Nuclear TMDs in CLAS12

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a CLAS Collaboration Proposal

Abstract

The development of transverse momentum dependent PDFs (TMDs) offers the opportunity to study nuclear effects, such as a transverse momentum EMC effect at the partonic level. Recent results from CLAS on nuclear GPDs offer a path forward to extend the longitudinal momentum information of partons in a nucleus to a full 3D (2D+1) imaging in position of the partons in nuclei. This information will need to be complemented to the parton dynamics information contained in the nuclear TMDs to provide a comprehensive modern description of the nucleus starting from the basic degrees of freedom namely quarks and gluons. To this end, we propose to measure the $\cos\phi$, $\sin\phi$ and Boer-Mulders asymmetries for semi-inclusive pion production (SIDIS) on the collection of nuclear targets approved to run in the RG-D. This experiment will use the same beam time and trigger and requires only the addition of beam polarization to the run group D plans. Various kinematic dependencies of SIDIS will be measured with the eventual goal of extracting the transport coefficient of the medium in an independent way. To this day, important controversy remains on the size of the transport coefficient in cold nuclear matter. This can be settled by this experiment which provides two completely independent and new access to the transport coefficient of cold nuclear matter. Another goal is to explore how the EMC effect is different or similar in transverse momentum compared to what we know in the longitudinal momentum through the Boer-Mulders asymmetries.

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 and will argue that this extension is important for both QCD studies and to uncover the dynamics of confined motion of quarks and gluons in nuclei, where the overlap of nucleons should bring about novel behavior compared to a single nucleon. This program is a natural extension of the more traditional hadronization studies, which mostly ignored the TMD framework in the past. In the past two decades, the theoretical developments of the TMD framework has been very rapid and we feel, it is now time to start dedicated studies of nuclear semi-inclusive deep inelastic scattering (SIDIS) in terms of the TMDs.

For this first study, we want to look exclusively 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 [1–3] 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 infamous EMC effect reflects into the nuclear TMDs. No theory background exists 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. The high statictics measurements of relevant data will undoubtedly trigger more studies on this topic.

It is an important time for the topic in the CLAS collaboration, as the first nuclear target runs are approaching. It is now time to complete and modernize the physics program of the relevant run groups. Indeed, in order to perform these studies, we propose to use the already approved run group-D (RG-D) with the simple addition of beam polarization. In this way, we will optimizes the beam time and provide some first data that will enrich the field of QCD studies and enlighten us on its possibilities.

Chapter 1

Physics Case

1.1 Transverse Momentum Dependent PDFs

In the recent past, the study of nucleon structure has been moving from the historic one dimensional view with tools like parton distribution functions (PDFs) and form factors (FFs) to three dimensional studies using generalized parton distributions (GPDs) and transverse momentum dependent PDFs (TMDs) [4]. These have also been extended to the study of nuclei, with a particular focus on GPDs [5–7]. In this proposition of experiment, we will focus on the TMD side, which offer 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.

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 and the hit quark (U for unpolarized, L for longitudinally polarized and T for transversely polarized.)

For nucleons, we have eight leading twist TMDs as described in Table 1.1. More generally this framework is valid for any spin 1/2 target and has been the most studied, both theoretically and experimentally [8] to this date. This framework can be linked to the expression of the cross section in this form [9]:

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

which highlights the different components of the semi inclusive deep inelastic scattering (SIDIS) cross section. We can immediately observe, that in the setup of run group D, with unpolarized target, only the $\cos\phi$, $\cos 2\phi$ and $\sin\phi$ components will contribute.

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 base most of the proposal on the calculations from the following papers on nuclear TMDs [1–3, 10]. 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. Interestingly, it can be directly related to the gluon density in the nucleus [11]:

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

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.

