Prospects of Color Transparency Measurements with NICA SPD

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Color Transparency

Color transparency refers to the situation when hadrons propagate through nuclear medium with less interaction than was expected. This phenomenon occurs in processes with high momentum transfers and is attributed to the fact that hadrons form so-called point-like configurations (PLCs) that are color-neutral ($q\bar{q}$ or qqq) and interact with the nuclear medium with the reduced cross section. Therefore, color transparency is really about how a medium can be transparent to objects without color [1, 2].

For the **$q\bar{q}$ configuration**, clear indications of the enhanced nuclear transparency were observed in experiments of meson electroproduction at JLab:

- Ref. [3] for π^+-production off ^{2}H, ^{12}C, ^{27}Al, ^{63}Cu, and ^{197}Au at 1.1 GeV^2 < Q^2 < 4.7 GeV^2.
- Ref. [4] for ρ^0-production off ^{12}C and ^{56}Fe at 1.0 GeV^2 < Q^2 < 2.2 GeV^2.

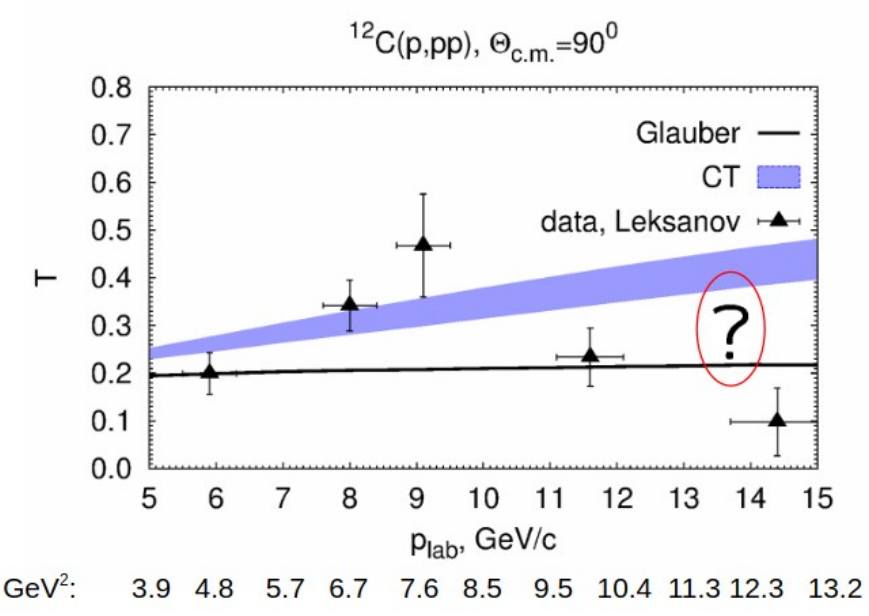
For the **qqq configuration**, CT effects have also been searched at JLab but no evidence of color transparency were revealed.

- Ref. [5, 6] for hard p knock-out off ^{2}H, ^{12}C, ^{63}Cu for Q^2 up to 14 GeV^2.

[1] H. Szumila-Vance, et al., Int. J. Mod. Phys. A, vol. 41, no. 09, p. 2630004, 2026.
[2] D. Dutta et al., Prog. Part. Nucl. Phys., vol. 69, pp. 1–27, 2013.
[3] B. Clasie et al., Phys.Rev. Lett., vol. 99, p. 242502, 2007.
[4] L. El Fassi, AIP Conf. Proc., vol. 1560, pp. 475–479, 2013.
[5] K. Garrow et al., Phys. Rev. C, vol. 66, p. 044613, 2002.
[6] D. Bhetuwal et al., Phys. Rev. Lett., vol. 126, no. 8, p. 082301, 2021.

Color Transparency

Meanwhile, some indications of color transparency were observer for the **qqq configuration** in the (p, 2p) quasi-elastic scattering off carbon with the EVA detector at the Brookhaven AGS at near 90° pp center of mass [7]. As follows from Ref. [7], for such a process, one can expect color transparency effects to become discernible starting from $Q^2 \gtrsim 5$ GeV^2 .



Nuclear transparency (T) is the cross section of a particular process off a nucleus (σ_{exp}) divided over the cross section of the same process calculated in the impulse approximation (IA).

$$T = \frac{\sigma_{\mathrm{exp}}}{\sigma_{\mathrm{IA}}}.$$

In summary, evidence for color transparency for protons has been less conclusive compared to mesons. Therefore, more measurements for the p knock-out process are needed, to better understand CT effects for the qqq configuration.

