^{118}Sn, and deuterium. This beamtime was confirmed with a more realistic simulation that has been performed using the CLAS12 GEant-4 Monte-Carlo package (GEMC) and a new target assembly that is currently built by the Hall-B engineers.

1 Physics Motivation

According to QCD, point like color-neutral objects, such as those produced in exclusive processes at sufficiently high momentum transfer, have small transverse size enabling them to travel through the nuclear medium with a significatly reduced attenuation [4]. This intrinsic QCD phenomenon, dubbed as color transparency, is essential for mapping the transition from the partonic to the hadronic degrees of freedom of strongly interacting matter. The phenomenon of CT refers to the suppression of the final (and/or initial) state interactions of hadrons with the nuclear medium. This suppression is caused by the cancellation of color fields produced by a compact system of quarks and gluons, commonly known as small size configurations[2] (SSC) with a transverse size, $r_\perp$, inversely proportional to the momentum

[1] The lifetime of the $q\bar{q}$ fluctuation of the virtual photon that get exchanged by the incident electron while scattering off the target nucleus.

[2] In literature, they are also called point-like configurations (PLC).

transfer, Q. Therefore, CT manifests the power of the hard (high virtuality of the virtual photon Q^2) exclusive reactions to isolate these special configurations in the hadron wave function as well as study their space-time evolution, and interactions with the nuclear medium when probed at intermediate energies [5, 6].

Experimentally, CT can be observed by measuring a reduced attenuation of produced hadrons as they exit the nucleus. This concept is basically inherited from the quantum elecrodynamics (QED) observation related to the decay of cosmic ray pion in an emulsion, where the ionization rate was found to increase as the (e^+e^-) pair travels far from the interaction point. That was interpreted as the pair of oppositely charged particles acts as an electric dipole with small radius and vanishing electromagnetic interaction cross section proportional to the square of its size. Thus, its interaction is suppressed near the interaction point [7]. In QCD, by analogy to QED, the scattering process preferentially selects a small singlet object made of a quark-antiquark ($q\bar{q}$) pair or a three quarks (qqq) object that acts as a color dipole in distances comparable to the nucleus size, hence, travels in the nuclear medium intact [8, 9].

In the last decades, several studies were dedicated to search for CT effects in mesonic and baryonic sectors. The CT studies in mesons production have been all promising, while the searches in the baryon sector, mainly the proton knockout, were deceiving (see the most recent CT review cited in our Ref. [9] for more details). Furthermore, as naturally expected, it is easier to bring the $q\bar{q}$ of a meson close together to form a SSC, than the qqq of a baryon [10]. This fact makes meson production more relevant for probing CT effects and searching for their onset.

Establishing CT on exclusive meson production is crucial for understanding the dynamics of hard processes, where it is possible to separate the perturbative and non-perturbative components of the process. In this case, the production amplitude is dominated by the contribution of small size configurations as induced by longitudinally polarized virtual photon, which upon its absorption the squeezed longitudinally polarized $q\bar{q}$ pair and the spectator baryon move fast in opposite directions with suppressed soft interactions (multiple gluon exchange) thus leading to factorization [11]. As a consequence, it is important to unambiguously observe the onset of CT to prove the validity of the QCD factorization theorem and determine the onset of its regime [11, 12]. Recently, CT was proposed [13] as the possible cause of the anomalous increase with centrality in the ratio of protons-to-pions produced at large transverse momenta in gold-gold collisions at the relativistic heavy ion collider in Brookhaven National Lab (BNL) [14].

2 Previous Measurements

2.1 Proton Knockout Experiment

The first attempt to search for the onset of CT at intermediate energy was carried out at BNL using the quasi-elastic proton scattering A(p, 2p) off nuclei [15–18]. The nuclear transparency, T_{A}, was defined as the ratio of the quasi-elastic cross section on a nuclear target to the free elastic pp cross section. The results showed a rise in T_{A} with the effective beam momentum up to $\mathrm{p_p}$= 9.5 GeV/c, which is consistent with a selection of a point like configuration. However, it was surprisingly followed by a drop at higher momenta. This energy dependence behavior has been explained to be deriven by an interference between the short and long distance amplitudes in the free *pp* cross section, where the nuclear medium acts as a filter for the long distance amplitudes [19, 20], or a crossing of a threshold for an open charm resonance or any other exotic QCD multi-quark states [21].

