Measurement of the Nuclear Dependence of $R = \sigma_L/\sigma_T$ in Semi-Inclusive Deep Inelastic Scattering

A Proposal to PAC 52

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May 1, 2024

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1 Executive Summary

There is little experimental information about the relative contribution of longitudinal photons to semi-inclusive deep inelastic scattering (SIDIS). Knowledge of $R = \sigma_L/\sigma_T$ in SIDIS is crucial for interpretation of SIDIS measurements in terms of the many response functions of interest. This lack of experimental information on the proton and deuteron (neutron) will soon be addressed by experiment E12-06-104 which is expected to run in the next few years in Hall C. While SIDIS on the nucleon is used to extract information about the longitudinal and 3D structure of the nucleon, nuclei can be used as a laboratory to study quark hadronization in SIDIS. Correct interpretation of these measurements also requires knowledge of R. To date, nuclear SIDIS measurements have assumed no nuclear dependence of R. This experiment will make limited exploratory measurements of a possible nuclear dependence of R in SIDIS to support hadron attenuation measurements. If a nuclear dependence is observed, this could be a sign of novel physics and would suggest further studies are merited. We request 4.4 days to measure SIDIS from carbon and copper targets using the HMS and SHMS in Hall C. These data, in combination with the proton and deuteron data from E12-06-104 will allow precise determination of the nuclear dependence of R in SIDIS.

2 Introduction and Overview

In the naive quark model, the p_T and ϕ integrated cross section for semi-inclusive deep inelastic scattering (SIDIS) can be written,

$$\frac{d\sigma}{dE_e d\Omega_e dz} = \sigma_e \frac{d\sigma}{dz}, \tag{1}$$

where σ_e is the inclusive electron scattering cross section and $d\sigma/dz$ can be written,

$$\frac{d\sigma}{dz} = \frac{\frac{d\sigma}{dE_e d\Omega_e dz}}{\sigma_e} = \sum_f e_f^2 q_f(x, Q^2) D_f^h(z), \tag{2}$$

where e_f and q_f are the charge and distribution of a quark of flavor f and D is the fragmentation function. This simple expression describes the connection between the probability to find a particular flavor quark in a nucleus and the probability for that quark to end up in a hadron of type h. However, Eq. 2 is only properly true for the cross section from transversely polarized virtual photons - there will also be contributions to the SIDIS process from longitudinal photons.

The longitudinal photon-quark cross section is described by a higher twist interaction and a simple estimate from [1] relates it to the transverse momentum of the quarks in the nucleon k_T^2:

$$R = 4(M^2 x^2 + k_T^2)/(Q^2 + 2k_T^2). \tag{3}$$

The unpolarized SIDIS cross section (with ϕ dependence) including the contribution from longitudinal photons can be written,

$$\sigma \sim F_{UU,T} + \epsilon\, F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h\, F_{UU}^{\cos\phi_h} + \epsilon \cos 2\phi_h\, F_{UU}^{\cos 2\phi_h}. \tag{4}$$

Typically, the longitudinal part of the cross section is just subtracted before the factorized description is used, and in the case of most SIDIS analyses, it is assumed that the value of $R = \sigma_L/\sigma_T$ is the same for SIDIS as in inclusive electron scattering.

The R-SIDIS experiment (E12-06-104) in Hall C will make a first systematic measurement of the longitudinal cross section of the SIDIS process from H and D targets as a function of z, p_T and hadron type. A variation of R as a function of these variables would indicate that the longitudinal and transverse components are sensitive to the photon polarization, hence the simple naive factorization must be more complicated. This could result from higher twist mechanisms being more predominant at different z and p_T.

If one now embeds the SIDIS process in a nuclear environment, one will have a fragmentation process that develops within an environment where additional interactions may occur after the initial photon-quark absorption. In addition, the k_T distribution within the nucleus may be modified from that of the free nucleon and the presence of nearby nucleons may enhance indirect gluon and higher-twist effects in a way that alters the initial longitudinal photon-quark process when coupled to a SIDIS final state.

