Measurement of Deep Inelastic Scattering from Nuclei with Electron and Positron Beams to Constrain the Impact of Coulomb Corrections in DIS

A Proposal to PAC 51

Spokespersons: N.Fomin, D. Gaskell, W. Henry

May 20, 2023

J. Caylor, S. Covrig, D. Gaskell (spokesperson), W. Henry (spokesperson), D. Jones, D. Mack, M. McCaughan
Thomas Jefferson National Accelerator Facility

B. Duran, N. Fomin (spokesperson), C. Morean
University of Tennessee, Knoxville

P. Markowitz
Florida International University

A. Schmidt
The George Washington University

G. Niuclescu
James Madison University

J. Arrington, T. J. Hague, S. Li, E. Sichtermann
Lawrence Berkeley National Laboratory

M. Elaasar
Southern University at New Orleans

E. Kinney
University of Colorado Boulder G. Huber

University of Regina

Cameron Cotton
University of Virginia

D. Androic
University of Zagreb

N. Kalantarians
Department of Natural Sciences, Virginia Union University

Jefferson Lab Positron Working Group Proposal

Contents

1 Executive Summary

The impact of the acceleration of electrons in the Coulomb field of heavy nuclei has drawn much attention in quasi-elastic electron scattering due in part to its importance in the extraction of the Coulomb Sum Rule. Coulomb Corrections have drawn less attention in Deep Inelastic Scattering (DIS) due to the (usually) higher energies involved. However, it has been shown that Coulomb Corrections could play an important role in measurements of the nuclear dependence of inelastic structure functions (the EMC effect) and more importantly, in measurements of the nuclear dependence of $R = \sigma_L/\sigma_T$. Recent analyses of existing data have demonstrated that the application of Coulomb corrections can result in a value of $R_A - R_D$ different from zero. If confirmed, this nuclear dependence of R has important consequences for our understanding of the EMC effect at large x and our interpretation of data in the anti-shadowing region at moderate x. Measurements with positron and electron beams from large Z nuclei will allow unambiguous determination of the relevance of Coulomb Corrections in DIS and allow detailed comparisons with existing approaches for applying these corrections to experimental data. We request 9.3 days in experimental Hall C, using the standard HMS spectrometer to measure DIS from gold and liquid deuterium targets with positrons. The positron data will be paired with data planned to be taken with electrons as part of E12-14-002 to make direct measurement of Coulomb Corrections in DIS.

2 Introduction and Overview

The distortion of the electron wave function by the electrostatic field of the target nucleus is addressed in the analysis of electron scattering data via the application of Coulomb Corrections. This is a distinct aspect of the data analysis, as these Coulomb effects are not included in the usual radiative effects prescription of, for example, the Mo and Tsai formalism [1, 2]. Coulomb Corrections have drawn much attention in quasielastic electron scattering, especially as they pertain to experiments that attempt to measure the Coulomb Sum Rule [3, 4]. **We propose a measurement with a large Z nucleus and a positron beam, which in combination with electron data, will allow for an unambiguous determination of Coulomb effects in Deep Inelastic Scattering**. A similar comparison [5] of electron and positron scattering data was performed for the quasi-elastic scattering process with great success and was instrumental in testing the efficacy of Coulomb Correction methods.

Formalism Coulomb Corrections[1] aim to address two effects: (1) the acceleration of the electron by the nucleus and (2) the focusing of the electron wave function. Coulomb Corrections are typically applied to experimental data using the Effective Momentum Approximation (EMA). The first effect of Coulomb Corrections is quantified by evaluating a model cross section with shifted values of incoming/outgoing electron momenta (with this shift being determined by the Coulomb potential) and comparing to the model with unshifted kinematics. There was some debate about the appropriate value for the Coulomb potential in the nucleus, whether it should be evaluated at the center of the nucleus or averaged over the volume. Fortunately, in the case of quasielastic scattering, it is possible to perform detailed DWBA calculations and through comparison with these calculations an improved EMA was developed [6, 7, 8]. The improved EMA can be implemented as follows:

- The incoming and outgoing electron momenta (E_e and E'_e) are replaced by their Coulomb-shifted counterparts:
  $E_e \to E_e + \bar{V}$,
  $E'_e \to E'_e + \bar{V}$.
- The effective potential energy experienced by the electrons is given by $\bar{V} = (0.75 - 0.8)V_0$, where V_0 is the potential at the center of the nucleus. The factor $0.75 - 0.8$ is determined through comparison with DWBA calculations and V_0 is given by $V_0 = \frac{3\alpha Z}{R}$, with R the radius of a uniform sphere with charge Z.
- An additional factor (F_i) due to focusing of the incoming electron must also be applied:
  $F_i = \left(1 - \frac{\bar{V}}{E_e}\right)$.

The final model cross section, including the effect of Coulomb acceleration is then

$$\sigma_{CC} = F_i^2 \sigma(E_e + \bar{V}, E_e + \bar{V}). \tag{1}$$

While there is consensus that the improved EMA is appropriate for quasielastic scattering, there is no clear guidance for Deep Inelastic Scattering (DIS). It seems intuitive that acceleration of electrons in the Coulomb field should also play a role in inelastic scattering, yet there has been little study dedicated to this area. SLAC E139 [9] addresses Coulomb Corrections in their measurements of the EMC effect, referring to

[1] It is worth noting that for DIS, Coulomb Corrections are perhaps more appropriately described in terms of multi-photon exchange effects in which the scattering occurs in a collective, or quasi-collective way with multiple nucleons. To date, experiments that attempt to correct for such effects have used the language and methodology of Coulomb Corrections. However, it should be noted that in this proposal, Coulomb Corrections should be taken to refer to multi-photon effects that are present in nuclei, not already incorporated in standard approaches to radiative corrections.