Due to the simplicity of the elementary electron-proton interaction mechanism compared to the proton-proton one, the quasi-free A(e, e'p) reaction was used in a series of experiments conducted at MIT-Bates [22], SLAC [23, 24] and JLab [25, 26] to look for the CT effects and its onset. Despite the wide coverage of Q^2 up to 8.1 (GeV/c)^2, the extracted nuclear transparencies were all energy-independent above $Q^2 = 2$ (GeV/c)^2, which is consistent with the conventional Glauber-type model of Pandharipande and Pieper [27].

The most recent A(e, e'p) experiment was carried out as one of the Hall-C commissioning experiments in 2018. Data were collected over a wider Q^2 range of 8 - 14.3 (GeV/c)^2, which corresponds to a proton momentum up to 8.5 (GeV/c) [28]. As depicted in Fig. 1, the preliminary results seem to exclude sizable CT effects, which is in disagreement with the reported rise (and fall) of nuclear transparency in the BNL A(p, 2p) results. This finding imposes challenging constraints on the theoretical models that were previously proposed to describe BNL data.

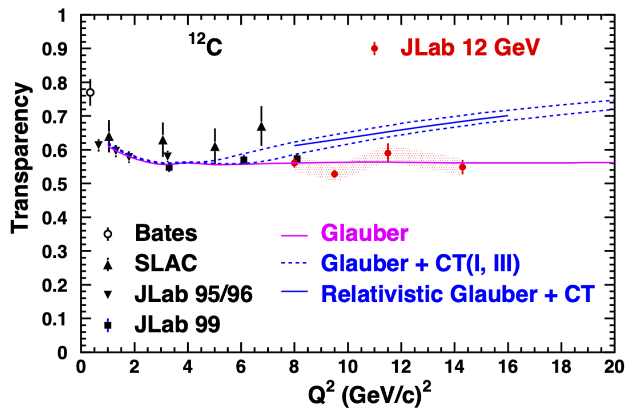


Figure 1: The preliminary Hall-C ^{12}C(e, e'p) transparency results along with all previous experiments. The solid red line is the Glauber calculation that excludes CT effects. The dashed lines are theory predictions including CT.

2.2 Meson Production Experiment

In contrast to the mentioned controversy in the baryon sector, CT studies have been successful in meson channels due to the simplicity of their production mechanism. The well-built CT signature was reported at high energies by the Fermi National Lab E791 experiment via the A-dependence of the diffractive dissociation into di-jets of 500 GeV negative pions scattering coherently from carbon and platinum targets [29]. At this regime, the SSC propagates in the medium with a frozen small size, and its creation is often interpreted as a proof of the QCD factorization theorem for deep exclusive meson processes (di-jet production) [12]. While at intermediate energies, the SSC starts expanding inside the nucleus, hence offers a distinctive probe to study the space-time evolution of these special configurations of the hadron wave function and their interactions with nuclei.

The strongest evidence of CT onset was reported at lower Q^2 in both 6 GeV JLab experiments of π^+ [2] and ρ^0 [3] electroproduction in Hall-C and Hall-B, respectively. The published results of both experiments are depicted in Fig. 2.

The pion-CT experiment measured the electroproduction of π^+ off ^{1}H, ^{2}H, ^{12}C, ^{26}Al, ^{64}Cu, and ^{197}Au over a wide Q^2 range from 1.1 to 4.7 (GeV/c)^2 [2]. The results of A and Q^2 dependence (Fig. 2 left) in nuclear transparency showed a positive slope, which is qualitatively consistent with theoretical predictions including CT effects [30, 31]. Furthermore, a well established positively charged pion-CT signal is expected with an extended measurements to higher Q^2 values up to 10 $(\mathrm{GeV/c})^2$ at the approved E12-06-10 expeiment that successffully passed PAC47 jeopardy process in summer 2019 [28].