One can study the impact the of nuclear environment experimentally by forming the ratio of multiplicities from a nucleus to that from deuterium,

$$R_A^h = \frac{N_A^h/N_A^e}{N_D^h/N_D^e} = \frac{\left(\frac{d\sigma}{dz}\right)_A^h}{\left(\frac{d\sigma}{dz}\right)_D^h}.$$

From the simple picture above (Eq. 2), deviations of this ratio from 1.0 should directly correspond to changes in the fragmentation process due to quark, pre-hadron, or hadron interactions in the nucleus. Such measurements have been made by several experiments, most recently by HERMES [2] and the CLAS collaboration [3]. Examples of the extraction of the hadron attenuation ratios for several nuclei in the CLAS spectrometer and as measured by the HERMES collaboration are shown in Figures 1 and 2.

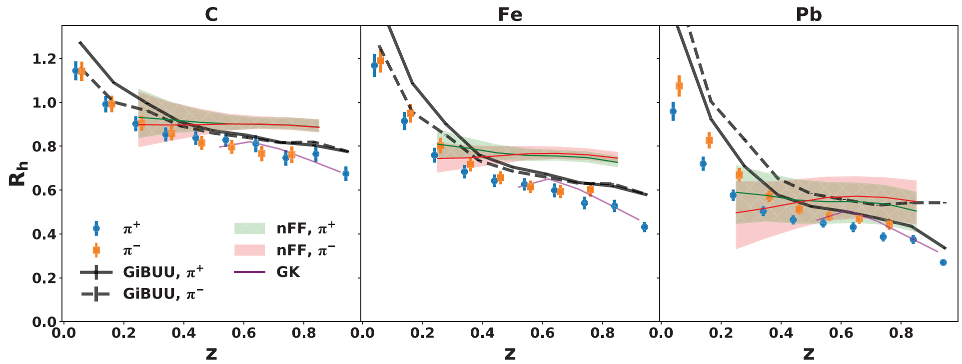

Figure 1: Hadron attenuation ratios in carbon, iron, and lead nuclei for charged pions from CLAS [3].

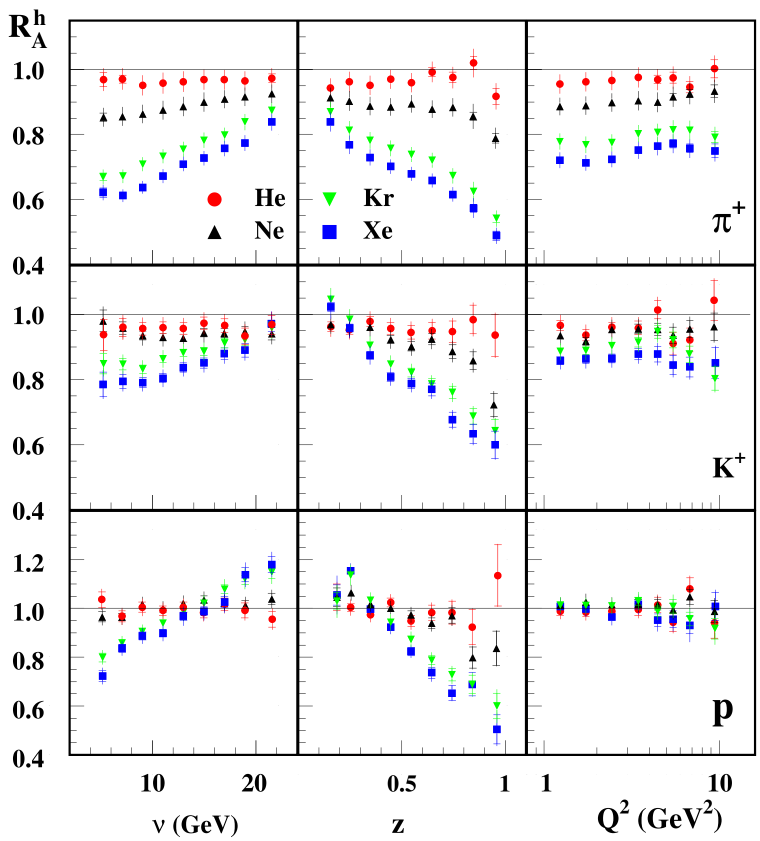

Figure 2: Hadron attenuation ratios in helium, neon, krypton, and xenon nuclei for positovely charged pions, kaons, and protons from HERMES [2].