a calculation in [10] to argue that the effect is small. In that reference, the relative contribution of the term including Coulomb field effects compared to the leading order term is given by:

$$\frac{H}{N/Q^2} = -\frac{Z\alpha}{12}\frac{(Q^2)^2}{\nu^2}\frac{p+p'}{pp'}\langle r\rangle, \tag{2}$$

where H is the contribution to the cross section from the nuclear Coulomb field, N/Q^2 is the leading order contribution, p and p' are the initial and final electron momenta and $\langle r\rangle$ is the mean radius of the charge distribution of the nucleus. In the paper, they state "For any reasonable kinematics, this is completely negligible." However, a quick examination of a few kinematic settings at both Jefferson Lab and SLAC suggest that this is not the case. For example, for a gold nucleus at $x = 0.5$, $Q^2 = 4$ GeV^2, at a beam energy of 5.8 GeV (the kinematics of the 6 GeV EMC experiment in Hall C [11]), $\frac{H}{N/Q2} = -0.98$, suggesting that the contribution from Coulomb Corrections is comparable to the leading order contribution. The estimate from this work is clearly inadequate.

In contrast to the above, the authors of Ref. [12] argue that Coulomb effects may indeed be significant and should not be ignored. While there are no quantitative estimates for inclusive DIS, they do calculate significant effects for coherent vector meson production. Coulomb Corrections are also examined in [13], however in this case estimates are made in the context of neutrino scattering. While the prescription developed in [13] is straightforward to calculate, it cannot be directly applied to electron scattering. Nonetheless, in a discussion of comparisons to other approaches, it is stated that this method would likely yield similar results to an EMA-like prescription.

Clearly, there is a dearth of information, both theoretical and experimental, related to Coulomb Corrections in DIS. This raises particular concern since these corrections could impact not only the extraction of DIS cross sections in nuclei, but also the interpretation of the nuclear dependence of inelastic structure functions and the EMC effect, some of the key questions our field is trying to answer.

Areas of Physics Impact The modification of inelastic structure functions in nuclei (the EMC effect) has been the subject of intense experimental and theoretical exploration for nearly 40 years, since its original observation by the European Muon Collaboration [14]. While measurements of the EMC effect at low to moderate x are dominated by experiments with very high energies (EMC, BCDMS, NMC, with beam energies of order 100 GeV) where Coulomb effects are likely to be small, the highest precision measurements of the EMC effect at large x (> 0.3) have been made at SLAC and Jefferson Lab. Both the SLAC E139 and E140 experiments did not apply Coulomb Corrections to their results, but Jefferson Lab experiments have opted to make an estimate of the Coulomb Corrections, using the same improved EMA approach that was benchmarked and tested for quasielastic scattering.

The impact of Coulomb Corrections using the EMA formalism in measurements of the EMC effect can be seen in Fig. 1. In this figure, we show measurements of the per-nucleon cross section ratio, σ_A/σ_D, for gold relative to deuterium from Hall C at 6 GeV [11] and SLAC E139 [9]. The plot on the left shows both data sets with no Coulomb Corrections applied while the plot on the right shows the same data with the application of Coulomb Corrections according to the improved EMA prescription described in [8]. At JLab kinematics, the correction is 3.7% at $x = 0.325$ and increases to 10% at $x = 0.8$. The effect is smaller in the SLAC results due to the higher beam energy, although non-zero, increasing from 0.5% at $x = 0.3$ to 2.4% at $x = 0.8$.

The observation that the Coulomb Correction is smaller for the SLAC data may motivate one to suggest that one can avoid the issue of Coulomb Corrections altogether by making measurements of DIS from nuclei at only high energies. There are a few shortcoming of this proposal, however.

- The smaller Coulomb Correction at higher energy is a consequence of the specific prescription that

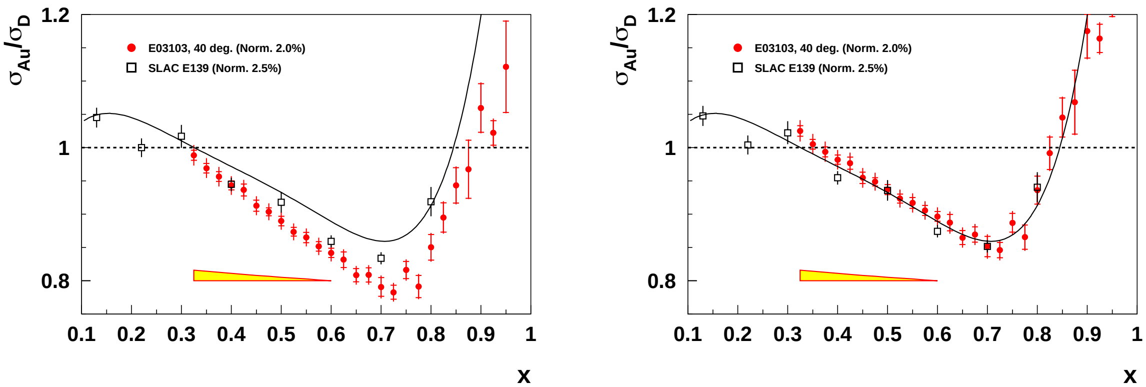

Figure 1: Impact of Coulomb Corrections on EMC Effect measurements from SLAC [9] and JLab Hall C [11]. The plot on the left shows both data sets with no Coulomb Corrections applied, the plot on the right shows the data with Coulomb Corrections applied using the improved EMA. Normalization uncertainties of 2.5% for the SLAC data and 2% for the JLab data are not shown. The yellow band indicates the correlated systematic uncertainty for the JLab results.

has been used to calculate the correction (the improved EMA). It is possible that this prescription is not appropriate for DIS, so should not necessarily be used as a guide for choosing "safe" kinematics.