Exclusive diffractive ρ^0 leptoproduction was used in several experiments to look for CT effects due to the simplicity of its production mechanism. In this process, the virtual photon originating from the scattering of the incident lepton over the target nucleus fluctuates into a $q\bar{q}$ pair [33] of small transverse size proportional to $1/Q$ [34]. The virtual $q\bar{q}$ pair can then scatter diffractively off a bound nucleon evolving from the initial to final state, where the SSC is formed and subsequently materializes into a ρ^0 vector meson. Thus, increasing the photon virtuality, Q^2, would guarantee the SSC production by squeezing the size of the $q\bar{q}$ wave packet.

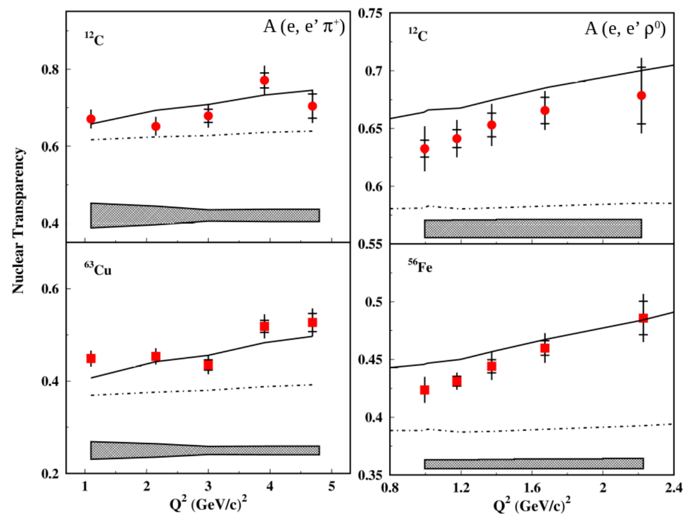


Figure 2: Nuclear transparency as a function of Q^2 for the 6 GeV Hall-C π^+-CT experiment on ^{12}C and ^{64}Cu (left) and Hall-B ρ^0-CT experiment on ^{12}C and ^{56}Fe (right). In both plots, the inner error bars are statistic uncertainties and the outer ones are statistic and point-to-point (Q^2 dependent) systematic uncertainties added in quadrature while the grey bands represent the normalization uncertianties for each measurment. The solid (dotted-dashed) curves are preditions of twin models that succeeded to describe both results using the same ingrdients with (without) CT effects [30–32]. The ρ^0 data seem to show a steeper increase with Q^2 while the pion data start to increase at a larger values of Q^2, around 3 $(\mathrm{GeV/c})^2$.

Furthermore, the CT search is sensitive to two time scales that can affect the measured signature. The first characteristic time is related to the propagation length of a $q\bar{q}$ pair, known as the coherence length, $l_c = 2\nu/(Q^2 + {M_{q\bar{q}}}^2)$, where ν is the virtual photon energy in the Lab frame, $-Q^2$ is its squared mass, and $M_{q\bar{q}}$ is the mass of the $q\bar{q}$ pair which is dominated by the ρ^0 mass in the case of exclusive diffractive ρ^0 production. In this case, the variation of l_c from long to short compared to the free mean path of a ρ^0 meson in the medium could lead to a rise of T_{A} with Q^2, hence mimic the CT signal [35]. This effect, known as the coherence length (CL), is caused by the hadronic initial state interaction of a $q\bar{q}$ pair with the medium. Thus, to keep this effect under control, the Q^2 dependence of T_{A} should be studied either at fixed or small l_c values (less than ~ 1 fm) where no Q^2 dependence on l_c is expected. The second time scale is related to the expansion time, dubbed as the formation time, of the SSC to evolve to a regular meson (or generally hadron). The latter should be larger than the nuclear radius to suppress final state interactions.

The first experiment to investigate CT using a diffractive ρ^0 leptoproduction off nuclei was carried out at Fermilab by the E665 collaboration [36] using a 470 GeV muon beam. Due to the lack of good statistical precision, the slight increase seen in the nuclear transparency as a function of Q^2 were suggestive but inconclusive regarding the CT signal. The latter was followed by the HERMES collaboration measurement at DESY in which the CT effects were investigated in the exclusive coherent and incoherent ρ^0 production off ^{2}H and ^{14}N targets using a 27.5 GeV positron beam [37]. In this case, to avoid mixing CL with CT, the Q^2 dependence on $T_{\rm A}$ was studied at fixed l_c bins. A simultaneous linear fit of all l_c bins was used to extract a common Q^2-dependence slope for both coherent and incoherent ρ^0 leptoproduction. Besides the limited statistical significance of the extracted result, the common Q^2-dependence slope was treated as a positve CT signal, which was found in good agreement with the existing theoretical model incorporating CT effects [38, 39].