As can be seen, this model includes nuclear modifications through the inclusion of a transport operator. The nuclear transport coefficient, included in Δ_{2F}, is a fundamental characteristic of QCD matter defined as the quarks squared transverse momentum induced per unit of length of the medium. This parameter is commonly used to characterize medium effects in heavy ion collisions at RHIC and LHC, where its increase with the center-of-mass energy of the collisions is interpreted as an increase in density of the medium. Similar studies have been performed using lepton beams at CERN, Fermi Lab, DESY and Jefferson Lab. Extracting a precise value of the transport coefficient from these data has however appeared to be problematic, as different calculations gave widely different results (see a review on the question in [12]). This issue has been carefully studied for energy loss calculations in quark-gluon plasma [13], highlighting the impact of assumptions between the existing perturbative QCD calculations. Interestingly, here, the transport coefficient affects directly the TMDs without interfering with hadronization effects. The cause of this is that the asymmetries considered arise at the parton level and can be factorized with the effect of fragmentation functions. This concept is developed in more details in the following papers focusing on specific observables of interest for us here [2, 3, 10], *i.e.* $\cos\phi$, $\sin\phi$ and p_T. In their 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 mumber 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 oversimplified, this shows directly how the transport coefficient contributes to the SIDIS asymmetries of interest.

1.3 Nuclear TMDs in CLAS12

While in principle, TMDs can be defined for any target's spin, we will focus here on spin-0 for convenience and simplicity. Indeed, even if it is unlikely because of the unpolarized targets used in the RG-D, a larger number of functions can in principle contribute in our observables. Therefore, for the projections, we will discuss only the carbon and tin targets, which are of spin 0 and particularly suitable for the study in question here.

We can see in Eq. 1.8 and 1.9 that if the nucleon TMDs width are known, we can immediately extract the broadening width Δ_{2F} from the measurement of any of these asymmetries, giving 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 can help determine them. We refer the reader to the original paper to obtain the full equations, which are illustrated here in Fig. 1.1 and 1.2. 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 can be particularly helpful to detect a possible nuclear modification of the TMDs width compared to the free nucleon data.

As shown above, measuring the $\cos\phi$ and $\sin\phi$ moments are especially interesting to

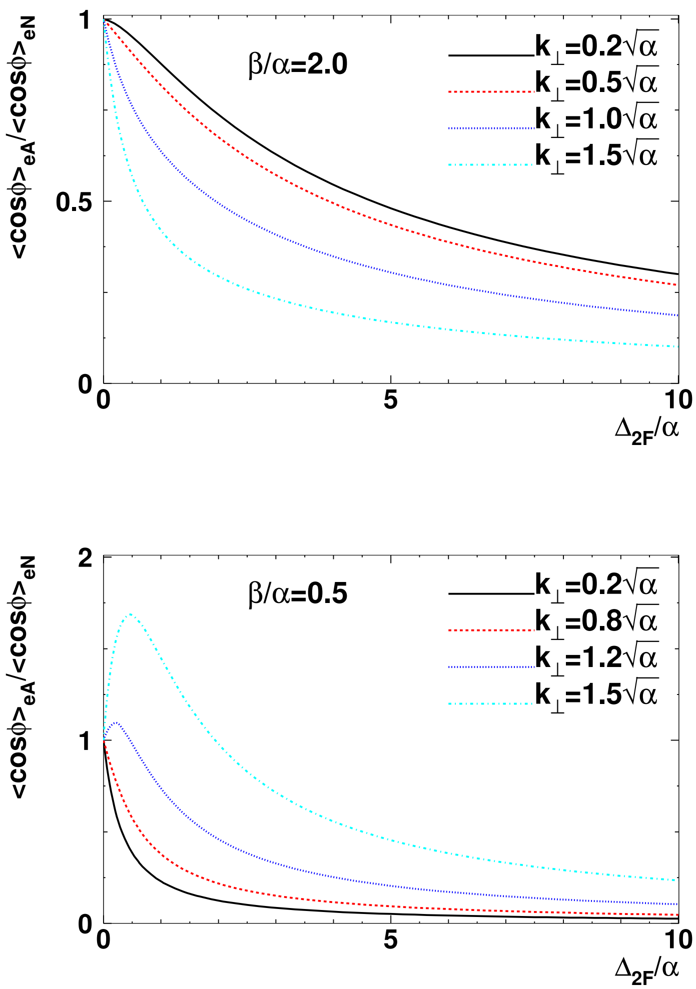

Figure 1.1: Ratio of cos asymmetries nuclei to nucleon, $\langle \cos\phi \rangle_{UU}^{eA} / \langle \cos\phi \rangle_{UU}^{eN}$, as a function of Δ_{2F}/α and for different β/α [2].