- Measurements from nuclei at lower energies and Q^2, aimed at probing nuclear effects in the resonance region in particular [15] are of significant interest and will serve as important input to models incorporated in neutrino experiments. Coulomb Corrections must be understood to appropriately analyze these data.
- Measurements of the nuclear dependence of $R = \sigma_L/\sigma_T$ in DIS require a Rosenbluth separation and must unavoidably take data at lower energies for low ϵ kinematics.

This last point is particularly important in that it could have significant impact on our understanding of the nuclear dependence of structure functions and the interpretation of that nuclear dependence in terms of parton distributions in nuclei.

Connection to E12-14-002 A key assumption in many (if not all) measurements of the EMC effect is the identification of the per-nucleon cross section ratio, σ^A/σ^D with the per-nucleon structure function ratio F_2^A/F_2^D. The deviation of these ratios from unity is then taken as modification of PDFs in nuclei. However, the relation between the cross section and structure function ratios is more exactly given by:

$$\frac{\sigma^A}{\sigma^D} = \frac{F_2^A}{F_2^D}\frac{(1+\epsilon R_A)(1+R_D)}{(1+R_A)(1+\epsilon R_D)}, \tag{3}$$

where ϵ is the usual virtual photon polarization and R is the ratio of longitudinal to transverse cross sections, σ_L/σ_T. The cross section ratio is equivalent to the structure function ratio in the case $\epsilon = 1$ or when $R_A = R_D$. It is worth noting that very high energy measurements of the EMC effect (i.e. EMC, NMC) tend to be dominated by kinematics with ϵ close to one, so are not terribly sensitive to possible differences in R_A and R_D. However, it is also true that the structure function F_2 includes contributions from both longitudinal and transverse cross sections:

$$F_2 = \frac{\nu K(\sigma_L + \sigma_T)}{4\pi^2\alpha\left(1 + \frac{Q^2}{4m_p^2 x^2}\right)}. \tag{4}$$

Hence, even at $\epsilon = 1$, the longitudinal cross section could play a role in modification of the F_2 structure function.

Hall C experiment E12-14-002 [16] will make precise measurements of $R_A - R_D$ over a large region of phase space in the DIS region. While there are existing extractions of $R_A - R_D$ or R_A/R_D, several analyses rely on global fits to world data, making particular assumptions about the kinematic dependence of the cross section ratios. Direct extraction via Rosenbluth separation in the DIS region has only been performed by E140 at SLAC [17]. In that experiment, $R_A - R_D$ was extracted by measuring the ϵ dependence of the DIS target ratios:

$$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_A^T}{\sigma_D^T}\left[1 + \frac{\epsilon}{1+\epsilon R_D}(R_A - R_D)\right]. \tag{5}$$

The published results saw no significant evidence of a nuclear dependence in $R_A - R_D$, however the original E140 analysis lacked consideration of possible effects due to Coulomb Corrections. Re-analysis of the E140 data to include Coulomb Corrections, including data from SLAC E139 [9] and the recent results from Hall C in a combined fit showed a difference of $R_A - R_D$ from zero at the level of 1.2 σ [11] (see Fig. 2) at $x = 0.5$. While there are other suggestions that $R_A - R_D$ might differ from zero [18], the Rosenbluth technique is the most direct way to access this quantity.

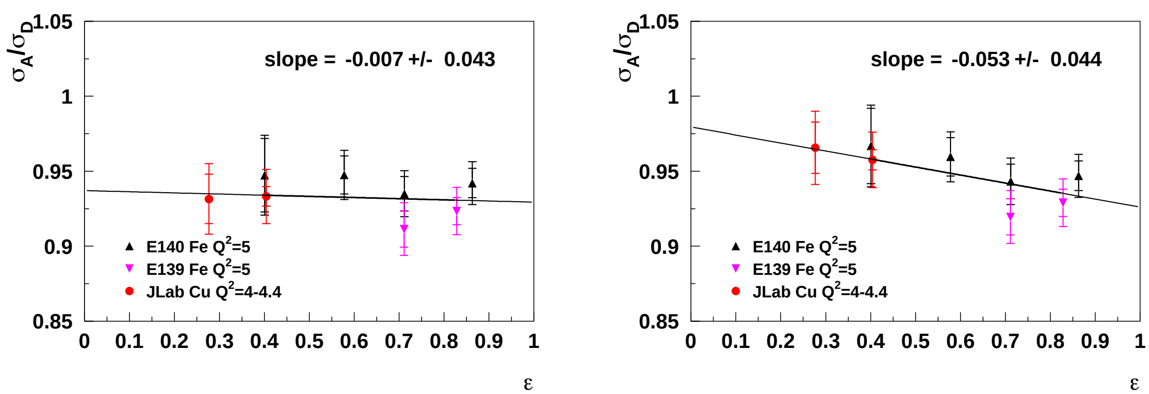

Figure 2: ϵ dependence of the EMC ratio for Fe and Cu targets from SLAC [9, 17] and JLab [11] without (left) and with (right) Coulomb Corrections.

The impact of a possible nuclear dependence of R is described at length in [16] and additionally in [19], but we summarize the main conclusions here:

- A nuclear dependence of R could imply that the small enhancement in the F_2 structure function ratio in the anti-shadowing region could be due to contributions from longitudinal photons, implying that anti-shadowing may be dominated by gluons instead of quarks.
- In addition, a nuclear dependence in R could impact measurements of the nuclear EMC effect at large x. This is especially important for measurements at Jefferson Lab, where $\epsilon < 1$.
- Changes to the EMC effect at large x in turn have implications for the observed correlation between the EMC effect and Short Range Correlations (SRCs), possibly worsening the degree of correlation between the two.