The 6 GeV ρ^0-CT experiment used the exclusive, diffractive and incoherent ρ^0 electroproduction off ^{12}C and ^{56}Fe nuclei [3]. As illustrated in Fig. 2 right, a statistically significant increase of the transparency as a function of Q^2 was observed for both targets. These results were not corrected for the effect of the ρ^0 decay inside the nucleus and subsequent pion absorption. This task was left to the theoretical models that are compared to our data. All models' calculations showed that this correction is relatively small and could not account for the observed rise of the transparency with Q^2 [32, 40, 41] [3]. Although in the absence of CT effects, hadronic Glauber calculations would predict the cancellation of a Q^2 dependence of the nuclear transparency ratio since the $\rho - N$ production cross section is constant in the energy range under study. The observed rise in the nuclear transparency with Q^2 correspond to $(11 \pm 2.3)\%$ and $(12.5 \pm 4.1)\%$ decrease in the absorption of the ρ^0 in Fe and C, respectively. It should be noted that the measured nuclear transparency was found independent of the coherence length, $l_{\rm c}$. That, as expected, is due to the small $l_{\rm c}$ values (≤ 1 fm) compared to the C and Fe nuclear radii of 2.7 and 4.6 fm, respectively. Thus, the Q^2 dependence was examined by integrating over the full $l_{\rm c}$ range since there is no risk in this measurement to mimic CT signal with the CL effect.

3 Future Measurement: E12-06-106 Experiment

The experiment E12-06-106 [1] (RG-D) aims to study CT in the exclusive diffractive ρ^0 electroproduction off nuclei, using the CLAS12 spectrometer. As previously described, the diffractive scattering of the virtual $q\bar{q}$ fluctuation off a bound nucleon inside the target nucleus leads to the formation of the SSC that subsequently materializes into a vector meson ρ^0 over the formation time $\tau_f = 2\nu/(M^2_{\rho'} - M^2_\rho)$, where $M_{\rho'}$ is the ρ meson first orbital excitation mass, and M_ρ is its ground state mass. The ρ^0 get identified via its decay products, π^+ and π^-, that are detected in coincidence with the scattered electron by the CLAS12 spectrometer.

The RG-D (CT) experiment was initially approved to run for 52 PAC days on three nuclear targets (^{12}C, ^{56}Fe and ^{118}Sn) with 11 GeV electron beam energy and an other 8 days on hydrogen for background and acceptance correction studies. The initial plan was to use a dual target with deuterium and nuclear targets mounted simultaneously in the beam-line. For that reason, no beam-time was initially dedicated to the liquid deuterium target (LD2).

[3] As indication of the growing interest to unravel the CT phenomenon, our reference [41] represents the recently developed model by W. Cosyn *et al.* to describe the ρ^0-CT results (to be included in the long CT paper). In addition, we should bring the reader's attention to the other cited theoretical papers and reviews that have been published in the last decade highlighting CT phenomenon in both meson and proton-knockout production and also motivating for some competitive future measurements at J-PARC (Japan) and FAIR (Germany) [42–48].

However, this plan has recently revised to use 1) ^{63}Cu instead of ^{56}Fe since the latter is a ferromagnetic material and can't be utilized with the CLAS12 5T solenoid field surrounding the target area, and 2) a new solid foils assembly (flag design) that is built and maintained by the Hall-B engineers. As seen in Fig 3 left, the two sets of 60 degrees separated flag's poles (yellow upward needles) will be mounted simultaneously in the beamline with the empty LD2 cell. The needles are crimped around the foils which are further glued to not move. The two-pole sets are soldered to the flag shaft (bottom yellow rod), which goes through an aluminum housing (dark green) that is bolted to the LD2 cell and held by an aluminum coupling (grey). This flag assembly is designed to maximize heat transfer from the foils by conduction from the flag's poles to the LD2 cell to the target condenser via the grey tubes. The heat from the four needles and shaft will be also radiated to the scattering chamber (yellow container) which is kept under vacuum. The empty LD2 cell can also be kept at 50K to help cool further the foils. There is a plan this fall to test this target assembly by using resistors to apply heat to the foils, and measure the temperature of the flag shaft and liquid target cell to make sure the foils do not overheat. Figure 3 right shows a sliced GEMC view of the full assembly, which is inserted inside the vacuum scattering chamber (green) and CLAS12 solenoid (blue). The beam is expected to travel from left to right. We should note that the advantage of using this flag assembly compared to the dual target is:

