Nuclear TMDs in CLAS12

W. Armstrong, S. Joosten, Z.-E. Meziani*, C. Peng, J. Kim, and J. Xie

Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

H. Szumila-Vance*, and S. Stepanyan

Jefferson Lab, Newport News, VA 23606, USA

M. Caudron, L. Causse, P. Chatagnon, R. Dupré*†, M. Ehrhart, A. Hobart, D. Marchand, C. Muñoz Camacho, S. Niccolai, H.-S. Ko, K. Price, V. Sergeyeva, E. Voutier, S. Zhao

Université Paris-Saclay, CNRS, IJCLab, 91405 Orsay, France

T. Chetry, and L. El Fassi

Mississippi State University, Mississippi State, Mississippi 39762, USA

A. El Alaoui, and T. Mineeva

Universidad Técnica Federico Santa María, Valparaíso, Chile

M. Hattawy

Old Dominion University, Norfolk, VA 23529, USA

a CLAS Collaboration Proposal

*Co-spokesperson

†Contact Person: `dupre@ipno.in2p3.fr`

Abstract

Transverse momentum dependent PDFs (TMDs) describe three-dimensional densities of nuclei constituents in momentum space and provide a unique insight to study nuclear effects (including the EMC Effect) in a completely novel way. TMDs complement the study of nuclear GPDs, a major experimental effort of the 12 GeV JLab program. Recent results from CLAS on GPDs extended the longitudinal momentum information of partons in a nucleus to a full 3D (2D+1) imaging in position-space of the partons in nuclei. This information, combined with the parton dynamics information contained in TMDs, provides a comprehensive modern description of the nucleus based on the basic degrees of freedom of QCD, namely quarks and gluons.

Additionally, TMDs enable us to access the transport coefficient in cold nuclear matter. Significant experimental effort has been dedicated to measuring the transport coefficient in hot dense mediums through jet quenching, but universal extraction of the transport coefficient in cold nuclear matter remains to be understood [1]. Measurement of the transport coefficient in cold nuclear matter is a check on the universality of the nuclear medium property and provides a critical test of the generalized factorization formalism [2].

We propose to measure the $\cos\phi$, $\sin\phi$ and Boer-Mulders asymmetries ($\cos 2\phi$) for semi-inclusive pion production (SIDIS) with the approved Run Group D using the CLAS12 detector. This experiment will use the same beam time and trigger as Run Group D and requires only the addition of beam polarization. We will concentrate for this experiment on the carbon and tin targets to measure our observables as they are spin 0 nuclei, for which the TMD phenomenology is simpler.

The large acceptance of CLAS12 enables us to study various kinematic dependencies of SIDIS with the ultimate goal to extract the transport coefficient of the nuclear medium in an independent way. While significant ambiguity remains on the size of the transport coefficient in cold nuclear matter, this proposed measurement provides two completely independent methods to access the transport coefficient. We will also explore how the EMC effect is different or similar in transverse momentum dependent observables compared to what we know in the longitudinal momentum. In time, we can also hope for a direct experimental test of the sign change of the Boer-Mulders function in SIDIS on a nucleus vs pion-nucleus Drell-Yan as compared to the nucleon case.

Contents

Introduction

While the topic of transverse momentum dependent parton distribution functions (TMDs) is largely developed in the JLab physics program, it is exclusively centered toward the measurement of the nucleon TMDs. We propose here to extend this program to nuclear targets to explore an essential aspect of QCD studies, the effect of the nuclear medium on the dynamics and motion of quarks and gluons. There, the overlap of nucleons brings about novel behavior both in the initial and final states compared to the proton. This program is a natural extension of the more traditional hadronization studies, which mostly ignored the TMD framework in the past. However, the recent theoretical developments of the field offer new ways to understand and study the semi-inclusive deep inelastic scattering (SIDIS). With this experiment, we propose for the first time to look at the nuclei with the terms and framework of the TMDs.

For this first study, we want to look at unpolarized targets, therefore the $\cos\phi$, $\sin\phi$ and, eventually, $\cos 2\phi$ moments are our observables of choice. For the first two, theoretical studies already exist [3–6] and can guide us in the interpretation of the data. These studies should provide direct information on the impact of the nuclear medium on TMDs and how it should be treated. The quoted literature indicates how the gluon density can be accessed through nuclear TMDs and how different contributions to nucleon TMDs can be separated by scanning the p_T distribution of nuclear $\cos\phi$ and $\sin\phi$ moments. Moreover, we want to study how the EMC effect is described and altered through nuclear TMDs. We do not have quantitative predictions on this topic, but it is a natural way to access medium effects on the orbital motion and spin of partons when nucleons are embedded in a nucleus. This first high statistics measurements of the relevant data will undoubtedly provide surprises and trigger more theoretical studies on this topic.

This proposal complements and modernizes the already approved physics program of CLAS12. In order to perform these studies, we plan to use the targets and beam time already approved for Run Group D (RG-D) with only the addition of beam polarization. In this way, we will optimize the beam time and provide some first data that will directly enrich the field of QCD studies and pave the way for more thorough nuclear TMD studies in the future.

Chapter 1

Physics Case

1.1 Generalities on TMDs

The study of nucleon structure has been moving from the historic one-dimensional picture based on parton distribution functions (PDFs) and form factors (FFs) to three-dimensional studies using generalized parton distributions (GPDs) and transverse momentum dependent PDFs (TMDs) [7]. These have also been extended to the study of nuclei, with a particular focus on GPDs [8–10]. In this proposition of experiment, we will focus on the TMD side, which offers a description in a three-dimensional momentum space of the hadrons and can be of special interest to understand the structure of nuclei in terms of quarks and gluons.