Observation of a nuclear dependence of R would have significant consequences for our understanding of nuclear effects in quark distributions. A state-of-art, measurement of $R_A - R_D$ via the Rosenbluth technique,

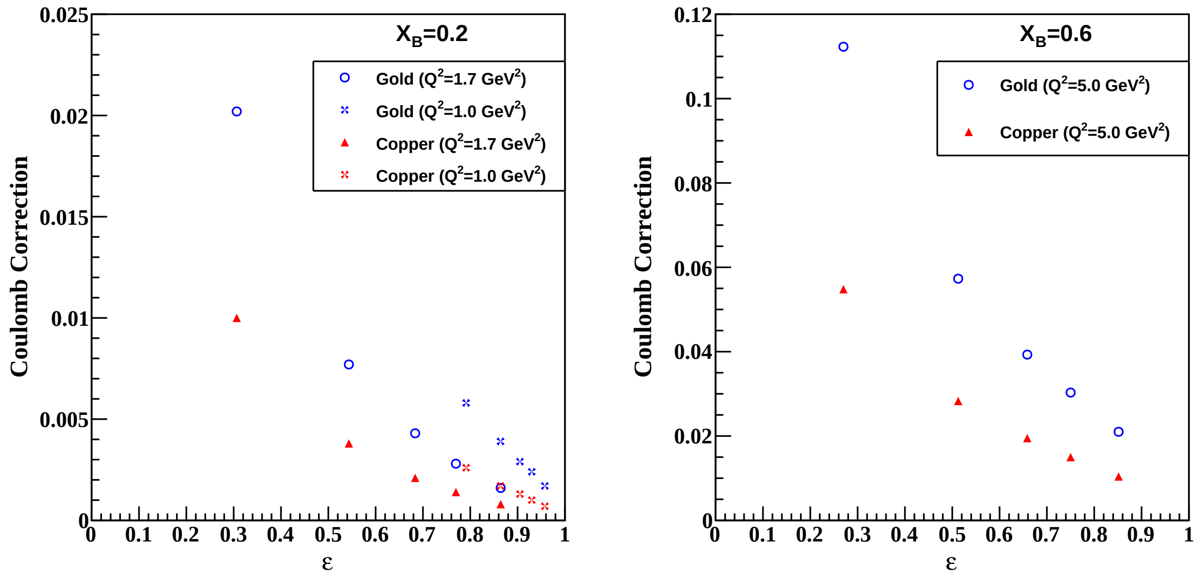

Figure 3: Coulomb Corrections (calculated using the improved EMA) vs. ϵ for a subset of the kinematics in E12-14-002 [16]. The corrections are largest at large x, but even at $x = 0.2$ must be included to obtain accurate measurements of $R_A - R_D$. Since the Coulomb Corrections are highly correlated with ϵ, it is crucial that their accuracy be verified.

as will be performed in E12-14-002 is crucial to make a clear determination of whether R is modified in the nuclear environment. However, as can be seen in Fig.3, Coulomb Corrections are highly correlated with ϵ and therefore introduce possible systematic effects in the measurement of $R_A - R_D$. E12-14-002 will perform dedicated, although indirect, tests of Coulomb Corrections to minimize the uncertainty in the extraction of $R_A - R_D$. **The availability of positrons beams at JLab will, for the first time, allow a direct test of Coulomb Corrections in DIS**.

3 Proposed Measurements and Experimental Details

For this experiment, we intend to measure the cross section ratio of gold to deuterium with positrons at the same kinematics as the ”Coulomb Corrections” test from E12-14-002. The kinematics for this test for E12-14-002 were chosen to give a range of values for the expected Coulomb Correction (as predicted from the improved EMA) for a fixed ϵ setting (to minimize effects due to a possible non-zero $R_A - R_D$) and at fixed x (to eliminate possible changes in the ratio due to the EMC Effect). The value of Q^2 will change between the two settings, but since the EMC Effect has been observed to display minimal Q^2 dependence at large x [11] any change in σ_A/σ_D must be due to Coulomb corrections.

The results from the E12-14-002 Coulomb Corrections test can be directly compared to measurements made with positron beams to give unambiguous information about the size of Coulomb Corrections in DIS from nuclei and test prescriptions used to estimate these corrections. Note that any additional effects (that do not depend on the charge of the nucleus Z) that may impact the absolute cross sections and might be different for positrons and electrons should cancel when taking the target ratios at fixed beam charge. For example, the small asymmetry between electrons and positrons that arises at the nucleon level due to the C_{3q} coupling in the neutral current effective Lagrangian should cancel in the σ_A/σ_D ratio.

3.1 Kinematics and Rate Estimates

The rates for the Coulomb Correction test for E12-14-002 were estimated using a 4 cm LD2 target and 2% radiation length gold target. Since the maximum available current for positron beams is expected to be significantly lower, we assume a 10 cm LD2 target and 6% RL gold target, to partially offset the loss of rate. The use of thicker targets will result in changes to the expected charge symmetric background and radiative corrections as compared to E12-14-002. Since a key part of this experiment is to compare the measurements using positron beams to those from E12-14-002 using electrons, it is important to understand the differences between the running conditions on these corrections. Measurements will be made using the High Momentum Spectrometer in Hall C. Since the SHMS is not required, this measurement is compatible with the installation of the NPS (which precludes use of the SHMS) required for conditionally approved experiment C12-20-012 (Deeply Virtual Compton Scattering using a positron beam in Hall C).