1. Take liquid and solid targets data in the same vertex position which will minimize the acceptance correction,

2. Reduce the amount of collected deuterium data as one set can be used with all nuclear targets to extract the physics results,

3. Can accommodate several thinner solid targets, allowing to take full luminosity even on heavy targets.

Figure 4 shows the electron z-vertex distribution for simulated (left) and experimental (right) data. It is clear from Fig. 4 right that the current 6 mm vertex resolution is good enough to resolve the two 5 cm apart Al windows of the empty target cell, the same separation adapted in the flag assembly. This resolution is expected to further improve with the ongoing CLAS12 efforts to optimize the calibration and reconstruction software.

3.1 Beam Time Request

Based on the update related to the newly adapted solid foils assembly for RG-D experiment, a new simulation was performed to adjust the initially approved beam-time to 1. dedicate time for LD2 target, and 2. take into account running with two foils at once.

The simulation was done using the event generator that was exclusively developed for the CT study, the newly-designed flag assembly, and the CLAS12 GEMC and reconstruction package. Our generator includes the measured production cross sections by Cassel *et al.* [49] of ρ^0 and the three background processes: Δ^{++}, Δ^0 and the phase space, non resonant (π^+, π^-) pairs. It was validated in our 5 GeV CT analysis and the mentioned background processes gave a good description of the background underneath the ρ^0 peak. Figure 5 left represents a superposition of the generated ρ^0 (blue), the sum of the three background

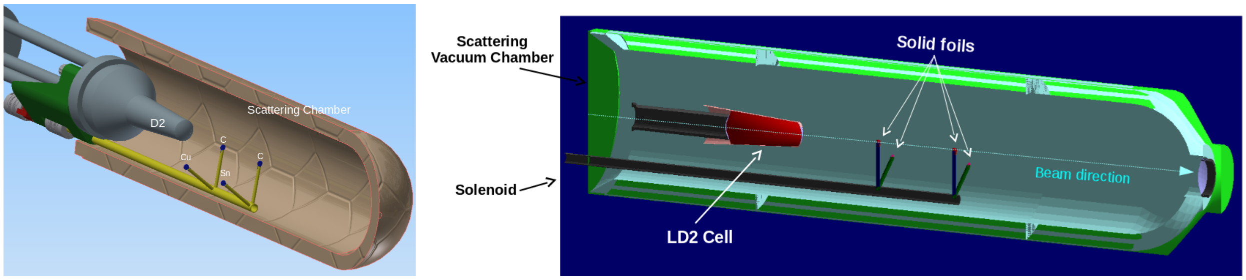


Figure 3: Left: The flag design with the 5 cm apart foils mounted on the same shaft (bottom yellow rod) with a 60 degrees opening between their holding needles (yellow upward sticks) that rotate together with a stepper motor. Each set of two foils will be inserted in the beam-line simultaneously with an empty LD2 target cell. Right: A sliced GEMC view of the Hall-B flag assembly along with the LD2 cell. The beam will travel from left to right.