The TMDs can be studied using different processes, here we focus on the lepton scattering process of semi-inclusive deeply inelastic scattering (SIDIS). In this process, a deeply virtual photon is exchanged by the scattering lepton to the target and we detect one of the produced hadrons. The cross section of the process results into a convolution of TMD parton distributions and TMD fragmentation functions, leading to the expression of the cross section in

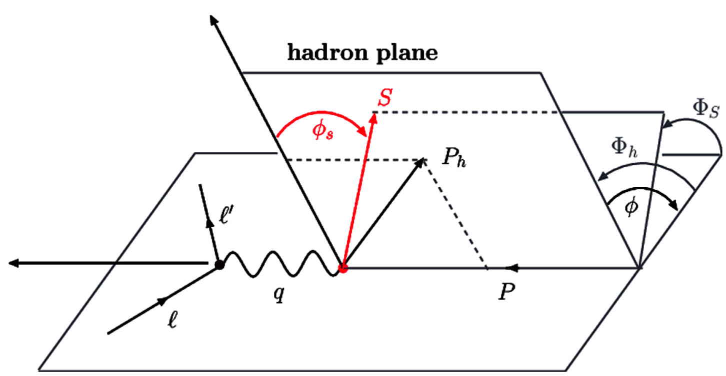

Figure 1.1: General layout of the SIDIS process, illustrating the azimuthal angles of the produced hadron (ϕ_h) and of the target's spin (ϕ_S).

this form [11]:

$$\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,d\phi\,d\phi_S\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi\,F_{UU}^{\cos\phi} \\
&\quad+\varepsilon\cos(2\phi)\,F_{UU}^{\cos 2\phi}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi\,F_{LU}^{\sin\phi} \\
&\quad+S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi\,F_{UL}^{\sin\phi}+\varepsilon\sin(2\phi)\,F_{UL}^{\sin 2\phi}\right] \\
&\quad+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi\,F_{LL}^{\cos\phi}\right] \\
&\quad+|\boldsymbol{S}_\perp|\Bigg[\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi-\phi_S)}\right) \\
&\qquad+\varepsilon\,\sin(\phi+\phi_S)\,F_{UT}^{\sin(\phi+\phi_S)}+\varepsilon\,\sin(3\phi-\phi_S)\,F_{UT}^{\sin(3\phi-\phi_S)} \\
&\qquad+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi-\phi_S)\,F_{UT}^{\sin(2\phi-\phi_S)}\Bigg] \\
&\quad+|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi-\phi_S)\,F_{LT}^{\cos(\phi-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} \\
&\qquad+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi-\phi_S)\,F_{LT}^{\cos(2\phi-\phi_S)}\Bigg]\Bigg\},
\end{aligned} \tag{1.1}$$

which highlights the different components of the semi inclusive deep inelastic scattering (SIDIS) cross section. We notice the importance of the azimuthal angles in this cross section, which are defined relative to the leptonic plane as shown in Fig. 1.1.

In the setup of run group D, with unpolarized targets, only the $\cos\phi$, $\cos 2\phi$ and $\sin\phi$ components will contribute in this formula. Thus, we propose here to measure these three observables and make the best of the existing run group D capabilities.

For the spin half nucleon, there is eight leading twist TMDs as described in Table 1.1. The f_1 and $h_1^\perp$ functions contribute through the Cahn and Boer-Mulders effects, respectively, to the cos modulations. Measuring both $\cos\phi$ and $\cos 2\phi$ is important to help disentangle them, especially when we only have a limited Q^2 coverage. In a prolongation of EMC effect studies in nuclei, the presence of a modified Boer-Mulders effect in the nucleus would be of particular interest and provide a completely new input to the problem of nucleon modifications in the nuclear medium. The $\sin\phi$ modulation does not have any contribution from leading twist and only arises at twist-3 [5]. Particularly interesting in this case is that the contribution to this observable is linked to multiple gluon scattering. The importance of quark gluon scattering in the final state effects of the lepton nucleus scattering makes this observable particularly interesting in nuclei.

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	h_{1T}^L
T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

Table 1.1: Naming convention of TMDs ordered by spin states of the target, N, and the hit quark, q (U for unpolarized, L for longitudinally polarized and T for transversely polarized).

1.2 Nuclear TMDs

The interest for nuclear TMDs lies in two different aspects, first the modification of the nucleons in the nuclear medium and second, the modification of the final state interactions. It is particularly interesting to study these within the TMD framework as different components of the cross section can be directly linked to parton level effects. This allows for an easier interpretation of the measured effects and a clearer separation of the origin of the nuclear effects associated.

In this section, we will present the calculations from the following papers on nuclear TMDs [3–6]. Their model can be summarized in a nutshell by the following equation describing the nuclear TMDs ($f_q^A(x,k_\perp)$) as a function of the nucleon ones ($f_q^N(x,k_\perp)$):

$$f_q^A(x,k_\perp) \approx \frac{A}{\pi\Delta_{2F}} \int d^2\ell_\perp e^{-(\vec{k}_\perp-\vec{\ell}_\perp)^2/\Delta_{2F}} f_q^N(x,\ell_\perp), \tag{1.2}$$

with the broadening width Δ_{2F} the total average squared transverse momentum broadening:

$$\Delta_{2F} = \int d\xi_N^- \hat{q}_F(\xi_N), \tag{1.3}$$

with $\hat{q}_F(\xi_N)$ the quark transport parameter. This contribution is directly linked with the final state interaction increase expected in a nucleus compare to a proton target. In a pure parton energy loss model, this single parameter encode fully the effect of the nuclear material on an out going quark, while the fragmentation functions are considered unchanged.