The rates and time estimates are shown in Table 1. Assuming a beam current of 1 μA, the beam time required for 50k electrons from LD2 and 25k electrons for gold is 160 hours, or 6.7 days at 100% efficiency. Note that additional time will be required for measurements of the LD2 cell wall backgrounds (about 20% of the LD2 run time) as well as time for measurement of the charge symmetric backgrounds.

ϵ	Q^2 (GeV^2)	E (GeV)	E'(GeV)	θ(deg.)	$C_{Coulomb}$	R_D (Hz)	T_D(h)	R_{Au} (Hz)	T_{Au} (h)
0.2	3.48	4.4	0.69	64.6	11.6%	0.95	14.6	0.2	33.9
0.2	9.03	11.0	1.38	45.5	6.2%	0.44	31.8	0.1	77.2
0.7	2.15	4.4	2.11	27.9	3.5%	54.6	0.3	11.2	0.6
0.7	5.79	11.0	4.83	19.0	1.9%	27.6	0.5	5.7	1.2

Table 1: Proposed kinematics for this experiment. These measurements will be made at the same kinematics as the Coulomb Corrections test from experiment E12-14-002. The kinematics are chosen to sample a range of Coulomb Correction factors at large and small ϵ. Rates are calculated assuming 1 μA on a 10 cm LD2 target and 6% radiation length gold target.

3.2 Charge-symmetric background

As noted above, some time will be required to make measurements of the charge-symmetric backgrounds (CSB) to electron scattering. These process are dominated by π^0 photoproduction and subsequent decay to higher energy photons which then convert to e^+e^- pairs. This process depends on the detailed geometry (radiation length) of the target, so although the background will be measured at the same kinematics during experiment E12-14-002, we must repeat these measurements for this experiment since we are using thicker targets. Measurement of the charge symmetric background will be made by changing the HMS polarity from positive (to detect scattered positrons) to negative (to detect electrons coming from π^0 photoproduction). Table 2 shows the estimated fractional contribution to the total rate from charge symmetric backgrounds for this experiment, as well as those predicted for E12-14-002. Note that the relative contributions for E12-14-002 are smaller due to the shorter targets. These rates are estimated from the Wiser parameterization of pion photoproduction [20]. The amount of beam time devoted to measuring the contribution from charge symmetric backgrounds will be equal to the predicted CSB fraction for that setting.

3.3 Radiative Corrections

The use of thicker targets (as compared to E12-14-002) for this experiment could result in differences in the radiative corrections, leading to additional systematic uncertainties when comparing the positron data from this experiment to the electron data from E12-14-002. Fortunately, the planned measurements are made at

ϵ	Q^2 (GeV^2)	E (GeV)	Target	Charge symmetric background	
				This experiment	E12-14-002
0.2	3.48	4.4	LD2	0.20	0.11
0.2	9.03	11.0	LD2	0.05	0.04
0.2	3.48	4.4	Au	0.48	0.18
0.2	9.03	11.0	Au	0.24	0.08
0.7	2.15	4.4	LD2	0.0	0.0
0.7	5.79	11.0	LD2	0.0	0.0
0.7	2.15	4.4	Au	0.0	0.0
0.7	5.79	11.0	Au	0.0	0.0

Table 2: Estimates of the relative contribution of charge symmetric processes $Y_{CSB}/(Y_e + Y_{CSB})$ for this experiment and estimates for experiment E12-14-002. Additional beam time will be allocated to measure these charge symmetric backgrounds.

rather large x, so the contribution from radiative tails from quasi-elastic and other inelastic processes is not too large.

The approach to radiative corrections for inclusive cross sections has more or less been standardized in Hall A and C measurements during the 6 GeV era, making use of the methods described by Mo and Tsai [1, 2]. For many experiments with a limited kinematic range at high x, the energy peaking approximation is adequate. However, for this measurement, the full 2-D integrals will need to be calculated as the energy peaking approximation is insufficient for thick targets at low x. This is significantly more computationally intensive, but is not a challenge with modern improved computing infrastructure at JLab. In this prescription, originally adopted and described in detail by Dasu [17], a complete calculation of external effects is done. For this reason, the program is nicknamed ”externals”. External corrections are calculated for radiative interactions that occur throughout the target and with materials before and after the target, including air, aluminum entrance/exit target windows, mylar and kevlar windows of the magnets, while internal corrections are included using the equivalent radiator approximation. Note that there are beam-charge dependent contributions to the radiative corrections that involve the emission of photons from the hadron or quarks, but these contributions will cancel in the target ratios since the nuclear cross section is predominately an incoherent sum of nucleon cross sections.

In Table 3, we compare the radiative correction factors ($\sigma_{Born}/\sigma_{radiated}$) for this experiment (which uses a 10 cm LD2 target and 6% RL gold target) to those from E12-14-002[2] (which will use a 4 cm LD2 target and a 2% RL gold target). Overall, the radiative correction factors are rather similar, with the largest differences appearing in the calculations for gold at large ϵ. Due to this difference we assign a slightly larger systematic uncertainty to the radiative correction for the positron σ_{Au}/σ_D ratios (to be described later).

3.4 Systematic Uncertainties

The systematic uncertainties for this experiment are expected to be similar to those from other cross section ratio experiments. Table 4 shows the expected uncertainties in the σ_A/σ_D cross section ratios, based on the values obtained during the 2018 running from E12-10-008 (a measurement of the EMC effect) [21]. There are a few a sources of uncertainty that merit discussion since the measurements from this experiment will be compared to those from E12-14-002, and there are some non-trivial differences in the running conditions between the two experiments.

[2]Note that these RC factors are different from those appearing in the E12-14-002 proposal due to a different convention in defining the correction, and use of an updated model in the radiative corrections program.

