



# Review Chasing QCD Signatures in Nuclei Using Color Coherence Phenomena

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Abstract: Over the last few decades, several experiments have used atomic nuclei as unique laboratories to probe the internal structure of the strongly interacting particles, namely hadrons. Indeed, the nucleus could be used as a revealing medium of the time evolution of elementary configurations of the hadron wave function. One of the ordinary approaches used to probe this picture involves searching for the onset of various phenomena which are naturally predicted by Quantum Chromo-Dynamics (QCD), the theory of strong interactions. One such phenomenon is the color transparency (CT), which refers to the production and propagation of a small size hadron-like configuration that, under specific conditions, stays intact in a transparent nuclear medium. In this paper, I will briefly review the status of the experimental search for CT effects and highlight the upcoming Jefferson Laboratory (JLab) 12 GeV experiment that will study CT at higher momentum transfer using the CLAS12 spectrometer.

Keywords: QCD in nuclei; color coherence; small size configurations; nuclear transparency

# 1. Introduction

According to Quantum Chromo-Dynamics (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 significantly reduced attenuation [1]. This intrinsic QCD phenomenon, dubbed color transparency, is essential for mapping the transition from hadronic to partonic degrees of freedom of strongly interacting matter. The color transparency (CT) phenomenon 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 (SSC) (or point-like configurations (PLC) as both terms are used interchangeably in literature [2]) with a transverse size,  $r_{\perp}$ , inversely proportional to the momentum transfer, Q [3,4].

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 [5]. 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 thus travels in the nuclear medium intact [2,6].

The experimental observable commonly used in the search for CT effects is the nuclear transparency,  $T_A$ , defined as the ratio of the cross-section per nucleon on a bound nucleon in the nucleus to that on a free nucleon. The signature of CT is the monotonic rise in  $T_A$  with the energy or four-momentum transfer squared,  $Q^2$ , involved in the process.



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**Copyright:** © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). In recent 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 Ref. [2] 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 [7]. 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 nonperturbative components of the process. In this case, the production amplitude is dominated by the contribution of small size  $q\bar{q}$  configurations induced by longitudinally polarized virtual photon. As viewed in the  $\gamma^*N$  (*N* denotes the nucleon) center of mass frame, 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 [8]. 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 [8–10]. Recently, CT was proposed [11] 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 Laboratory (BNL) [12].

#### 2. Previous Measurements

#### 2.1. Proton Knockout Experiments

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 [13–16]. 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  $p_p = 9.5 \text{ GeV/c}$ , which is consistent with a selection of a point-like configuration; here *c* denotes the speed of light. However, it was surprisingly followed by a drop at higher momenta. This energy dependence behavior has been explained to be driven by an interference between the short and long distance amplitudes in the free pp crosssection, where the nuclear medium acts as a filter for the long distance amplitudes [17,18], or a crossing of a threshold for an open charm resonance or any other exotic QCD multi-quark states [19].

Due to the relative simplicity of the elementary electron-proton interaction mechanism compared to proton–proton reactions, the quasi-free A(e, e'p) reaction was used in a series of experiments conducted at MIT-Bates [20] (where MIT stands for Massachusetts Institute of Technology), SLAC (Stanford Linear Accelerator) [21,22], and JLab (Jefferson Laboratory) [23,24] to look for the CT effects and its onset. Despite the wide coverage of  $Q^2$  up to 8.1 (GeV/c)<sup>2</sup>, the extracted nuclear transparencies were all energy-independent above  $Q^2 = 2$  (GeV/c)<sup>2</sup>, which is consistent with the conventional Glauber-type model of Pandharipande and Pieper [25].

The most recent A(e, e'p) experiment was carried out as one of the JLab Hall-C commissioning experiments in 2018. Data were collected over a wider  $Q^2$  range of 8–14.2 (GeV/c)<sup>2</sup>, which corresponds to a proton momentum up to 8.5 GeV/c. As depicted in Figure 1, the extracted results exclude any sizable CT effects [26], 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, and stimulates more efforts to resolve this proton-CT controversy.