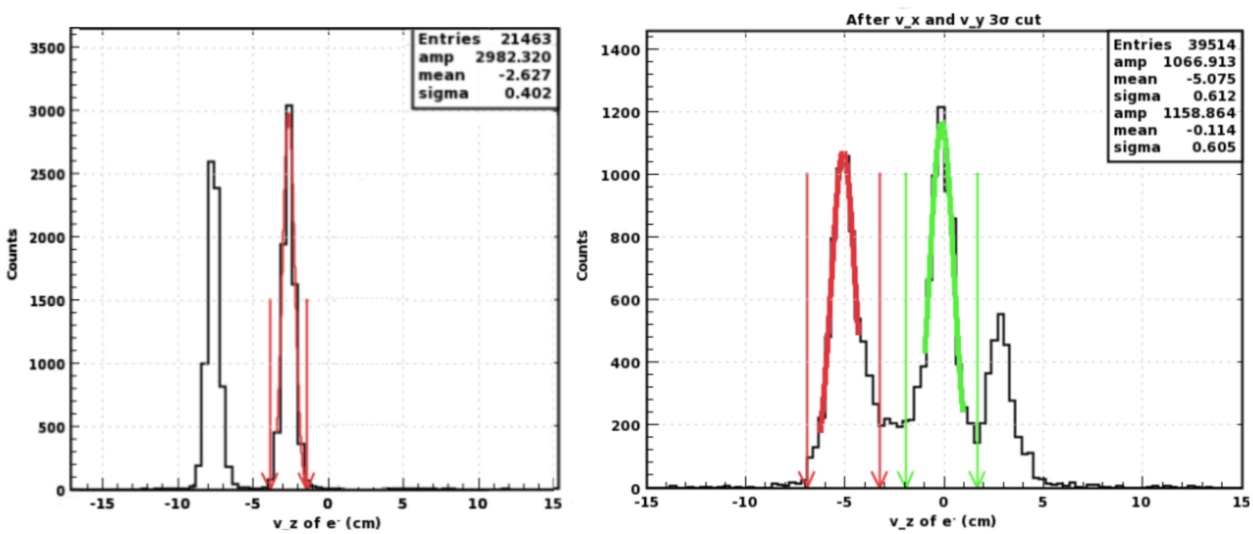


Figure 4: Left: The simulated electron z-vertex distribution showing the peaks of the 5-cm apart solid foils. The second peak is fitted and the two arrows indicate the 3 σ limit. Right: Electron z-vertex distribution from an empty target RG-A run. The three peaks are respectively the 5 cm apart entrance and exit windows (30 μm Al) of the LD2 cell and a thermal insulation foil, 12 μm, heat shield, which doesn't exist in the flag design because it is not needed in this case. The distribution is plotted after applying 3 σ cut on the electron's transverse vertex components, V_x and V_y, to reduce the background contribution. The vertex resolution is in the range of 6 mm, and the red and green arrows indicate the 3 σ limit which is sufficient to resolve the two 5 cm apart Al windows from each others.

processes (cyan) along with their sum (black), and the obtained ρ^0 distribution from RG-A and RG-B data-sets. Figure 5 right illustrates the contribution of the mentioned three background processes in our 5 GeV ρ^0 mass distributions. These processes are the main physics background that we are expecting to dilute our ρ^0 production channel. Moreover, any remaining contamination related for example to particle's misidentification will get improved over time with the development of CLAS12 software and advanced analysis tools.