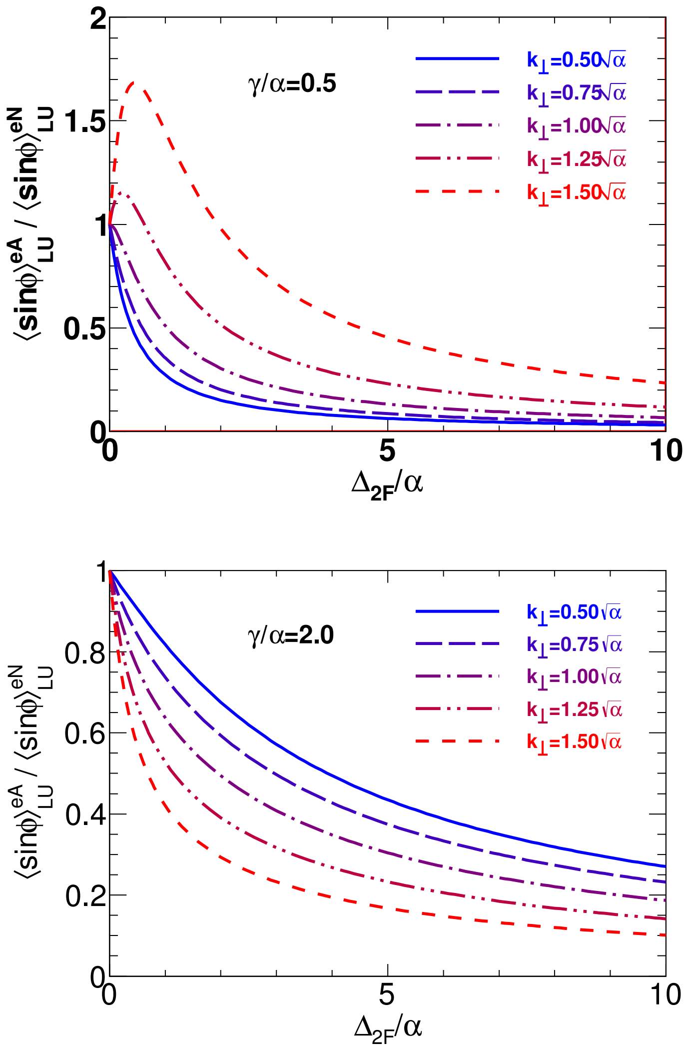

Figure 1.2: Ratio of sin asymmetries nuclei to nucleon, $\langle \sin\phi\rangle^{eA}_{LU}/\langle \sin\phi\rangle^{eN}_{LU}$, as a function of Δ_{2F}/α and for different γ/α [3].

understand the nuclear smearing, but we also will attempt to extract the $\cos 2\phi$ moment for the nuclei. Phenomenological work will be performed in the future to analyse the physics contained in this specific observable, one should however expect a similar picture.

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 [14]. 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, stays 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 [15, 16].

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 [17] of small transverse separation proportional to $1/Q$ [18], 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_{A} with increasing Q^2 (decreasing l_c) [19]. 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 [20]. 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) [21]. 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^+ [22] and ρ^0 [23] 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 [21, 24].

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 linked to this proposal

Because this 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 enough commissioning time to perform these Moller runs without impacting the original physics goals of the run group.