The transport parameter is widely used in the heavy ion collision community and in the hadronization community in general as the fundamental parameter governing the energy loss of partons crossing QCD matter [1,2,12,13]. It is defined as the average transverse momentum square acquired by a parton per unit of length of nuclear material crossed. Interestingly, the quark transport parameter has been directly related to the gluon density in the nucleus [14]:

$$\hat{q}_F(\xi_N) = \frac{2\pi^2\alpha_s}{N_c}\rho_N^A(\xi_N)[xf_g^N(x)]_{x=0}, \tag{1.4}$$

where $\rho_N^A(\xi_N)$ is the spatial nucleon number density inside the nucleus and $f_g^N(x)$ is the gluon distribution function in a nucleon. To this day, it is widely acknowledged that $\hat{q}$ of QCD matter grows with the temperature of the medium, but the precise determination of $\hat{q}$ in cold nuclear matter remains controversial [1].

The issue of measuring $\hat{q}$ has been carefully studied for energy loss calculations in quark-gluon plasma [15], highlighting the impact of assumptions between the existing perturbative QCD calculations. Interestingly, in the model from Liang *et al.* [3–6] the transport coefficient affects directly the TMDs and therefore the ϕ modulations we are going to detect. Thus, based on the hypothesis made in the presented calculation, $\hat{q}$ leads to a direct modification of SIDIS asymmetries generated at the parton level. This is the opportunity to have an independent probe of the transport coefficient.

The calculations [4–6] lead to predictions for specific observables. Particularly, of interest for us in this proposal are $\cos\phi$, $\sin\phi$ and p_T. In the model, the TMDs are parametrized in this form:

$$f_1^N(x,\ell_\perp) = \frac{1}{\pi\alpha}f_1^N(x)e^{-\vec{\ell}_\perp^2/\alpha}, \tag{1.5}$$

$$f^{\perp N}(x,\ell_\perp) = \frac{1}{\pi\beta}f^{\perp N}(x)e^{-\vec{\ell}_\perp^2/\beta}, \tag{1.6}$$

$$g^{\perp N}(x,\ell_\perp) = \frac{1}{\pi\gamma}g^{\perp N}(x)e^{-\vec{\ell}_\perp^2/\gamma}. \tag{1.7}$$

where the α, β and γ parameters contain the information on the width of the quark distributions in transverse momentum space. From these, the asymmetries on nuclear targets can be calculated with a limited number of parameters. Taking $\alpha = \beta$, we have

$$\frac{\langle\cos\phi\rangle_{UU}^{eA}}{\langle\cos\phi\rangle_{UU}^{eN}} \approx \frac{\alpha}{\alpha+\Delta_{2F}}, \tag{1.8}$$

and similarly for $\alpha = \gamma$, we have

$$\frac{\langle\sin\phi\rangle_{LU}^{eA}}{\langle\sin\phi\rangle_{LU}^{eN}} \approx \frac{\alpha}{\alpha+\Delta_{2F}}. \tag{1.9}$$

While these are the most simplified versions of the equations, they show directly how the transport coefficient contributes to the SIDIS asymmetries of interest. Moreover, we see that it is directly connected with the width of the quark distributions. In this simplified version, it is assumed that these quark widths are equivalent for the different nuclear TMDs. We will detail below the strategy to resolve these parameters using the different nuclear observables

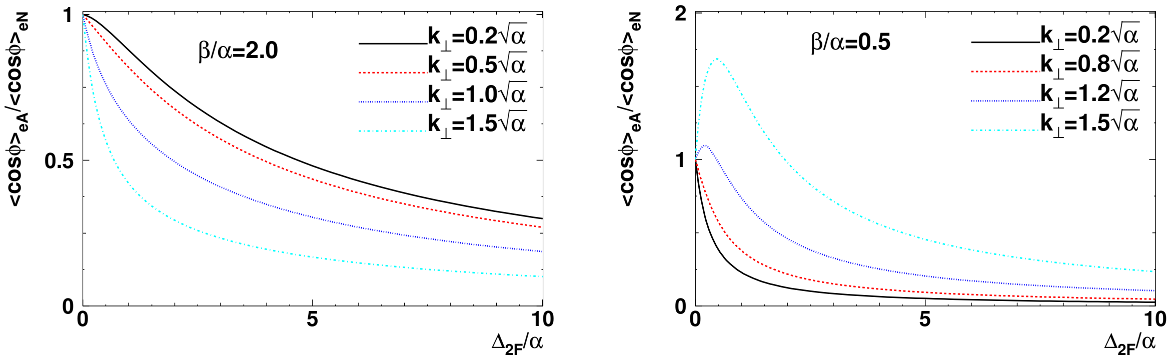

Figure 1.2: Ratio of cos asymmetries nuclei to nucleon, $\langle\cos\phi\rangle_{UU}^{eA}/\langle\cos\phi\rangle_{UU}^{eN}$, as a function of Δ_{2F}/α and for different β/α [4].

and the experimental results from proton target to be obtained by CLAS' run group A.

1.3 Opportunities with CLAS12

While TMDs can be defined for any target's spin, we will focus in this proposal on observables based on beam polarization or no polarization at all, such that the target spin does not intervene directly. Moreover, small spin (zero or one-half) will avoid the possible contributions from new functions. Therefore, we will concentrate our study on the carbon and tin targets of the run group D. We can see in Eq. 1.8 and 1.9 that if the nucleon TMD width is known, we can immediately extract the broadening width Δ_{2F} from the measurement of any of these asymmetries. Thus in this proposal, we can provide two independent accesses to the transport coefficient of the nucleus. Interestingly, if we do not know or are unsure about the values of the different TMD widths in the nucleon, the nuclear measurements as a function of p_T^2 can help determine them. We refer the reader to the original paper to obtain the full equations, which are illustrated here in Fig. 1.2 and 1.3. From these, one can see that all parameters can be uniquely determined with $k_\perp$ dependent measurements of the two asymmetry ratios presented in Eq. 1.8 and 1.9.