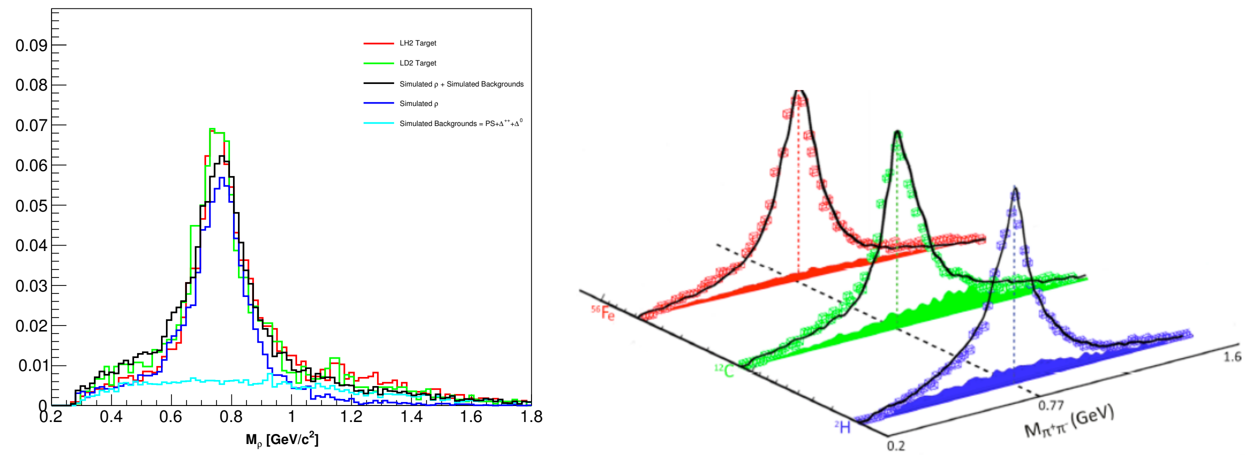


Figure 5: Right: The normalized (π^+, π^-) invariant mass obtained from experimental data runs: RG-A LH2 (red) and RG-B LD2 (green), and MC: generated ρ^0 + background processes (black), generated ρ^0 (blue), and the sum of the three background processes (cyan). Left: The (π^+, π^-) invariant mass extracted from our 5 GeV CT data [3] showing the contribution of the background processes as a shaded area in the bottom (see text for details).

Figure 6 shows our revised beam time along with new estimations of the statistical uncertainties for the lowest l_c bin, 0.4 - 0.5 fm. As reported in the 2010 CT update [50], we are still considering on the extraction of the 11 GeV projections the fact that the statistical uncertainties of the second largest Q^2 points should match the expected systematic point-to-point (Q^2 dependent) uncertainties. The latter are expected to be in the range of 3.3% for ^{12}C and 4% for ^{63}Cu, which substituted ^{56}Fe, as for our 5 GeV CT data (please see table 1 of Ref. [50] for more details). These new projections are comparable to the ones claimed in 2010, please see table 3 in page 6 of Ref. [50]. However, based on the new simulation study, our first Q^2 bin is now covering the range from 1 to 2 $(\mathrm{GeV/c})^2$. The initially proposed lowest Q^2 bin, 1 - 1.5 $(\mathrm{GeV/c})^2$, has been merged with its close neighbor, 1.5 - 2 $(\mathrm{GeV/c})^2$, because the former is in the edge of the acceptance and can not stand by itself with a good statistical precision.

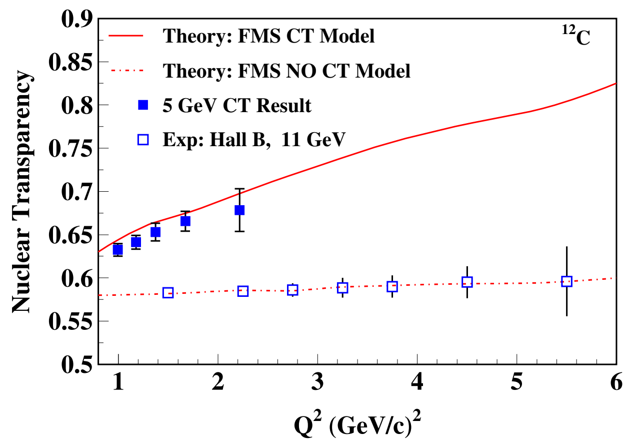
Figure 7 shows the projected statistical uncertainties for ^{12}C (top), ^{63}Cu (bottom-left) and ^{118}Sn (bottom-right), respectively, along with predictions from the theoretical model by Frankfurt, Miller, and Strikman (FMS [32]), which was tailored to our kinematics to describe our 5 GeV CT results and incorporated the effects of color transparency and ρ^0 decay. Measurements with different nuclei sizes are important for a quantitative understanding of the SSC formation time and its interaction in the nuclear medium.