[7] A. Leksanov et al., Phys. Rev. Lett., vol. 87, p. 212301, Nov 2001.

Hard Proton Knock-out off a Deuteron

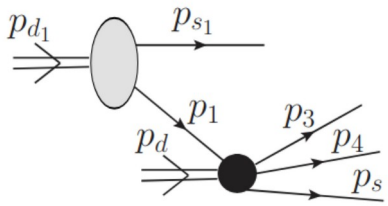
We propose to use d–d interactions to study the process of p knock-out from a deuteron in hard p–d collisions, assuming the neutron in one of the deuterons to be a spectator to the suggested process.



Figure 3.1: Impulse approximation (IA) diagram for the process $pd \to ppn$ (left) and Feynman diagram for the process $dd \to ppnn$ (right). For both diagrams, the following notations are used for the particles' four-momenta: p_d and p_{d_1} correspond to deuterons in the initial state, p_1 – incoming/initial proton, p_2 – intermediate/reaction proton (not shown in the right diagram), p_s and p_{s_1} – spectator neutrons, and p_3 and p_4 – final protons.

Kinematic Variables

The variables are defined in the rest frame of the deuteron *d*.

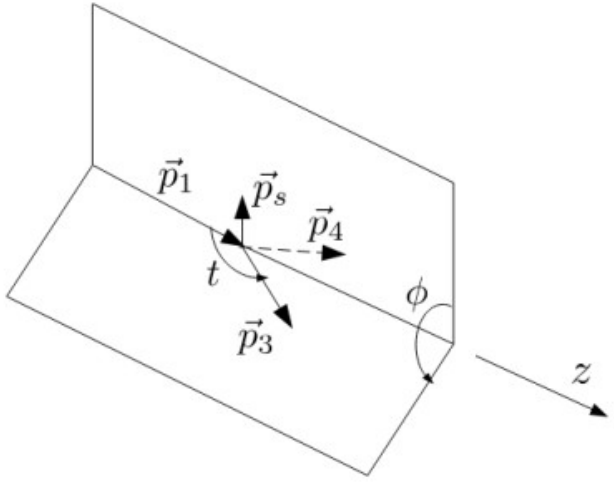


$\alpha_s = \dfrac{2(E_s - p_s^z)}{m_d}$ - the light cone variable ($\alpha_s/2$ = momentum fraction of the deuteron carried by the spectator neutron in the infinite momentum frame where the deuteron moves fast backward)

p_{st} - the transverse momentum of the spectator neutron

$\phi = \phi_3 - \phi_s$ - the relative azimuthal angle between the scattered proton and spectator neutron

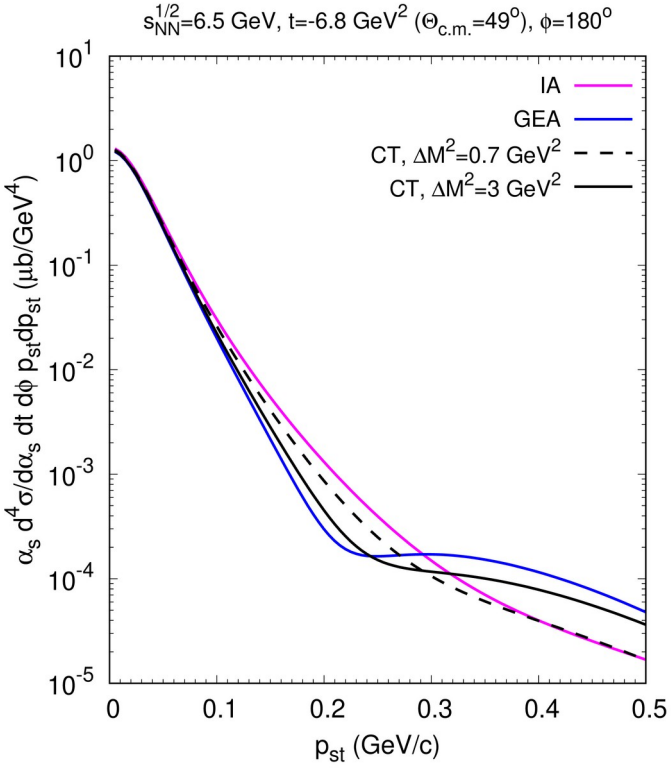
$t = (p_1 - p_3)^2 \equiv t_{\text{hard}}$ - Mandelstam variable



The cross section is written as $\dfrac{\alpha_s}{p_{st}} \dfrac{d^4\sigma}{dp_{st} d\alpha_s dt d\phi}$.