This method can be particularly helpful to detect a possible nuclear modification of the TMDs width compared to the free nucleon data. However, one needs to account for the nuclear fragmentation function to decipher between these two parameters. The resolution of this problem is significantly simplified by the use of several nuclear targets of different sizes. Between the nuclear targets the density varies little while the nuclear material is largely augmented, *i.e.* we expect a large difference of Δ_{2F} and a small difference on α.

The second tool at our disposal for the extraction of the Δ_{2F} and the quark distribution width parameters is the access to several observables. The measurement of the p_T^2 dependence should first give a strong indication about the relative sizes of α, β and γ. Moreover, the

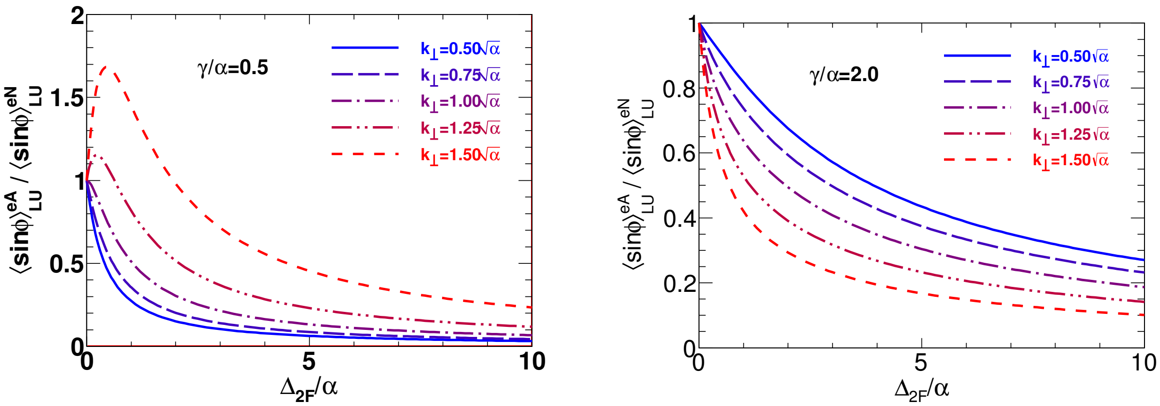

Figure 1.3: Ratio of sin asymmetries nuclei to nucleon, $\langle\sin\phi\rangle^{eA}_{LU}/\langle\sin\phi\rangle^{eN}_{LU}$, as a function of Δ_{2F}/α and for different γ/α [5].

results should be largely consistent with the measurements of from free proton targets. Any significant deviation will clearly indicate a strong nuclear effect.

We discussed measuring the $\cos\phi$ and $\sin\phi$ moments and why they are especially interesting to understand the nuclear transport parameter, but we will also extract the $\cos 2\phi$ moment for the nuclei. No predictions exist for this observable yet, but it appears clear that it is doable within the framework established above. Therefore, the phenomenological work will be performed in the future to analyze the physics contained in this specific observable, and we expect a similar picture will be obtained. This will offer a third observable to confirm the proper extraction of transport coefficient and verify directly if the effect of it is indeed constant for these observables as the presented model predicted.

1.4 Conclusion

We have presented the physics motivations for the study of nuclear TMDs. A theoretical group [3–6] has made some initial studies predicting a strong nuclear effect on SIDIS asymmetries. We propose to test these predictions by performing a measurement of the $\cos\phi$ and $\sin\phi$ moments observed on nuclear targets as part of the run group D of CLAS12. The measurement of these asymmetries should also help justify more theoretical developments in the field of nuclear TMDs

We showed here that the large acceptance of CLAS12 allows us to directly access many complementary observables that will enable us to extract the transport coefficient and interpret our results in terms of the presented calculations. The use of multiple targets and access to several observables is key in such a first time measurement where the interpretation of the results can be challenging.

Chapter 2

Run Conditions

2.1 Presentation of Run Group D

The single RG-D experiment, E12-06-106, aims to study the color transparency (CT) phenomenon in exclusive diffractive ρ^0 electroproduction off nuclei [16]. CT is a direct prediction of Quantum Chromo Dynamics (QCD), the fundamental theory of strong interactions. It refers to the production and propagation of small size hadron-like configurations (SSC)[1] which, under specific conditions, stay intact while traveling in the nuclear medium. The produced SSC has a small transverse size inversely proportional to the momentum transfer involved in the reaction. Thus, it propagates in the nuclear medium as a color dipole with diminished interactions cross-section proportional to its square size. This leads to a reduced attenuation due to the cancellation of color fields produced by its compact system of quarks and gluons. Therefore, CT manifests the power of the hard 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 [17,18].

The CT experiment plans to use an 11 GeV electron beam energy, four nuclei (^{2}H, ^{12}C, ^{63}Cu[2], and ^{118}Sn), and the CLAS12 spectrometer in its standard configuration. In this process, the incident electron scatters off the target nucleus and exchanges a virtual photon. The latter then fluctuates into $q\bar{q}$ pair [19] of small transverse separation proportional to $1/Q$ [20], which can propagate over a distance l_c, known as the coherence length. 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 vector meson ρ^0 over the formation time τ_f. The ρ^0 get identified via its decay products π^+ and π^-.