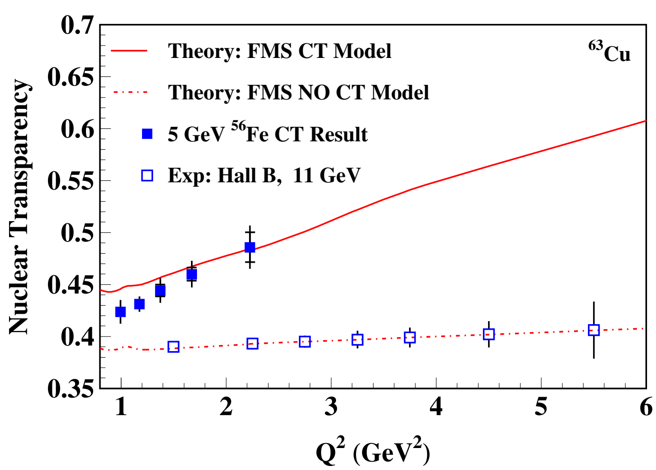
It is worth mentioning that the RG-D experiment has successfully passed the experimental readiness review (ERR) in 2019 [51]. The current tentative plan is to schedule its partial

Targets	Beam Time (PAC days)
^{12}C / ^{12}C	14
LD_2	14
^{63}Cu / ^{118}Sn	28
LH_2	4

$Q^2(GeV^2)$ / Targets	1.5 ± 0.5	2.25 ± 0.25	2.75 ± 0.25	3.25 ± 0.25	3.75 ± 0.25	4.5 ± 0.5	5.5 ± 0.5
^{12}C (%)	0.8	1.1	1.3	2.0	2.2	3.1	6.8
^{63}Cu (%)	0.9	1.2	1.5	2.2	2.5	3.3	7.0
^{118}Sn (%)	0.9	1.3	1.6	2.3	2.7	3.2	7.1

Figure 6: Top: The adjusted RG-D beam time for the new Hall-B flag assembly and the approved 60 PAC days by PAC36 in 2010 (see Ref. [50] page 7 table). A four PAC days are still dedicated to a hydrogen target run to better understand the other processes that contribute to the ρ^0 background. Bottom: Expected statistical uncertainties for the coherence length between 0.4 and 0.5 fm and the above run plan.





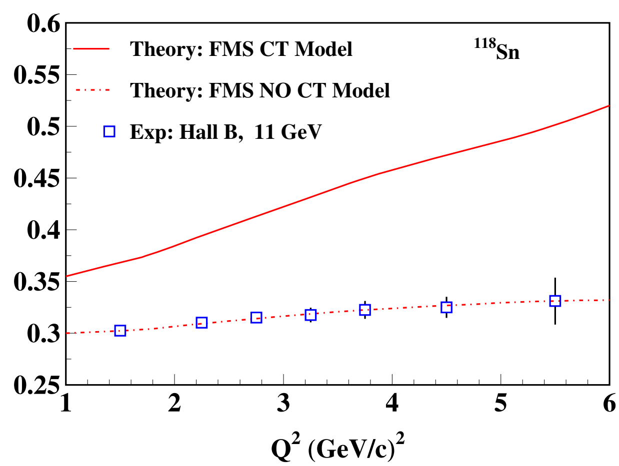


Figure 7: Expected statistical uncertainties for nuclear transparency of ^{12}C (top), ^{63}Cu (bottom-left) and ^{118}Sn (bottom-right) for the coherence length between 0.4 and 0.5 fm.

run ($\sim$ 50% of the approved 60 PAC days) in spring 2021 as the first CLAS12 nuclear target experiment [52], assuming, of course, the CT experiment will get endorsed by the PAC48.

4 Summary

The study of CT via vector meson electroproduction is a clean probe of small size configurations in the hadron wave function. The observed CT onset at lower Q^2 in the published Hall-B ρ^0 results compared to Hall-C π^+ data proves that the diffractive meson production is the optimal mechanism to verify CT and study the features of such exotic configurations at intermediate energies. The proposed measurements with an 11 GeV electron beam energy and three nuclear targets ^{12}C, ^{63}Cu, and ^{118}Sn in addition to deuterium, intend to study CT effects at fixed coherence length and extend the Q^2 range up to 5.5 (GeV/c)^2. This Q^2 extension to much higher values will lead to a significant increase in the momentum and energy transfer involved in the reaction. Therefore, it is expected to produce much smaller configurations that live longer, expand slower, and exit the medium intact; the three primary pillars for any CT studies. In addition, the measurements on several nuclei with different sizes will allow studying the space-time properties of the SSC during its evolution to a full size hadron. With a total beam time of 120 calendar days, the experiment is expected to make quantitative studies of a fundamental property of QCD, dubbed as color transparency.

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