Possible contributions from longitudinal photons are also relevant in the interpretation of the R_A^h ratios extracted from measurements of SIDIS from nuclei. It is implicitly assumed that there is no nuclear dependence in the contribution from longitudinal photons in SIDIS. If the value of R in SIDIS differs from that in DIS, and that value of R is nuclear dependent, there will be non-trivial impact on measurements of hadron attenuation in nuclei.

While a possible nuclear dependence of R has not yet been studied in semi-inclusive DIS, it has been investigated in both inclusive DIS, and exclusive processes.

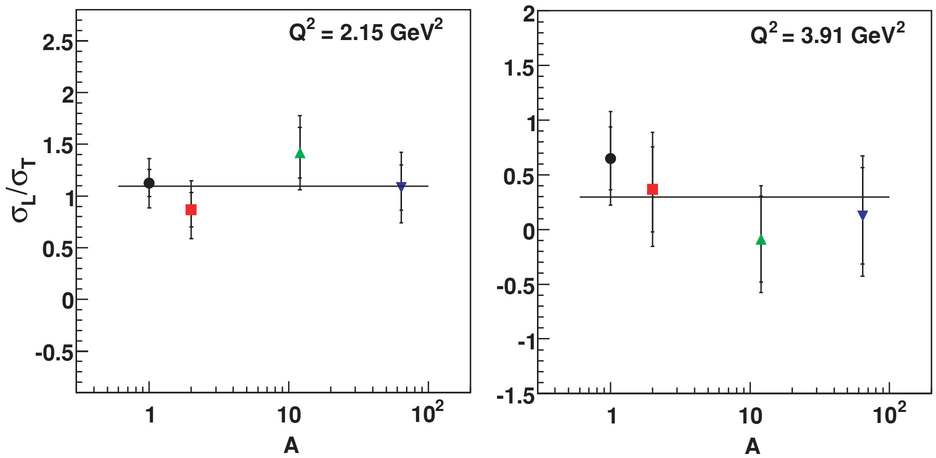

Figure 3: Measurements of $R = \sigma_L/\sigma_T$ for ^{1}H, ^{2}H, ^{12}C, and Cu for exclusive π^+ production [4]. The data at $Q^2 = 2.15$ GeV^2 correspond to $W = 2.21$ GeV and $x = 0.35$, while the points at $Q^2 = 31.9$ GeV^2 are at $W = 2.26$ GeV, $x = 0.43$.

Direct measurement (via Rosenbluth separation) of the nuclear dependence of R in inclusive DIS has been studied by the SLAC E140 experiment [5]. The results from this experiment suggested no nuclear dependence of R, however, re-analysis of the E140 data with appropriate Coulomb Corrections suggests a non-zero nuclear dependence [6]. Furthermore, an analysis of the ϵ dependence of σ_A/σ_D for copper and iron target data at $x = 0.5$ from several experiments also suggests a non-zero nuclear dependence [7]. In addition, preliminary results from Hall C experiment E04-001 [8] also suggest a non-zero nuclear dependence of R in the resonance region. The nuclear dependence of R will be studied in more detail by Hall C experiment E12-14-002 [9].

On the other hand, a possible nuclear dependence of the longitudinal cross section in exclusive charged pion production from light nuclei has been investigated by Hall C E91-003 [10] and the nuclear dependence of R in heavier nuclei in Hall C E01-107 [4] (see Fig. 3). Neither experiment saw evidence of nuclear dependence within the precision of their results.

The addition of measurements of the nuclear dependence of R in SIDIS will allow us to obtain a more complete picture of the role of longitudinal photons, filling in the "gap" between inclusive DIS and exclusive processes. The relatively modest amount of beam time requested in this proposal will either support the assumptions generally made about the nuclear dependence of R in SIDIS and in the interpretation of nuclear effects in semi-inclusive production of pions, or, in the event of the observation of some nuclear dependence, suggest that our picture of SIDIS from nuclei is incomplete.

3 Proposed Measurements and Experimental Details

We intend to measure $R = \sigma_L/\sigma_T$ in semi-inclusive π^+ production with carbon and copper targets at x =0.2, 0.4, and 0.5. At $x = 0.2$, we will measure the z dependence, while measurements at $x = 0.4$ and 0.5 will only be made at $z = 0.5$.