**Figure 1.** The JLab Hall-C  ${}^{12}C(e, e'p)$  transparency results along with all previous experiments [20–24]. The momentum transfer squared, as well as the momentum of the knocked out proton are shown, respectively, in the bottom and top scale of the x-axis. The solid magenta line is for a constant value of 0.56. The dashed lines are theory predictions, including CT [27] for two different set of parameters and the solid blue line is a prediction from a relativistic Glauber calculation with CT [28]. The error bars show the statistical uncertainty while the band shows the 4% systematic uncertainty [26]. See text for details.

#### 2.2. Meson Production Experiments

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 Laboratory (Fermilab) 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) [9]. 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.

### 2.2.1. Pion Production at JLab

The next pion production experiment to look for CT was performed at intermediate energy in Hall-A at JLab [30]. The experiment studied the  $\gamma n \rightarrow \pi^- p$  process at  $\theta_{CM}^{\pi} = 70^{\circ}$ and 90°. The nuclear transparency was calculated as the ratio of the pion photoproduction cross-section from <sup>4</sup>He to <sup>2</sup>H. The results showed a deviation from the traditional nuclear calculations at higher energies [31]. However, due to a poor statistical precision, it was concluded that further measurements are needed to confirm this observation. The latter will be, indeed, satisfied with the recently completed JLab Hall-D experiment that was carried out to search for CT and to measure photon structure in photonuclear processes using a 8.5 GeV tagged coherent photon beam [32].

The most recent experiment to look for pion–CT was conducted in Hall-C at JLab [33]. The experiment measured the electroproduction of  $\pi^+$  from several nuclear targets over a wide  $Q^2$  range from 1.1 to 4.7 (GeV/c)<sup>2</sup>. The results of *A* and  $Q^2$  dependence in nuclear transparency showed a positive slope, which is qualitatively consistent with theoretical predictions, including CT effects [28,34]. Furthermore, a well established positively charged pion–CT signal is expected with an extended Hall-C measurements to higher  $Q^2$  values up to 10 (GeV/c)<sup>2</sup> [35], where CT is manifested to be stronger as reported by the Fermilab E791 experiment.

Exclusive diffractive  $\rho^0$  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 [36] of small transverse size proportional to 1/Q [10]. 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  $\rho^0$  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.

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  $\nu$  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  $\rho^0$  mass in the case of exclusive diffractive  $\rho^0$  production (for reviews and references see, e.g., [36,37]). In this case, the variation of  $l_c$  from long to short compared to the free mean path of a  $\rho^0$  meson in the medium could lead to a rise of  $T_A$  with  $Q^2$ , hence mimic the CT signal [38]. 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, as depicted in Figure 2 right. 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  $\sim 1$  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). This formation time  $\tau_f = 2\nu/(M_{\rho'}^2 - M_{\rho}^2)$ , where  $M_{\rho'}$  being the  $\rho$  meson first orbital excitation mass and  $M_{\rho}$ is its ground state mass, should be larger than the nuclear radius to suppress final state interactions [3,4,37,39].



**Figure 2.** The nuclear transparency as a function of the coherence length  $l_c$ , illustrating the CL effect, observed by the HERMES Collaboration (**right**) and the CLAS experiment result (**left**), where the carbon data have been scaled by a factor of 0.77 to match the iron data scale [40]. The dashed curve in the right diagram is a model calculation by Hufner et al. [41] while the arrows indicate the  $l_c$  range covered by the CLAS6 measurement compared to HERMES. See text for details.

The first experiment to investigate CT using a diffractive  $\rho^0$  leptoproduction off nuclei was carried out at Fermilab by the E665 Collaboration [42] 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 effects. The latter was followed by measurements of the HERMES Collaboration at DESY (Deutsches Elektronen-Synchrotron), in which the CT effects were investigated in the exclusive coherent and incoherent  $\rho^0$  production off <sup>2</sup>H and <sup>14</sup>N targets using a 27.5 GeV positron beam [43]. In this case, to avoid mixing CL with CT, the  $Q^2$  dependence on  $T_A$  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  $\rho^0$  leptoproduction. In addition to the limited statistical significance of the extracted result, the common  $Q^2$ -dependence slope was treated as a positive CT signal, which was found in good agreement with the existing theoretical model of Kopeliovich, et al. [39]. This model is based on a light-cone Green's function formalism to describe the propagation of the  $q\bar{q}$  pair in the nuclear medium, thereby incorporating the effects of coherence length, CT, and  $\rho^0$  decay, as well as absorption.