2.3 Run plan of the Run Group D

The RG-D (CT) experiment is initially approved to run for 52 PAC days on three nuclear targets (^{12}C, ^{63}Cu and ^{118}Sn) with 11 GeV electron beam energy and an other 8 days on

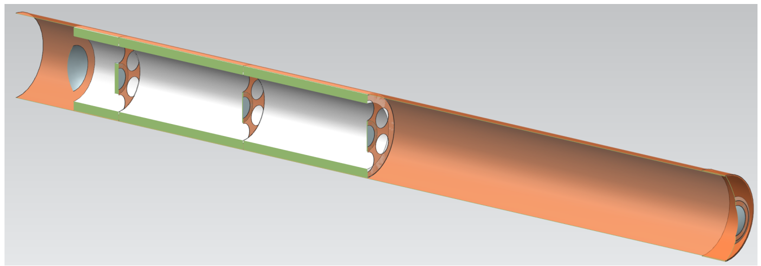

Figure 2.1: A sliced view of the Hall-B nuclear targets assembly. The beam will travel from the top left to the bottom right corner.

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 deuterium target. However, this plan has recently revised to use the single nuclear targets assembly built and maintained by the Hall-B engineers, see Fig 2.1, where the sliced grey circles are the solid target's foils. In this setup, the solid target foils are glued to a kapton disk, then to a foam cylinder, and mounted inside a 20 mm diameter kapton cell (similar to the liquid target cell). The cell will be purged with a cold helium to dissipate heat from the beam interaction. The advantage of using this 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.

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 three target foils, 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.

Targets/Plan	Beam Time (PAC days)
^{12}C / ^{12}C / ^{12}C	10
LD_2	10
^{63}Cu / ^{118}Sn / ^{118}Sn	36
LH_2	4

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

Chapter 3

Projections for the Proposed Measurements

3.1 Monte-Carlo Simulation

For our simulation, we used an *ad hoc* event generator providing SIDIS production. We used sample specifically dedicated to both charged pions and kaons. The generator do not include directly the polarization effects, such that the final asymmetry fit precision has been estimated based on statistics in an independent manner.

The events have been processed in the standard CLAS12 software with GEMC simulation and CLARA reconstruction. As depicted in Fig 3.1, the Hall-B built solid target foils assembly has been implemented in GEMC. The setup assumes using three concurrent nuclear foils (red semi-disks) which are attached to kapton disks separated by Rohacell foam cylinders and held inside a 20 mm diameter Kapton cell (similar to the liquid target cell). The full assembly is encapsulated in the scattering vacuum chamber (green cylinder) and held inside the CLAS12 solenoid.

3.2 Projections

The statistics available for the nuclear target is much smaller than the one available in dedicated experiments. This is due to several factors, mainly the beam time allocated for each targets, presented in the previous chapter, is only of 10 to 24 days of running. For the projection shown in Fig. 3.2, we use the lower value of 10 days, since the longer beam time for heavy targets is mainly there to compensate hadron absorption and should therefore not result in a significantly larger amount of data.

Fig. 3.2 shows that for selected bins – here $1.5 < Q^2 < 2.5$ GeV^2, $0.15 < x_{Bj} < 0.25$ and $0.4 < z < 0.5$ – the statistics will be large enough to obtain a measurement dominated by systematic error bars, yet not allowing as large a p_T^2 coverage as the SIDIS proton or kaon

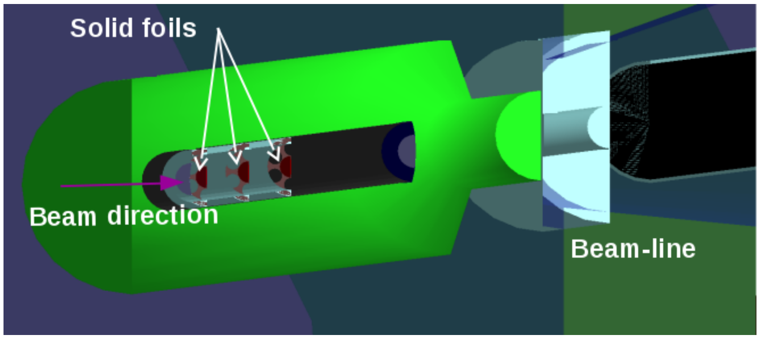

Figure 3.1: Illustration of x-sliced Hall-B nuclear target assembly as implemented in GEMC. The red semi-circles are the solid target foils which are mounted in a Kapton cell and held in the green vacuum scattering chamber. The snapshot is showing the CLAS12 solenoid in the background and some components of the beamline.