3.1 Kinematics and Rate Estimates

This experiment will make measurements of semi-inclusive π^+ production from carbon and copper using a subset of the kinematics planned for the E12-06-104 [11]. The full kinematics for E12-06-104 are shown in Table 1. E12-06-04 will make a comprehensive survey of R in SIDIS, measuring the z-dependence at $x = 0.2$ and 0.4, measuring the p_T dependence at $x = 0.3$, and measuring the x-dependence at fixed z from $x = 0.15$ to 0.5 for proton and deuteron targets. The scope of this proposal is more limited, aiming to make measurements over a range of z at $x = 0.2$, and additional measurements at a fixed value of z-0.5 for $x = 0.4$ and 0.5 using carbon and copper. There will not be a dedicated attempt to measure the p_T dependence, but the spectrometer acceptance will allow measurements out $p_T \approx 0.3$ GeV, with full azimuthal coverage to 0.2 GeV (see Fig. 4).

x	Q^2 (GeV^2)	z	θ_{pq} (degrees)	Targets	E_{beam} (GeV)	ϵ
0.2	**2.0**	**0.3,0.4,0.5,0.65,0.85**	**0.0**	LH2,LD2,**C**,**Cu**	**6.6**	**0.34**
		0.3,0.4,0.5,0.65,0.85	**0.0**	LH2,LD2,**C**,**Cu**	**8.8**	**0.66**
		0.3,0.4,0.5,0.65,0.85	**0.0**	LH2,LD2,**C**,**Cu**	**11.0**	**0.80**
0.4	**4.0**	0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C**,**Cu**	**6.6**	**0.31**
		0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C**,**Cu**	**8.8**	**0.65**
		0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C**,**Cu**	**11.0**	**0.79**
0.3	3.0	0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	6.6	0.33
		0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	8.8	0.66
		0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	11.0	0.88
0.15	1.5	0.5	0.0	LH2	6.6	0.35
		0.5	0.0	LH2	8.8	0.67
0.5	**5.0**	**0.5**	**0.0**	LH2, **C**,**Cu**	**6.6**	**0.30**
		0.5	**0.0**	LH2, **C**,**Cu**	**8.8**	**0.64**
		0.5	**0.0**	LH2, **C**,**Cu**	**11.0**	**0.79**

Table 1: Kinematics from the proposal for E12-06-104. The additional kinematics for exploring $R = \sigma_L/\sigma_T$ in nuclei are denoted in **bold**. Note that while E12-06-104 will make measurements of both π^+ and π^-, the measurements from C and Cu targets will be for π^+ only.

The High Momentum Spectrometer (HMS) will be used to detect the scattered electrons while the Super-High Momentum Spectrometer (SHMS) will be used to detect the semi-inclusive charged pions. A combination of the heavy gas Cherenkov detector and lead-glass calorimeter will be used for electron identification in the HMS, while an HGC and aerogel detector will be used for pion identification in the SHMS. Beam energies of 6.6, 8.8, and 11 GeV will be used to make measurements at 3 values of the virtual photon polarization parameter, ϵ. The scattered electron momenta and angles will range from 1.27 to 5.67 GeV and 10.5 to 45.41 degrees respectively. Momenta and angles in the SHMS will be from 1.59 to 4.53 GeV and 6.3 to 15.96 degrees. All spectrometer requirements are within their nominal capabilities.

SIDIS rates for π^+ production were estimated with the Hall C simulation package "SIMC", using a parametrization of the SIDIS process developed by P. Bosted during analysis of Hall C experiments E12-09-017 ("Transverse Momentum Dependence of Semi-Inclusive Pion Production") and E12-09-002 ("Charge Symmetry Violating Quark Distributions via Precise Measurement of π^+/π^- Ratios in Semi–inclusive Deep Inelastic Scattering"). Hadron attenuation effects in the C and Cu targets are included via a fit to hadron attenuation results from HERMES for Ne (A=10) and Xe (A=54) [2]. The fit is of the form $R^h_A = \frac{1}{N_{DIS}} \frac{dN^\pi}{dz} = N_0 z^\alpha (1-z)^\beta$ and is shown in Fig. 5.