Theoretical Calculations

The theoretical cross section approximation is obtained in the framework of the generalized eikonal approach (GEA) supplemented by the quantum diffusion model (QDM) of color transparency(CT) [8–10]. The model is adjusted to experimental data from Ref.[11] and therefore is expected to provide realistic and reliable cross section predictions.



IA – Impulse approximation, full CT.
GEA – Generalized Eikonal Approach, no CT.
CT07 – GEA+QDM, large CT.
CT3 – GEA+QDM, small CT.

ΔM^2 is the free parameter of the QDM that reflects the degree of ISI and FSI suppression due to CT.

[8] L. L. Frankfurt et al.,Phys. Rev. C, vol. 56, pp. 2752–2766, 1997.
[9] A. B. Larionov, Phys. Rev. C, vol. 107, p. 014605, Jan 2023.
[10] A. B. Larionov, Phys. Part. Nucl., vol. 56, no. 2, pp. 381–386, 2025.
[11] G. Cocconi et al., Phys. Rev., vol. 138, pp. B165–B172, 1965.

Proposed Kinematics for CT Measurements

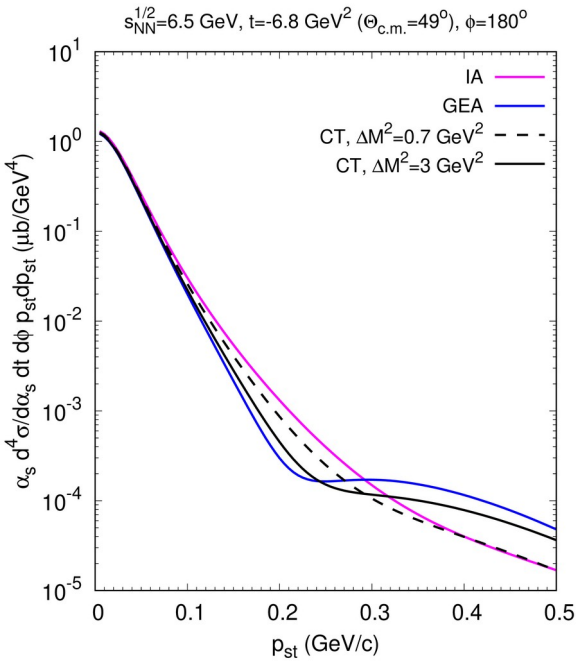
$\sqrt{s}$ – the largest possible.

$\alpha_s = 1$ – transverse kinematics which minimizes relativistic corrections to the deuteron w. f. and maximizes ISI/FSI.

$\theta_{c.m.}$ – as close to 90° as possible (the hard process in transverse kinematics) to maximize CT effects.

Since the cross section drops quickly with *t*, measurements are proposed to be performed at $\theta_{c.m.} < 90^o$, which will lead to smaller CT effects but will allow for much higher event rate.

The CT contribution is maximal at $\theta_{c.m.} = 90^o$ but CT effects are still discernible for much smaller $\theta_{c.m.}$. Going below $Q^2 \sim$ 4-5 GeV^2 is not recommended as no observable CT effects are expected there.



What to measure:

- Measure the p_{st} dependence of the cross section with the smallest possible binning in p_{st}, with α_s close to unity and the largest possible $\theta_{c.m.}$ that delivers reasonable statistics.
- If statistics permits, measure the azimuthal dependence, too.