The 5 GeV  $\rho^0$ –CT experiment was carried out to study exclusive, diffractive, and incoherent  $\rho^0$  electroproduction off <sup>12</sup>C and <sup>56</sup>Fe nuclei [40] using the CLAS6 spectrometer [44], which was decommissioned post the JLab 6 GeV era. As expected, the nuclear transparency ratio was found independent of the coherence length,  $l_c$ , as shown in Figure 2 left, due to its small values compared to the C and Fe nuclear radii of 2.7 and 4.6 fm, respectively. Thus, the coherence length effect can not mimic the color transparency signal in our kinematics.

As depicted in Figure 3, a statistically significant increase in the transparency as a function of  $Q^2$  is observed for both energies and nuclear targets. The 4 and 5 GeV iron results are consistent even though the two datasets have different  $\nu$  average of 2.7 GeV and 3.2 GeV, respectively [40,45]. The CT results were not corrected for the effect of the  $\rho^0$ decay inside the nucleus and subsequent pion absorption. This task is left to the theoretical models that are compared to our data, and based on which this correction is relatively small and could not account for the observed rise of the transparency with  $Q^2$  [46–48]. 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 monotonic rise in the nuclear transparency with  $Q^2$  corresponds to a  $(11 \pm 2.3)\%$  and  $(12.5 \pm 4.1)\%$  decrease in the absorption of the  $\rho^0$  in 5 GeV Fe and C, respectively, and only (3.5  $\pm$  1.5)% for 4 GeV Fe data. The  $Q^2$  dependence was fitted by a linear form  $T_A = a Q^2 + b$ . The extracted slopes "a" of 5 GeV carbon, as well as 4 and 5 GeV iron data are compared to different model predictions in Table 1. The measured slope for carbon corresponds to a drop in the absorption of the  $\rho^0$  from 37% at  $Q^2 = 1$  (GeV/c)<sup>2</sup> to 32% at  $Q^2 = 2.2$  (GeV/c)<sup>2</sup>, in reasonable agreement with the calculations.



**Figure 3.** The extracted nuclear transparency for 4 GeV (**left**) and 5 GeV (**right**) iron and carbon data as a function of  $Q^2$  along with the theoretical curves of Frankfurt–Miller–Strikman (FMS) [46] (green), Gallmeiter–Kaskulov–Mosel (GKM) [47] (red), and Cosyn–Ryckebusch (CR) [48] (magenta) models with (dashed and dashed-dotted curves and hatched band, respectively) and without (dotted and dashed-dotted curves and open-square band, respectively) CT. All models include the effect of the  $\rho^0$  decay inside the nucleus. The upper and lower limits of the CR bands are evaluated by varying the decaying pions angles ( $\pi$ – $\rho$  angles) in the center of mass frame.

The 4 and 5 GeV CT results are consistent with both Gallmeister-Kaskulov-Mosel (GKM) [47] and Kopeliovich–Nemchik–Schmidt (KNS) [49] predictions, but a bit larger than the Frankfurt-Miller-Strikman (FMS) [46] (the FMS curves for carbon data were re-evaluated after fixing a bug in the FMS model [2], thus they are different than those already published on [40,46]) and Cosyn–Ryckebusch (CR) [48] calculations. The FMS model is based on semi-classical Glauber formalism and implements the CT effects, final state interactions (FSI) and  $\rho^0$  decay in terms of an effective interaction. The effective interaction is introduced based on the quantum diffusion model [50], which depends on the propagation length of the expanding SSC object. The GKM calculations are based on the Boltzmann–Uehling–Uhlenbeck (BUU) transport formalism to describe FSI and the propagation of all produced prehadrons and hadrons through the nuclear medium. In this case, the SSC expansion time is determined by the quantum diffusion model [50], and the CT effects are included for  $\rho^0$  produced only in deep inelastic scattering. Finally, the CR model is developed based on the relativistic multiple-scattering Glauber approximation integrated over the kinematic range of the experiment and the plane-wave approximation to compute the nuclear transparency. In this model, the propagated wave function is a convolution of a relativistic plane-wave and a Glauber-type eikonal phase that parametrizes the FSI effects. CT effects are implemented using an effective interaction cross-section based on the quantum diffusion model similarly to the FMS model. Despite of the difference in the formalism used in each model to describe the diffractive incoherent  $\rho^0$  electroproduction and the formation and propagation of the SSC in the nuclear medium, all models have yielded an approximately linear  $Q^2$  dependence, as shown in Figure 3. This  $Q^2$  behavior is a clear evidence of the onset of CT and, thus, confirms the creation, slow expansion and reduced interaction of the produced  $\rho^0$  small size configuration with the nuclear medium.