The expected SIDIS rates and time requirements for each setting are shown in Table 2. We have matched

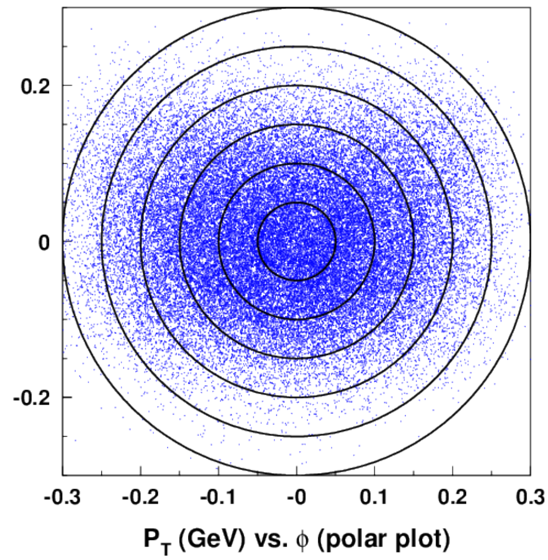

Figure 4: p_T vs. ϕ (polar plot) coverage for the $x = 0.5$, Q^2=5 GeV^2 setting. Each circle indicates a step in p_T of 0.05 GeV. The p_T dependence can be extracted for the region of full ϕ coverage, out to p_T=0.2 GeV^2.

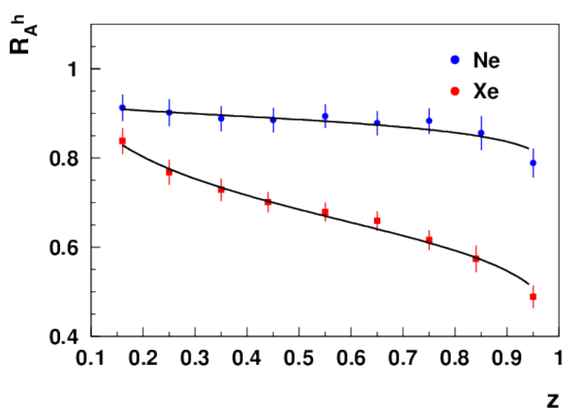

Figure 5: Fits to hadron attenuation ratios for π^+ production from Ne and Xe from [2]. Fits are of the form $R_A^h = N_0 z^\alpha (1-z)^\beta$.

the statistics goals for E12-06-104 for all relevant settings (5,000 events for all settings for the z-scan measurements at $x = 0.2$ and for the low ϵ setting at $x = 0.5$, 10,000 events at all other settings). We have assumed a minimum of 1 hour of run time for each setting, even in cases where the projected run time is less than 1 hour.

x	Q^2 (GeV^2)	E_{beam} (GeV)	ϵ	z	Target	Rate (Hz)	I_{beam} (μA)	N_{events}	Time (hours)
0.2	2.0	6.6	0.34	0.3	C	1.5	25	5000	1.0
					Cu	0.6	25	5000	2.3
				0.4	C	1.7	25	5000	1.0
					Cu	0.7	25	5000	2.1
				0.5	C	1.7	25	5000	1.0
					Cu	0.6	25	5000	2.2
				0.65	C	3.1	50	5000	1.0
					Cu	1.1	50	5000	1.3
				0.85	C	1.5	50	10000	1.8
					Cu	0.5	50	10000	5.6
0.2	2.0	8.8	0.66	0.3	C	16.4	25	5000	1.0
					Cu	6.7	25	5000	1.0
				0.4	C	19.8	25	5000	1.0
					Cu	7.7	25	5000	1.0
				0.5	C	18.8	25	5000	1.0
					Cu	7.1	25	5000	1.0
				0.65	C	17.5	25	5000	1.0
					Cu	6.1	25	5000	1.0
				0.85	C	16.7	50	10000	1.0
					Cu	5.4	50	10000	1.0
0.2	2.0	11.0	0.80	0.3	C	59.2	25	5000	1.0
					Cu	24.0	25	5000	1.0
				0.4	C	68.2	25	5000	1.0
					Cu	27.1	25	5000	1.0
				0.5	C	65.7	25	5000	1.0
					Cu	25.2	25	5000	1.0
				0.65	C	59.0	25	5000	1.0
					Cu	20.9	25	5000	1.0
				0.85	C	57.9	50	10000	1.0
					Cu	17.6	50	10000	1.0
								Subtotal ($x = 0.2$)	39.1
0.4	4.0	6.6	0.31	0.5	C	0.5	50	10000	5.1
					Cu	0.6	50	10000	14.0
0.4	4.0	8.8	0.65	0.5	C	5.8	50	10000	1.0
					Cu	2.2	50	10000	1.3
0.4	4.0	6.6	0.79	0.5	C	20.4	50	10000	1.0
					Cu	7.8	50	10000	1.0
								Subtotal ($x = 0.4$)	23.4
0.5	5.0	6.6	0.30	0.5	C	0.2	50	10000	12.0
					Cu	0.1	50	10000	16.8
0.5	5.0	8.8	0.64	0.5	C	2.5	50	10000	1.1
					Cu	0.9	50	10000	2.9
0.5	5.0	6.6	0.79	0.5	C	8.8	50	10000	1.0
					Cu	3.4	50	10000	1.0
								Subtotal ($x = 0.5$)	35.0
								Total production time	88.1