ϵ	Q^2 (GeV^2)	E (GeV)	Target	Radiative Correction	
				This experiment	E12-14-002
0.2	3.48	4.4	LD2	0.85	0.86
0.2	9.03	11.0	LD2	0.90	0.90
0.2	3.48	4.4	Au	0.88	0.88
0.2	9.03	11.0	Au	0.92	0.92
0.7	2.15	4.4	LD2	1.05	1.04
0.7	5.79	11.0	LD2	1.08	1.06
0.7	2.15	4.4	Au	1.10	1.05
0.7	5.79	11.0	Au	1.18	1.10

Table 3: Radiative correction factors for this experiment and E12-14-002 calculated using the "externals" program commonly employed for inclusive electron scattering experiments in Halls A and C at JLab. There are some differences due to the thicker targets that will be used for this experiment as compared to E12-14-002.

- Beam current measurement: Since this experiment will run at lower beam currents than are typically used in Hall C (1 μA), the large noise contribution from the Unser monitor (used to provide the absolute calibration of the resonating current monitor cavities) means that the BCM cavities must be calibrated using an alternate technique. In the past, low current BCM calibrations in Hall C have been carried out using the Faraday Cup in the injector. We will do the same for this experiment. Also, since we will be measuring the cross section ratio, we are less sensitive to the absolute calibration of the BCMs and are most sensitive to the time dependence of the BCM response - this can be checked by taking multiple calibration measurements. We assume a point-to-point systematic uncertainty of 0.35% due to the BCM calibration based on the observed time variation in 2018, although it is possible this may be smaller for this experiment.

- Target thickness: If data with both the electron and positron beams were taken in the same run period using the same targets, contributions from the absolute target thickness to the comparison of the electron and positron beam data sets would totally cancel. Since the two data sets will be taken at different time periods and with different target cells and lengths, the absolute target thickness uncertainty must be included when comparing the electron and positron data. The uncertainty in the gold to deuterium ratio from this contribution is estimated to be 1.21%.

- Radiative corrections: Since this experiment will use a larger radiation length solid Au target (6%) than E12-14-002 (2%), the systematic uncertainty in the target ratios will be larger. Taking as guidance the results from Hall C 6 GeV experiment E03-103 (which also used 6% RL targets) we assign a scale uncertainty of 1% to the target ratio (due primarily to the difference in RL between the gold and LD2 targets), and 0.5% point-to-point uncertainty based primarily on the model cross sections used in the radiative corrections. The corresponding scale uncertainty for the E12-14-002 data will be smaller since the radiation lengths of the gold and LD2 targets will be more similar.

- Charge symmetric backgrounds: Since the charge symmetric backgrounds will be significant in some cases, we assign a larger uncertainty from this contribution than was assigned in the analysis of the 2018 Hall C data. In that case, a point-to-point uncertainty of 0.13% was assigned based on the uncertainties inherent in a polynomial fit to the measured background (which was on the order of 4% for the 2018 data). Based on these results, and scaling it by the expected backgrounds for this experiment, we expect that the uncertainty in the charge symmetric background should be at most 1% - smaller in most cases.

Source	$\delta R/R$ (%) point-to-point	$\delta R/R$ (%) scale
Spectrometer momentum	-	$< 0.1\%$
Beam energy	-	$< 0.1\%$
θ_{spec}	-	$< 0.1\%$
Charge	0.35%	-
Target Boiling	-	$< 0.1\%$
Total dead time	0.15%	0.14%
Detector efficiency	0.11%	-
Charge Symmetric Background	0-1%	-
Radiative Corrections	0.55%	1.0%
Acceptance	0.5%	0.5%
LD2 wall subtraction	-	0.5%
LD2 target thickness	-	0.6%
Au target thickness	-	1.0%
Total	0.84-1.3%	1.71%

Table 4: Projected systematic uncertainties for this experiment. Uncertainties are broken into point-to-point and overall scale contributions. Uncertainties are based on those achieved for EMC ratio data taken in Hall C in 2018 as described in the text, with some modifications to account for the different running conditions.

4 Summary and Beam Time Request

Activity	Time (hours)
Production data	159.9
Charge symmetric backgrounds	39.3
Target cell walls	9.1
Pass change	8
Kinematics and target changes	7
Total	223.3 (9.3 days)

Table 5: Beam time requested for this experiment.

The total time requested for this experiment is summarized in Table 5. The required time for production data taking is summarized in Tab. 1 and the time needed for measurement of the target cell wall backgrounds is taken to be 20% of the production time on LD2. The beam time requested for measurement of charge symmetric backgrounds is determined by the expected size of the background (see Sec. 3.2). One pass change will be required (between 5 and 2 pass) for which we have allocated one shift. We assume one hour is required for each HMS kinematic change (4 momentum/angle settings)) and 15 minutes for each target change (3 targets at each HMS setting). The total time requested is 9.3 days. Note that a key assumption in this proposal is that data from the Coulomb Correction test planned for E12-14-002 will be available for comparison with the positron data taking proposed here. If it is not available, then about one extra day (not including the time required to switch from positron beam to electron beam) will be required.