**Table 1.** Fitted slopes of the  $Q^2$ -dependence of the nuclear transparency for 4 and 5 GeV datasets, as well as nuclei. The results are compared with theoretical predictions of CR [48], FMS [46], GKM [47], and KNS [49]. The two fit values of the CR model are extracted using the upper and lower curves of the hatched bands, shown in Figure 3.

5 GEV DATASET RESULTS					
Nuclei	Measured Slopes ( GeV/c) <sup>-2</sup>	Model Predictions			
		CR	FMS	GKM	KNS
С	$0.044 \pm 0.015_{stat} \pm 0.019_{syst}$	0.026 <sub>Upper</sub> Limit 0.027 <sub>Lower</sub> Limit	0.029	0.06	0.06
Fe	$0.053 \pm 0.008_{stat} \pm 0.013_{syst}$	0.02 <sub>Upper Limit</sub> 0.021 <sub>Lower Limit</sub>	0.032	0.047	0.047
4 GEV DATASET RESULTS					
Fe	$0.037 \pm 0.015_{stat} \pm 0.027_{syst}$	0.027 <sub>Upper</sub> Limit 0.029 <sub>Lower</sub> Limit	0.033	-	-

# 3. Forthcoming CLAS12 CT Experiment

The JLab CLAS12 experiment, E12-06-106 (RG–D, run-group D) [51], aims to study CT in the exclusive diffractive  $\rho^0$  electroproduction off nuclei, <sup>12</sup>C, <sup>63</sup>Cu, which substituted <sup>56</sup>Fe that was utilized in the former CLAS6 CT study [40] given it is a ferromagnetic material and cannot be employed with the CLAS12 5T solenoid field surrounding the target area [52], and <sup>118</sup>Sn, using the CLAS12 spectrometer and the Hall-B flag assembly, see Figure 4. 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  $\rho^0$  over the formation time  $\tau_f$ . The  $\rho^0$  are identified via its decay products,  $\pi^+$  and  $\pi^-$ , that are detected in coincidence with the scattered electron by the CLAS12 spectrometer.



**Figure 4. 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 beamline simultaneously with an empty liquid deuterium (LD2) target cell. **Right**: a sliced GEMC (GEant-4 Monte-Carlo [53]) view of the Hall-B flag assembly along with the LD2 cell. The beam is anticipated to travel from left to right.

The RG-D experiment is scheduled to take place in summer 2023 using an 11 GeV electron beam energy and the three mentioned nuclear targets carbon, copper, and tin in addition to deuterium. In this measurement, CT effects will be studied at fixed coherence length and relatively large  $Q^2$  up to 5.5 (GeV/c)<sup>2</sup>. Figure 5 shows the projected statistical uncertainties for the three nuclei (open squares) along with predictions from the FMS model which are tailored to our kinematics and incorporate the effects of color transparency and  $\rho^0$  decay in the medium.



**Figure 5.** The CLAS12 projections (open squares) for  ${}^{12}$ C (**right**),  ${}^{63}$ Cu (**middle**), and  ${}^{118}$ Sn (**left**) for the lowest  $l_c$  bin plotted randomly on the FMS NO CT curve (dashed-dotted line) as their magnitude will be measured in this study. It also includes the 5 GeV  ${}^{12}$ C and  ${}^{56}$ Fe CT results (solid squares) [40] along with the FMS [46] model, which successfully described our 5 GeV CT results, and its 11 GeV predictions are tailored to our kinematics.