The experimental signature of CT is the significant rise of the nuclear transparency, T_{A}, the ratio of the cross section per nucleon on a bound nucleon to that on a free nucleon, with Q^2. Further, the CT studies should be performed either at small or fixed coherence length

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

[2] ^{63}Cu is substituting the initially proposed and approved ^{56}Fe, which is a ferromagnetic material and can not be used with the CLAS12 5T solenoid field surrounding the target area.

to not mimic the CT signal with the so-called coherence length effect (CL). The latter arises when l_c varies from long to short compared to the free mean path of a ρ^0 meson in medium, leading to a rise of $T_{\rm A}$ with increasing Q^2 (decreasing $l_{\rm c}$) [21]. In this case, the initial state interactions (ISIs) are dominated by the hadronic interaction of a $q\bar{q}$ pair with the medium, in contrast with the case when l_c is small and the ISIs are purely electromagnetic interactions.

CT is well established at high energies since the Fermilab E791 that reported its strong signature in the A-dependence of the diffractive dissociation into di-jets of 500 GeV negative pions scattering coherently from carbon and platinum targets [22]. 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) [23]. 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^+ [24] and ρ^0 [25] electroproduction 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 production [23, 26].

The planned CT studies will allow a quantitative understanding of the SSC formation time and its interaction with the nuclear medium. It will 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 with reduced attenuation. 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.

2.2 Changes to the run group D

Because the present proposal necessitates the use of a polarized beam, it impacts a bit the run group. Mild changes have to be made to reserve some of the commissioning time of the run group to perform regular Moller measurements to monitor the beam polarization. Luckily some of the changes in the setting of nuclear targets for CLAS12 have lead to free some commissioning time to perform these Moller runs without impacting the original physics goals of the run group. The Moller runs are taking up to two hours and are planned to be taken about every week, which should account for less than a PAC day over the full run.

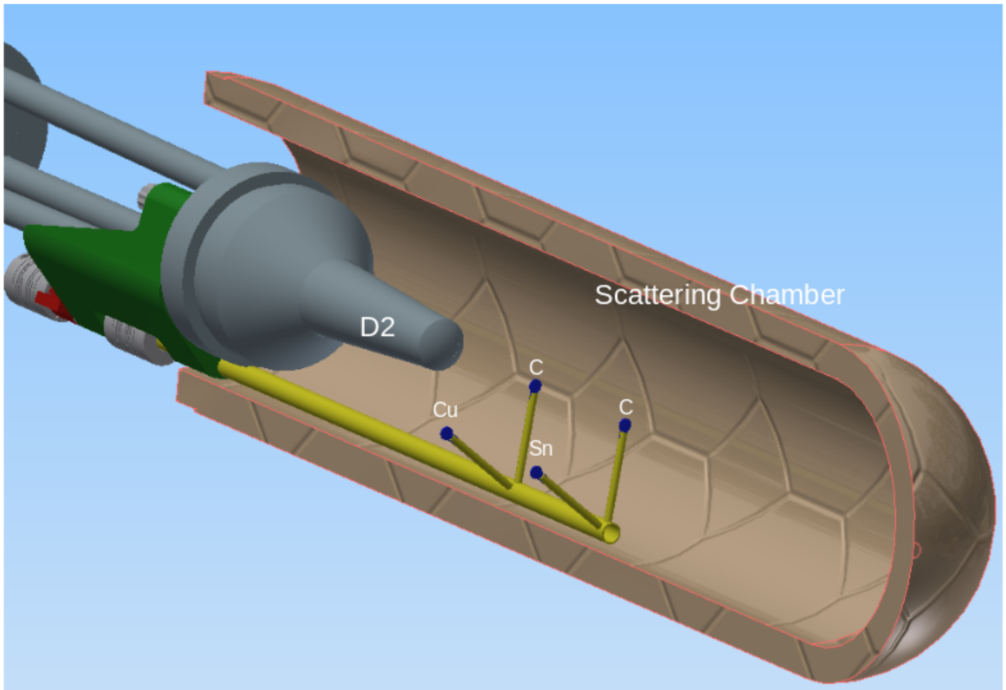

Figure 2.1: A sliced view of the Hall-B nuclear targets assembly. The beam will travel from the top left to the bottom right corner.

2.3 Run plan of the Run Group D

The RG-D (CT) experiment is initially approved to run for 60 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 in a similar manner with eg2. For that reason, no beam-time was initially dedicated to the deuterium target as it was assumed to run in parallel all the time.

This plan has recently been revised for several reasons. First, the long 5cm liquid deuterium target available now is too thick to accommodate a nuclear target behind it. Second, it was found that systematics are not drastically reduced while running both targets at the same time due to large remaining acceptance corrections. In consequence, it was decided to run either deuterium or nuclear targets and not both simultaneously. To do so, we will use the nuclear targets assembly built and maintained by the Hall-B engineers shown in Fig 2.1, where the blue circles are the solid target's foils. In this setup, the solid target foils are manipulated by a support tube that can be rotated to change the target in the beam line.

As a consequence, the initially approved beam-time has been adjusted to dedicate time for the deuterium target, and to take into account running with two target foils simultaneously in the beam line, see Fig. 2.2. We are still considering taking 4 days data with hydrogen to better understand the other processes that contribute to the ρ^0 background. The reduced

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

Figure 2.2: The adjusted RG-D beam time for the new Hall-B nuclear target assembly.

beam time allocated to the deuterium target will be dedicated in part to the acquisition of Moller runs

2.4 Conclusion

The run group D is dedicated to the measurement of the onset of color transparency in three nuclei (^{12}C, ^{63}Cu and ^{118}Sn). It can easily accommodate the polarization of the beam and allow for a widening of its scientific program. The present proposal can indeed run with the updated setup of run group D without issues and only the small overlay of taking regular Moller measurements of the beam polarization. The time dedicated to these runs will be inferior to one PAC day.