Estimations of the Event Rate

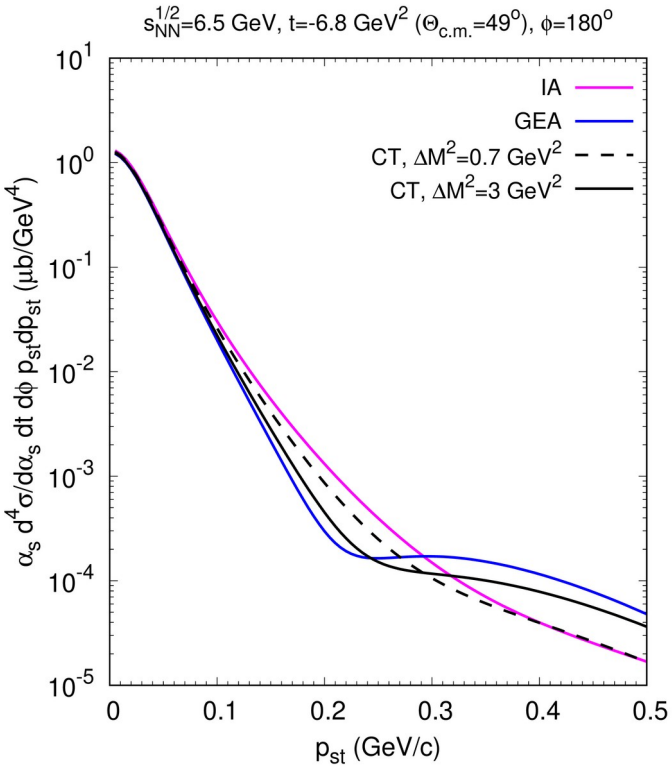
Theoretical predictions for the cross section values at four different points in p_{st}, $\sqrt{s} = 13$ GeV, $\alpha_s = 1$, $t = -6.8$ GeV^2 (which corresponds to $\theta_{c.m.} = 49^o$), and $\phi = \pi$.

Model	Cross section value, μb/GeV^4			
	$p_{st} = 0.1$ GeV/c	$p_{st} = 0.2$ GeV/c	$p_{st} = 0.3$ GeV/c	$p_{st} = 0.4$ GeV/c
GEA	$20.0 \cdot 10^{-3}$	$0.30 \cdot 10^{-3}$	$0.17 \cdot 10^{-3}$	$0.12 \cdot 10^{-3}$
CT3	$22.3 \cdot 10^{-3}$	$0.45 \cdot 10^{-3}$	$0.12 \cdot 10^{-3}$	$0.079 \cdot 10^{-3}$

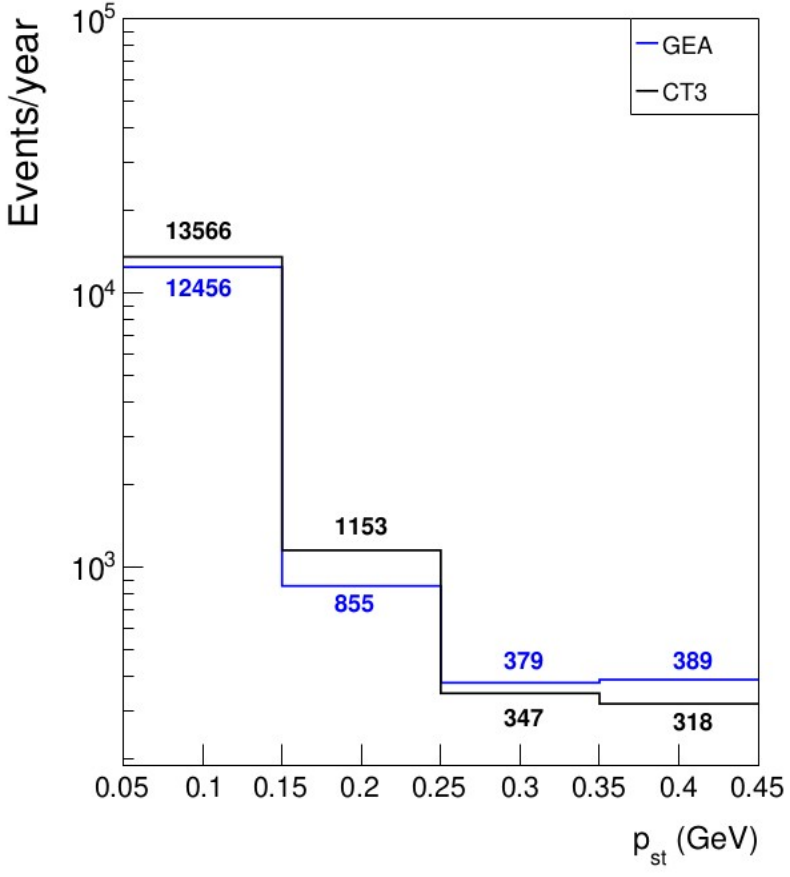
In general, for a small kinematic bin $\Delta^4\tau = \Delta\alpha_s \Delta t \Delta\phi \Delta p_{st}$, the following expression can be used to estimate the number of events in this bin based on the value of the differential cross section in the center of the bin.

$$\Delta N(\Delta^4\tau) = \mathcal{L} \cdot \frac{\mathrm{d}^4\sigma}{p_{\mathrm{st}}\mathrm{d}p_{\mathrm{st}}\mathrm{d}\alpha_s\mathrm{d}t\mathrm{d}\phi} \cdot p_{st} \cdot \Delta\alpha_s \cdot \Delta t \cdot \Delta\phi \cdot \Delta p_{st} \cdot T.$$

Here $\mathcal{L}$ is the luminosity of the experiment, $\Delta\alpha_s$, Δt, $\Delta\phi$, and Δp_{st} are the bin widths in all four kinematic variables, and T is the duration of the experiment.