The simulation of the presented 11 GeV projections was performed using the event generator that was exclusively developed for our CT study [40], the newly-designed Hall-B flag assembly, and the CLAS12 GEMC [53] and reconstruction package. The CT event generator includes the measured production cross-sections by Cassel et al. [54] of  $\rho^0$  and three main background processes:  $\Delta^{++}$ ,  $\Delta^0$ , and the phase space describing the non-resonant ( $\pi^+$ ,  $\pi^-$ ) pairs. It was validated in the CLAS6 5 GeV CT analysis and the mentioned three background processes gave a good description of the background underneath the  $\rho^0$  peak, as illustrated in Figure 6. Thus, the combination of generated integrated cross-section and flux, the nominal CLAS12 per-nucleon luminosity of  $10^{35}$  cm<sup>-2</sup> s<sup>-1</sup>, and the approved beam time for each target nucleus yields the  $Q^2$ -binned projected statistical precision depicted in Figure 5.



**Figure 6.** The three-dimensional illustration of  $(\pi^+, \pi^-)$  invariant mass extracted from our 5 GeV CT data [40] showing the total contribution of the three background processes,  $\Delta^{++}$ ,  $\Delta^0$  and the phase space, as a shaded area in the bottom. The peak positions and widths of the  $\rho^0$  meson agree with the Particle Data Group values for all targets. The solid lines are obtained from our event generator simulations.

## 4. Conclusions

Color Transparency is a distinctive property of QCD. It offers a unique probe of "color", a key feature of QCD, that is completely invisible in the ordinary structure of nuclei. CT is well established at very high energies, where the small size configuration is highly relativistic, thus its size remains small while traversing the nuclear medium. At low to intermediate energies, the scenario is quite challenging given the SSC starts expanding before exiting the nucleus. Still, studying CT at this energy level is crucial to improve our understanding about the SSC formation and expansion dynamics, as well as its interactions with the surrounding color field in terms of its underlying structure. Additionally, the onset of CT is an important condition to validate the QCD factorization theorem and determine the onset of its regime, which is critical for accessing Generalized Parton Distributions, particularly, in deep exclusive meson production.

Tremendous efforts have been dedicated to search for CT effects on a broad energy range, yet no clear CT onset in the baryon sector. However, measurements in the meson sector have been successful in probing CT effects and their onset. The strongest evidence of the CT onset at intermediate energies was reported by both 6 GeV JLab Hall-C  $\pi^+$  [33] and Hall-B  $\rho^0$  [40] experiments. The early CT onset seen on  $\rho^0$  results ( $Q^2 \sim 1 \text{ (GeV/c)}^2$ ) compared to  $\pi^+$  ( $Q^2 \sim 3 \text{ (GeV/c)}^2$ ) proves that the diffractive meson production is the optimal mechanism to verify CT and study the features of such exotic configurations.

In the JLab 12 GeV era, the CLAS12 CT studies via exclusive, diffractive, and incoherent  $\rho^0$  electroproduction off nuclei will allow a quantitative understanding of the SSC formation time and its interaction with the nuclear medium. These measurements intend to extend the  $Q^2$  range to much higher values allowing 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 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 the fully dressed hadron wave function with its gluonic field.

Due to the controversy in the proton knockout CT results, experimentalists and theorists in the community should work closely to resolve the proton-CT controversy and, thus, continue improving our understanding of the CT phenomenon in both meson and baryon sectors. The foreseeable goal is, besides the JLab 12 GeV experiments, in which CT will be additionally explored in new sectors such as the backward-angle kinematics [55,56], the planned high-energy measurements at J-PARC (the Japanese Pro-

ton Accelerator Research Complex) and FAIR (the German Facility for Antiproton and Ion Research) [57–63] or Deep Inelastic Scattering in e–A (electron–nucleus), p–A (proton–nucleus) or A–A (ion–ion) collisions at the Large Hadron Collider, Relativistic Heavy Ion Collider, and the future Electron-Ion Collider would shed more light on CT effects for various production channels, including strange and heavy charmonium states such as  $\phi$  and  $J/\psi$ , and help resolve such a proton–CT controversy.

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