Table 2: Coincidence rates and times required for each setting for this proposal. Statistical goals and nominal running currents are matched to those from E12-06-104. We assume a minimum run time of 1 hour at each setting on each target, even for those settings that would otherwise require less than an hour.

3.2 Projected Results

Projected results for the measurement of R in semi-inclusive π^+ production from C and Cu are shown in Fig. 6. Projections are generated using the statistics from Tab. 2 and assuming point-to-point systematic uncertainties of 1.6% at each ϵ setting. As noted in the E12-06-104 proposal, point-to-point uncertainties of 1.9% were achieved in the 6 GeV era using the SOS+HMS [12]. Since the SHMS is expected to have superior performance than the SOS (especially with respect to acceptance and magnet saturation effects), improved systematic uncertainties are expected for L-T separations in Hall C during the 12 GeV era.

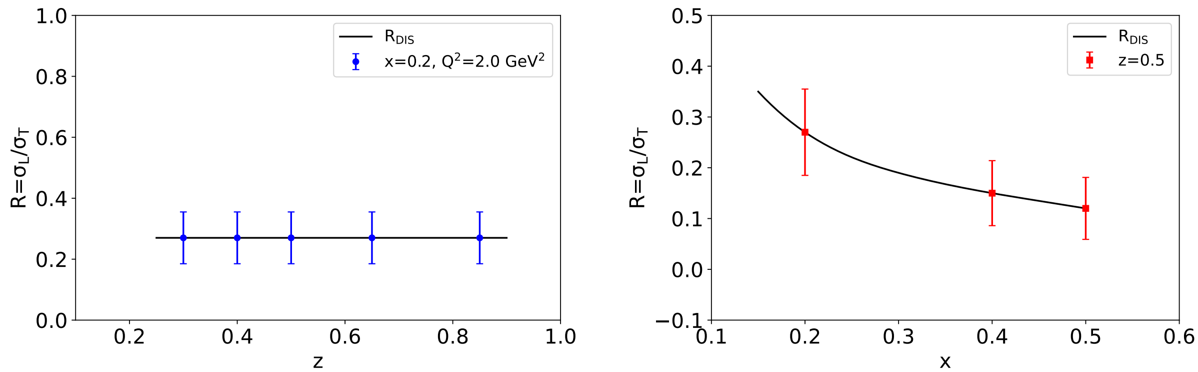

Figure 6: Projected precision for $R = \sigma_L/\sigma_T$ for semi-inclusive π^+ production from C and Cu. The plot on the left shows the expected precision for measurement of R vs. z at fixed (x, Q^2)=(0.2, 2 GeV^2). The plot on the right shows R vs. x for fixed $z = 0.5$. Curves denote the value of R_{DIS} from a global fit to inclusive electron scattering.