Estimations of the Event Rate (MC-Based)



The estimation was performed based on the Monte Carlo simulation for $\sqrt{s} = 13$ GeV, $\alpha_s = 1$ and $t = -6.8$ GeV^2 (which corresponds to $\theta_{c.m.} = 49^o$), using the following bin widths for the kinematic variables, $\Delta\alpha_s = 0.25$, $\Delta t = 2.5$ GeV^2, $\Delta\phi = 2\pi$, and $\Delta p_{st} = 0.1$ GeV/c, experiment duration $T = 10^7$ s (1 year), and the luminosity value $\mathcal{L} = 10^{30}\text{cm}^{-2}\text{s}^{-1}$.

Numbers highlighted in red correspond to the $p_{st} = 0.2$ GeV/c, where the largest relative difference between the two model curves is expected.

Model	Number of events per year			
	$p_{st} = 0.1$ GeV/c	$p_{st} = 0.2$ GeV/c	$p_{st} = 0.3$ GeV/c	$p_{st} = 0.4$ GeV/c
GEA	12456	**855**	379	389
CT3	13566	**1153**	347	318

Both histograms were scaled with the global factor of 0.751576 that corresponds to the integral of the wave function of the deuteron d_1 within the cuts imposed on the d_1 momentum to ensure that the neutron p_{s1} goes in the forward direction.

Estimations of the Event Rate (MC-Based)

To make a decisive conclusion regarding CT contributions, the collected experimental statistics should be sufficient for distinguishing between σ_{GEA} and σ_{CT3} on a stage of theoretical analysis.

$f = \frac{N_{CT3} - N_{GEA}}{N_{GEA}} = \frac{\Delta N_\sigma}{N_{GEA}}$ – the relative difference between σ_{GEA} and σ_{CT3}.

ε – the accuracy with which the absolute difference between σ_{GEA} and σ_{CT3} can be measured.

$$\sqrt{N_\varepsilon} = \varepsilon \cdot \Delta N_\sigma$$
$$\sqrt{N_\varepsilon} = \varepsilon \cdot f \cdot N_\varepsilon$$
$$1 = \varepsilon \cdot f \cdot \sqrt{N_\varepsilon}$$
$$N_\varepsilon = \frac{1}{\varepsilon^2 \cdot f^2}$$

at p_{st} = 0.2 GeV/c

For ε = 15%, N_ε = 363

For ε = 20%, N_ε = 204

At p_{st} = 0.2 GeV/c the largest relative difference between σ_{GEA} and σ_{CT3} is expected.

Summary on the Event Rate Estimations

The performed calculations correspond to a general and conservative estimation of the event rates for the proposed experiment, which was intended to prove the overall feasibility of the proposed color transparency measurements at the energy and luminosity values that are expected to be available at the NICA collider.

Based on actual experimental conditions, different variations to the suggested kinematics and/or binning should be introduced. In particular, if statistics permits, one should consider

- more detailed binning in p_{st},
- measuring the cross section azimuthal dependence, and possibly,
- measurements at higher $\theta_{c.m.}$.

In case of very limited statistics, measurements should be attempted at smaller $\theta_{c.m.}$, where contributions from "hard" amplitudes (and thus the CT effects themselves) are smaller but the total cross section is higher as the model is still capable of making informative conclusions on CT contributions for smaller $\theta_{c.m.}$ (going below $Q^2 \sim$ 4-5 GeV^2 is not recommended, though).

Model	Number of events per year			
	$p_{st} = 0.1$ GeV/c	$p_{st} = 0.2$ GeV/c	$p_{st} = 0.3$ GeV/c	$p_{st} = 0.4$ GeV/c
GEA	12456	**855**	379	389
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Next Steps

- Investigate the influence of the detector acceptance/efficiency on the experimental event yield.
- More detailed study of polarization observables (A_{zz}, A_{xx}, A_{yy}).

Thank you!