Chapter 3

Projections

3.1 Monte-Carlo Simulation

For our simulation, we used an *ad hoc* event generator providing SIDIS production: `gmc_trans`. We generated a sample specifically dedicated to positively charged pions, though this study can be extended to other hadrons. The generator included polarization effects, but only for protons and here we only used the information to access the statistical precision. Therefore, the simulation presents projected statistical error bars on the asymmetries.

The events have been processed in the standard CLAS12 software with GEMC simulation and CLARA reconstruction. This include a solid target foils assembly that has been implemented in GEMC. The setup assumes using nuclear foils encapsulated in the cryo target scattering chamber and held at the center of the CLAS12 solenoid.

We present in the Fig. 3.1 and 3.2 the main kinematic distributions of the events after reconstruction. We can see the normal coverage of CLAS12 for each variables. It is indeed expected that no major difference should be seen here with nuclear targets compared to the proton target.

3.2 Projections for the observables

The statistics available for the nuclear target is much smaller than the one available in dedicated proton experiments. This is due to several factors, mainly the beam time allocated for each targets, presented in the previous chapter, is only of 14 days of running per nuclear target. For the projection shown in Fig. 3.3, we use this value of 14 days and account for inefficiencies linked to particle identification cuts and analysis cuts to select the SIDIS kinematics.

In Fig. 3.3, we show the kinematic range expected for selected bins and for $2 < Q^2 < 3$ GeV^2. We observe that the statistics will be large enough to obtain a measurement dominated by systematic error bars in a large phase space. While not allowing as large a p_T^2 coverage as

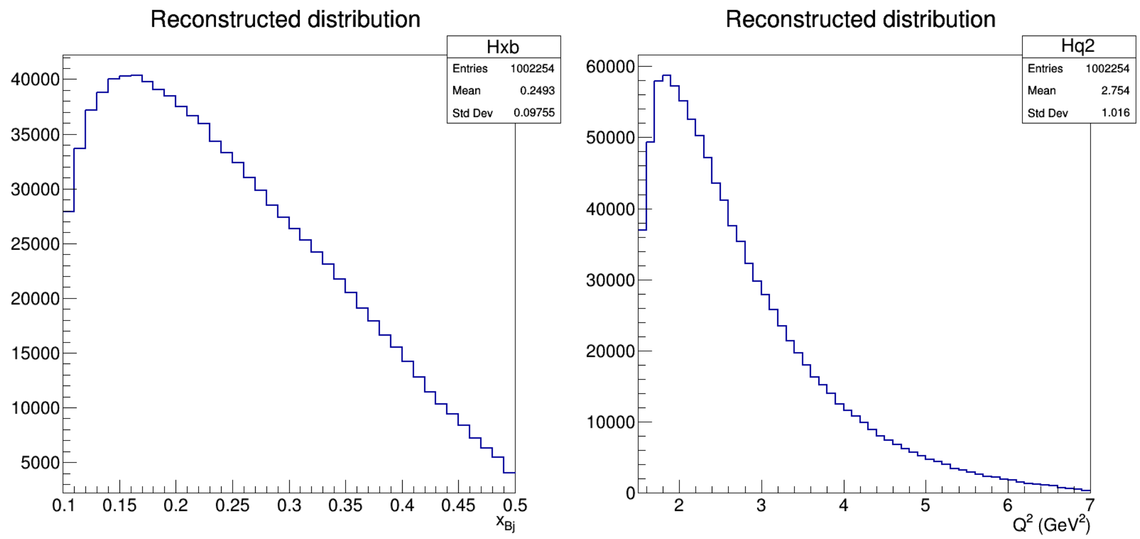

Figure 3.1: Kinematic distribution of simulated electrons in x_{Bj} and Q^2 (GeV^2).

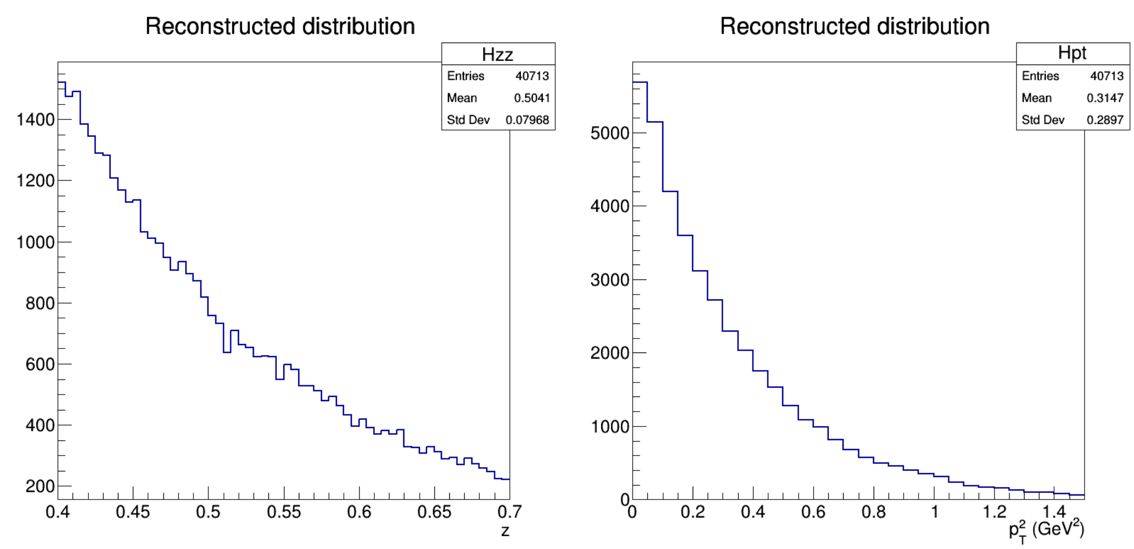

Figure 3.2: Kinematic distribution of simulated SIDIS π^+ in z and P_T^2 (GeV^2).