While we can compare the value of R in nuclei to that from the proton and deuteron from the measurements of R_A, R_D, and R_H, we can also make use of the technique used in SLAC experiment E140 [5] and that will be used in Hall C experiment E12-14-002 [9], i.e., measurement of the ϵ dependence of the target ratios. This technique is less sensitive to particular classes of systematic uncertainty (in particular, reaction kinematics and acceptance). Based on the experience from recent measurements of the EMC effect in Hall C [13], we expect the point-to-point uncertainty in the target ratios to be on the order of 1%.

The ratio of cross sections between nuclear and hydrogen targets can be expressed,

$$\frac{\sigma_A}{\sigma_H} = \frac{\sigma_A^T}{\sigma_H^T}[1 + \epsilon^{/}(R_A - R_H)], \tag{5}$$

where $\epsilon^{/} = \epsilon/(1 + \epsilon R_H)$. The slope of the line extracted when fitting the target ratios vs. $\epsilon^{/}$ results in the difference $R_A - R_H$. Projections for the precision of the measurement of $R_A - R_H$ are shown in Fig. 7. Uncertainties due to knowledge of R_H are also included. The plot on the right in Fig. 7 also includes the inclusive electron scattering measurements of $R_A - R_D$ from SLAC E140 [5].

4 Summary and Beam Time Request

The total beam time required for these measurements is summarized in Tab. 3. Note that we have not allocated any time for spectrometer configuration changes or beam energy changes since these will be in common with the approved E12-06-104. We have added overhead for the extra target changes that will be required for this experiment. We assume that each target change will take 10 minutes and that 2 target

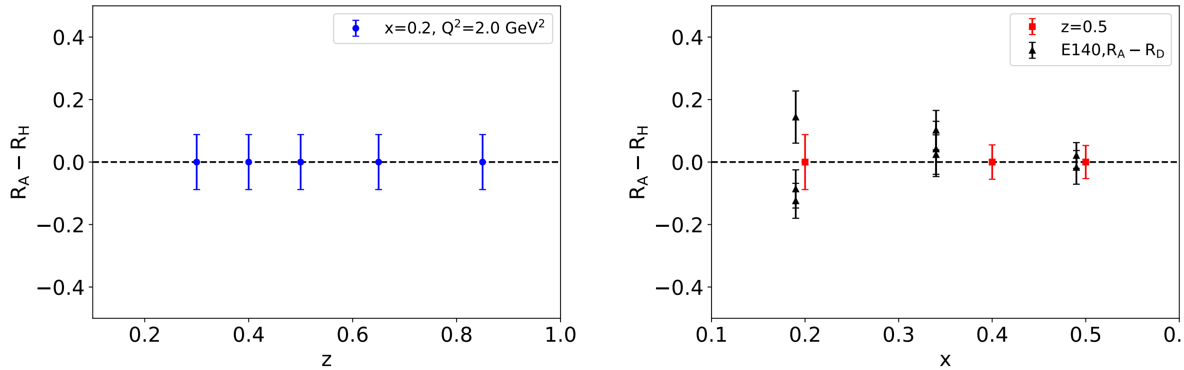

Figure 7: Projected precision for $R_A - R_H$ for semi-inclusive π^+ production from C and Cu compared to hydrogen. $R_A - R_H$ is extracted by fitting the $\epsilon^{/}$ dependence of the target ratios. Points are plotted assuming R has no nuclear dependence. The plot on the right includes the measurements of $R_A - R_D$ from the SLAC E140 experiment [5] made using inclusive electron scattering (points shifted in x for visibility.

Activity	Time (hours)
Production data	97.5
Target changes	7
Total	104.5 (4.4 days)

Table 3: Beam time requested for this experiment.

changes at each of 21 settings will be needed, resulting in a total time of 7 hours. Production data taking will require 37.2 hours for the 3% RL carbon target and 60.3 hours for the 6% RL copper target, resulting in a total time of 104.5 hours.

These measurements of the nuclear dependence of $R = \sigma_L/\sigma_T$ in SIDIS will provide important data that will supplement the interpretation of hadron attenuation measurements. A non-zero nuclear dependence would indicate novel physics that could range from unexpected effects in the initial state or the possible presence of ϵ-dependent backgrounds that have some nuclear dependence (for example, diffractive ρ production).

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