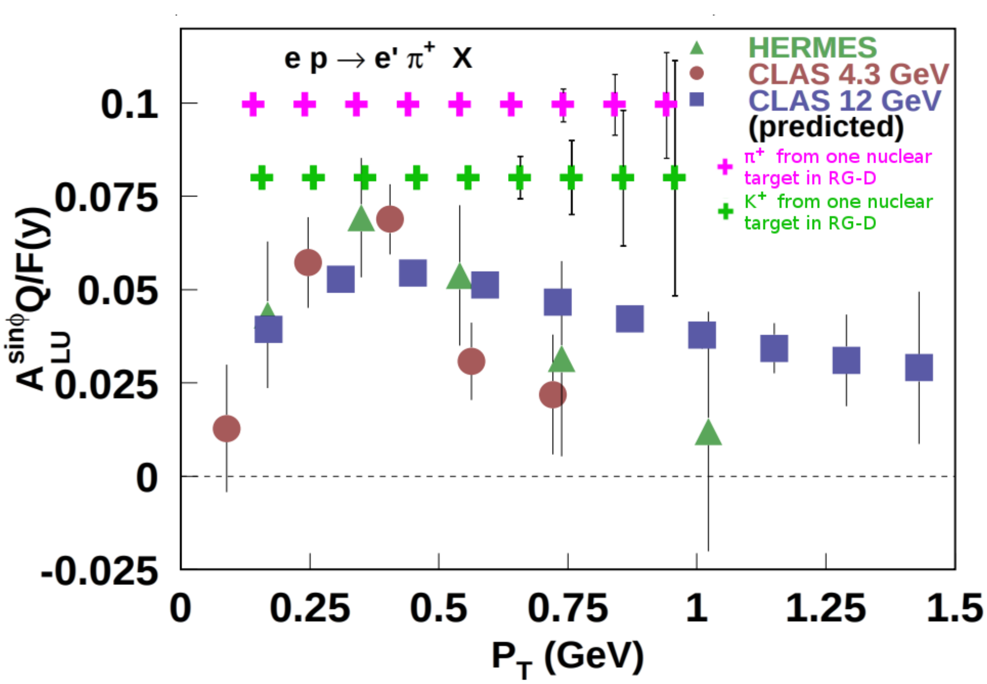

Figure 3.2: Ratio of cos asymmetries nuclei to nucleon, $\langle\cos\phi\rangle^{eA}_{UU}/\langle\cos\phi\rangle^{eN}_{UU}$, as a function of Δ_{2F}/α and for different β/α [2].

experiments [25,26]. However, this lack in coverage should not hamper the main goal of the experiment to measure the nuclear modifications. Indeed, predictions from [3], shown in Fig. 1.2, 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 the largest. 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 large enough.

We do not represent here every bins and each observables ($\cos\phi$ and $\cos 2\phi$) as they show an identical behavior as for the $\sin\phi$ asymmetry presented in Fig. 1.2. As mentioned above, this is due to the fact that we solely rely on this generation to evaluate realistic rates in our phase space, while fitting errors are estimated independently with pseudo-data based on the statistics accumulated in the bin. These other observables give therefore very similar results. However, we should expect different impact from systematic effects, such as from resolution or theoretical uncertainties from higher-twist contributions. These are expected to be very similar to the one on a proton target, evaluated around 3-4% [25]. Altogether, it will be possible to evaluate the size of the nuclear effects for all three observables accessible with beam polarization only.

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 size of the transport coefficient, in particular offering a way to compare it widely different nucleus.

We think the cost-benefit ratio is overwhelmingly positive to perform such studies together with approved experiments such as the one of run group D. We also identified other measurements that can be performed in the same manner by taking advantage of the polarization. In particular, incoherent nuclear DVCS will be possible to extend the work performed in CLAS at 6 GeV on helium target [7].

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