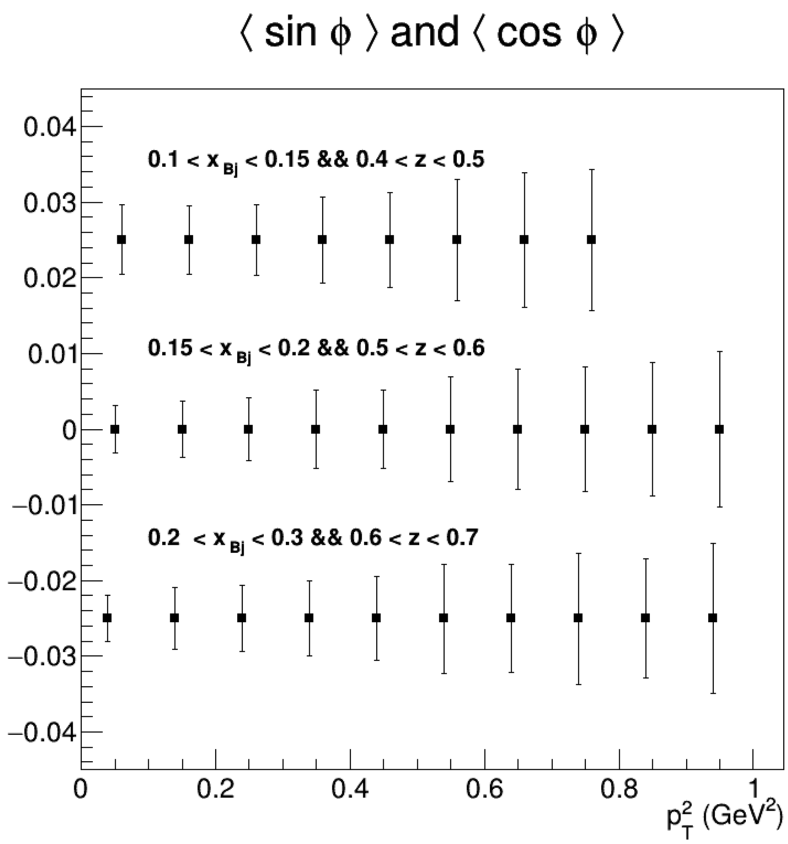

Figure 3.3: Projected statistical error bars for sin and cos moments from nuclear targets using the run group D data.

the SIDIS proton or kaon experiments [27, 28], it is comparable and should allow for direct comparisons. Indeed, predictions from [5], shown in Fig. 1.3, indicate an overall suppression of the asymmetries of about 50%. Such a nuclear effect will be well within our reach and most visible for intermediate p_T^2, where asymmetries are expected to be up to 5%. The amount of data should be even enough to detect any unexpected behavior in the Q^2, x_{Bj}, z or p_T^2 distributions, if these are of similar amplitude.

We do not represent here every bin and observable since they show an identical behavior from the statistical point of view. However, we expect different impacts from the systematic effects, such as from resolution or detector efficiencies. Precise analysis of these errors has been made elsewhere for CLAS12, and we expect our measurement to be similar to the one on a proton target, evaluated to be around 3-4% [27].

When comparing with the predictions of [3–6], we will use the CLAS12 proton data for the construction of the nuclear ratios. We expect that the main part of the systematic error related to the detector resolution and acceptance will cancel out.

3.3 Conclusion

We show that the data from run group D will contain enough SIDIS events to measure the cos and sin modulations for $p_T^2 < 1$ GeV^2. Based on estimations made for proton TMD studies, the errors should largely be dominated by systematic effects in this range, thus there is no apparent need for a larger data set at this point in time. We also argue that if the nuclear modification are as large as predicted by the model, the precision of the experiment will allow to measure them.

Summary

We presented in this run group proposal opportunities to measure TMDs in CLAS within the run group D. This measurement comes at a very mild cost, polarizing the beam during the run, while promising very interesting results. Indeed, we showed that while covering a smaller phase space, we could measure the nuclear TMDs with a precision equivalent to the approved measurements on the proton. The ratio of these measurements will shed light on the effect of the transport coefficient on TMD observables, in particular offering a way to compare it in widely different nuclei.

We think the cost-benefit ratio is overwhelmingly positive to perform nuclear TMD studies together with the approved experiment of Run Group D. The success of this measurement will pave the way for more precision and other observables in the field of nuclear TMDs.

Bibliography

[1] A. Accardi, F. Arleo, W. K. Brooks, D. D'Enterria, and V. Muccifora, "Parton Propagation and Fragmentation in QCD Matter," *Riv. Nuovo Cim.*, vol. 32, pp. 439–553, 2010.

[2] P. Ru, Z.-B. Kang, E. Wang, H. Xing, and B.-W. Zhang, "A global extraction of the jet transport coefficient in cold nuclear matter," 2019.

[3] Z.-t. Liang, X.-N. Wang, and J. Zhou, "The Transverse-momentum-dependent Parton Distribution Function and Jet Transport in Medium," *Phys. Rev.*, vol. D77, p. 125010, 2008.