The projections for this experiment are summarized in Figures 4, 5, and 6. Figures 4 and 5 show the DIS per-nucleon cross section target ratios for σ_A/σ_D for electrons and positrons with no corrections applied for Coulomb effects. All measurements will be made at $x = 0.5$, where the EMC effect is expected to be ≈ 0.89 (based on the A-dependent parameterization from [9]). Effects due to Coulomb acceleration are expected to

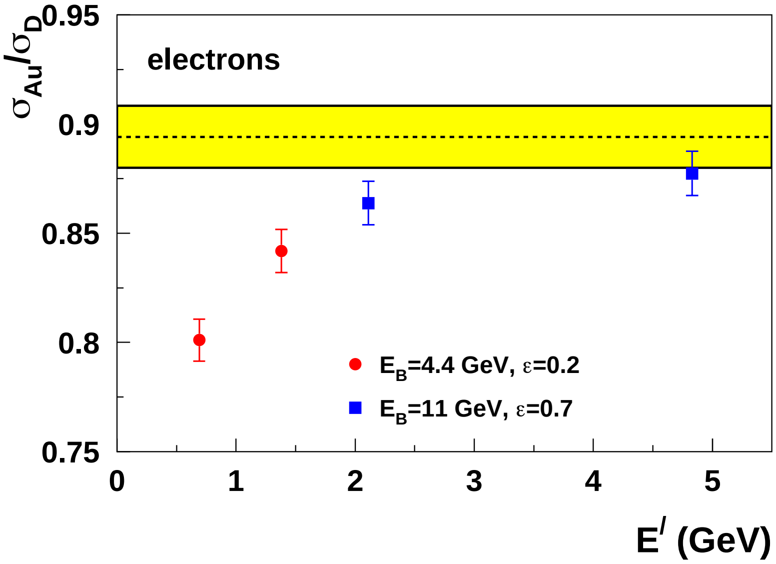

Figure 4: Cross section ratio for σ_{Au}/σ_D at $x = 0.5$ for the low (circles) and high (squares) ϵ settings of the Coulomb Corrections test from E12-14-002. Plotted ratios assume that Coulomb acceleration will modify the nominal ratio according to the improved EMA. Error bars are statistical and point-to-point systematic uncertainties added in quadrature. The dashed line denotes the value of the EMC effect on gold at $x = 0.5$, and the width of the yellow band indicates the size of the 1.6% normalization uncertainty in the measured ratios. We assume these data will be available from earlier running of E12-14-002.

reduce the measured cross section for electrons (Fig. 4) and increase the measured cross section for positrons (Fig. 5). As described earlier, the low ϵ data should have larger effects due to Coulomb acceleration, while effects in the larger ϵ data are expected to be a few percent. The electron beam measurements will be made as part of the E12-14-002 running. Note that if there is the possibility to take electron data during the same run period, this would be advantageous with respect to systematic uncertainties and would take very little beam time (scaling from Table VI from the E12-14-002 proposal [16], about 5 hours of beam on target time and another 15 hours for kinematics and pass changes).

Assuming that the positron beam measurements are made at the same beam energy, we can then make a direct comparison of of the positron and electron target ratios:

$$R = \frac{\left(\frac{\sigma_{Au}}{\sigma_D}\right)^{e^+}}{\left(\frac{\sigma_{Au}}{\sigma_D}\right)^{e^-}}. \tag{6}$$

Taking the double-ratio allows the cancellation of possible time-dependent systematics as well as reducing the sensitivity to small differences in the beam energy since the change in the EMC effect should be very small with changing beam energy. Projections for the double-ratio are shown in Fig. 6. Assuming that effects due to Coulomb acceleration can be described using the improved EMA, this experiment, combined with the data from E12-14-002, will provide evidence for the need for Coulomb Corrections in DIS with a great degree of confidence. In addition, the measurements will be of sufficient precision to quantitatively test alternate descriptions if the EMA turns out to not describe Coulomb effects adequately.

Figure 7 shows the impact on the double-ratio if the electron data were taken during the same run period

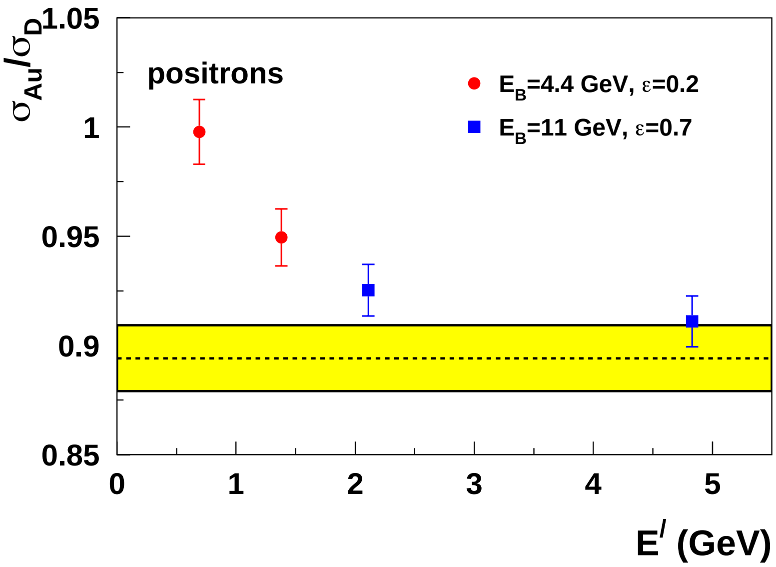

Figure 5: Cross section ratio for σ_{Au}/σ_D at $x = 0.5$ for the low (circles) and high (squares) ϵ settings of this proposal. Plotted ratios assume that Coulomb acceleration will modify the nominal ratio according to the improved EMA. Error bars are statistical and point-to-point systematic uncertainties added in quadrature. The dashed line denotes the value of the EMC effect on gold at $x = 0.5$, and the width of the yellow band indicates the size of the 1.7% normalization uncertainty in the measured ratios.

as the positron data. In this case, the target thickness systematic uncertainties totally cancel, and other target-related systematics (like radiative corrections) are reduced.