[4] J.-H. Gao, Z.-t. Liang, and X.-N. Wang, "Nuclear dependence of azimuthal asymmetry in semi-inclusive deep inelastic scattering," *Phys. Rev.*, vol. C81, p. 065211, 2010.

[5] Y.-k. Song, J.-h. Gao, Z.-t. Liang, and X.-N. Wang, "Azimuthal asymmetries in semi-inclusive DIS with polarized beam and/or target and their nuclear dependences," *Phys.Rev.*, vol. D89, no. 1, p. 014005, 2014.

[6] Y.-k. Song, Z.-t. Liang, and X.-N. Wang, "Nuclear suppression of azimuthal asymmetries in semi-inclusive deep inelastic scattering off polarized targets," *Phys. Rev.*, vol. D89, no. 11, p. 117501, 2014.

[7] M. Diehl, "Introduction to GPDs and TMDs," *Eur. Phys. J.*, vol. A52, no. 6, p. 149, 2016.

[8] R. Dupré and S. Scopetta, "3D Structure and Nuclear Targets," *Eur. Phys. J.*, vol. A52, no. 6, p. 159, 2016.

[9] M. Hattawy *et al.*, "First Exclusive Measurement of Deeply Virtual Compton Scattering off ^{4}He: Toward the 3D Tomography of Nuclei," *Phys. Rev. Lett.*, vol. 119, no. 20, p. 202004, 2017.

[10] ——, "Exploring the Structure of the Bound Proton with Deeply Virtual Compton Scattering," *Phys. Rev. Lett.*, vol. 123, no. 3, p. 032502, 2019.

[11] A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P. J. Mulders, and M. Schlegel, "Semi-inclusive deep inelastic scattering at small transverse momentum," *JHEP*, vol. 02, p. 093, 2007.

[12] J. Qiu and G. Sterman, "Qcd and rescattering in nuclear targets," *International Journal of Modern Physics E*, vol. 12, no. 02, p. 149âĂŞ164, Apr 2003.

[13] J. Qiu, "Rescattering effects in hadron-nucleus and heavy-ion collisions," *The European Physical Journal C*, vol. 43, no. 1-4, p. 239âĂŞ247, Jul 2005.

[14] R. Baier, Y. L. Dokshitzer, A. H. Mueller, S. Peigne, and D. Schiff, "Radiative energy loss and p(T) broadening of high-energy partons in nuclei," *Nucl. Phys.*, vol. B484, pp. 265–282, 1997.

[15] N. Armesto *et al.*, "Comparison of Jet Quenching Formalisms for a Quark-Gluon Plasma 'Brick'," *Phys. Rev.*, vol. C86, p. 064904, 2012.

[16] L. El Fassi, K. Hafidi, M. Holtrop, B. Mustapha *et al.*, "Study of color transparency in exclusive vector meson electroproduction off nuclei," *CLAS12 proposal E12-06-106; 2010 Update*, 2006.

[17] L. L. Frankfurt, G. A. Miller, and M. Strikman, "The Geometrical color optics of coherent high-energy processes," *Ann. Rev. Nucl. Part. Sci.*, vol. 44, pp. 501–560, 1994.

[18] P. Jain, B. Pire, and J. P. Ralston, "Quantum color transparency and nuclear filtering," *Phys. Rept.*, vol. 271, pp. 67–179, 1996.

[19] T. H. Bauer, R. D. Spital, D. R. Yennie, and F. M. Pipkin, "The Hadronic Properties of the Photon in High-Energy Interactions," *Rev. Mod. Phys.*, vol. 50, p. 261, 1978, [Erratum: Rev. Mod. Phys.51,407(1979)].

[20] S. J. Brodsky, L. Frankfurt, J. F. Gunion, A. H. Mueller, and M. Strikman, "Diffractive leptoproduction of vector mesons in QCD," *Phys. Rev.*, vol. D50, pp. 3134–3144, 1994.

[21] K. Ackerstaff *et al.*, "Observation of a coherence length effect in exclusive rho0 electroproduction," *Phys. Rev. Lett.*, vol. 82, pp. 3025–3029, 1999.

[22] E. M. Aitala *et al.*, "Observation of color transparency in diffractive dissociation of pions," *Phys. Rev. Lett.*, vol. 86, pp. 4773–4777, 2001.

[23] J. C. Collins, L. Frankfurt, and M. Strikman, "Factorization for hard exclusive electroproduction of mesons in QCD," *Phys. Rev.*, vol. D56, pp. 2982–3006, 1997.

[24] B. Clasie *et al.*, "Measurement of nuclear transparency for the A(e, e-prime' pi+) reaction," *Phys. Rev. Lett.*, vol. 99, p. 242502, 2007.

[25] L. El Fassi *et al.*, "Evidence for the onset of color transparency in ρ^0 electroproduction off nuclei," *Phys. Lett.*, vol. B712, pp. 326–330, 2012.

[26] M. Strikman, "QCD factorization theorems for DIS exclusive processes and inclusive diffraction: New probes of hadrons and nuclei," *Nucl. Phys.*, vol. A663, pp. 64–73, 2000.

[27] H. Avakian, P. Bosted, S. Boyarinov *et al.*, "Probing the proton's quark dynamics in semi-inclusive pion production at 12 gev," *CLAS12 proposal E12-06-112*, 2006.

[28] K. Hafidi, H. Avakian, F. Benmokhtar *et al.*, "Studies of partonic distributions using semi-inclusive production of kaons," *CLAS12 proposal E12-09-007*, 2009.