In summary, we request 9.3 days with an unpolarized positron beam at a current of 1 μA in Hall C to make measurements that will provide information about the existence and size of Coulomb Corrections in Deep Inelastic Scattering. If electron running is also possible with the same setup, then the systematic errors of the measurements will be reduced and about one extra day (not including time to switch from positrons to electrons) will be needed to take the required electron data. This experiment requires use of only the High Momentum Spectrometer so could be scheduled to run in the same run period as the conditionally approved experiment C12-20-012 (Deeply Virtual Compton Scattering using a positron beam in Hall C). This experiment should be straightforward to execute, with only modest systematic uncertainty requirements.

Coulomb Corrections represent a poorly constrained correction to DIS cross section and cross section ratio measurements. While there is clear theoretical guidance for quasi-elastic scattering from nuclei, the situation is much less clear for DIS. Correct application of Coulomb Corrections is important for measurements of the EMC Effect and measurements of $\Delta R = R_A - R_D$ are particularly sensitive to Coulomb Corrections since these corrections are correlated with beam energy and scattered electron momentum and directly impact the perceived ϵ dependence of the cross section. Application of Coulomb Corrections using the improved EMA to existing data suggests a non-zero value of ΔR, which could have significant implications for our interpretation of data aimed at measuring the EMC Effect. The existence of a positron beam at Jefferson Lab provides a unique opportunity to fully constrain this correction, which is vital to properly analyzing DIS from nuclear targets.

While this experiment has focused on Coulomb Corrections in inclusive DIS, it is important to note that

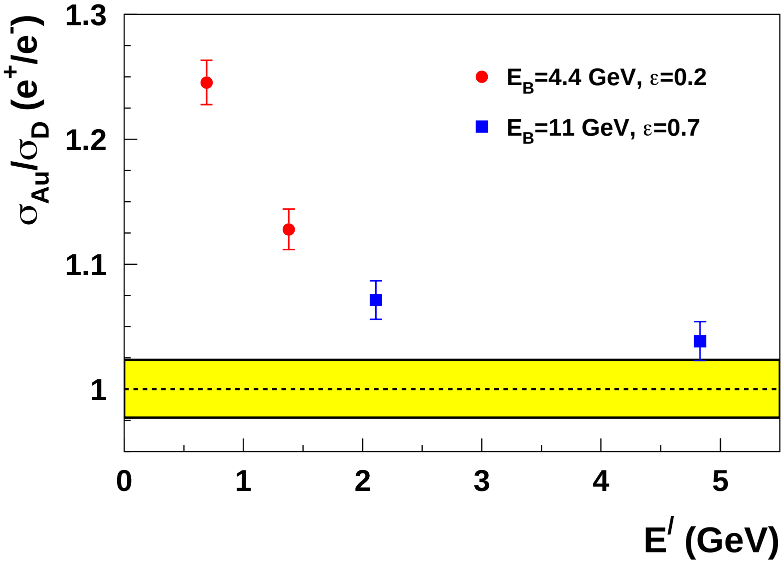

Figure 6: Double-ratio, $(\sigma_{Au}/\sigma_D)^{e^+}/(\sigma_{Au}/\sigma_D)^{e^-}$, as measured using positron and electron beams. In the absence of Coulomb acceleration the double-ratio should be 1.0. Error bars are statistical and point-to-point systematic uncertainties added in quadrature. The width of the yellow band at 1.0 indicates the 2.3% normalization uncertainty in the measurement of the double-ratio. Any measured deviation of the double ratio from 1.0 is a clear indication of the presence of Coulomb effects.

the results of this experiment could have implications for other measurements, for example in the analysis of SIDIS cross sections from nuclei to study hadronization effects, and in experiments that measure cross sections at $x > 1$ and very large Q^2 (to make measurements of so-called ”superfast quarks”), where inelastic processes compete with the quasielastic cross section.

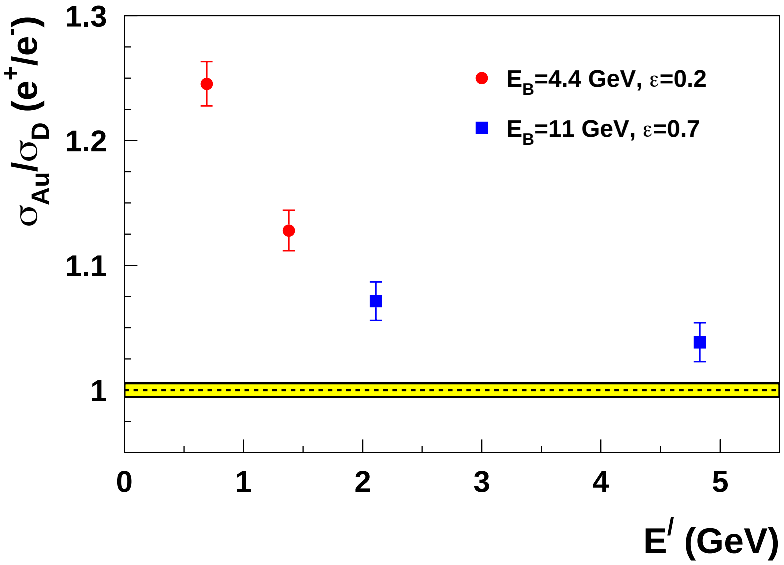

Figure 7: Double-ratio, $(\sigma_{Au}/\sigma_D)^{e^+}/(\sigma_{Au}/\sigma_D)^{e^-}$, as measured using positron and electron beams. In this case, we assume that the positron and electron data are taken during the same run period (using the same targets) resulting in a reduction of the normalization uncertainty to about 0.5%.

References

[1] Luke W. Mo and Yung-Su Tsai. Radiative Corrections to Elastic and Inelastic e p and mu p Scattering. *Rev. Mod. Phys.*, 41:205–235, 1969.

[2] Yung-Su Tsai. RADIATIVE CORRECTIONS TO ELECTRON SCATTERINGS. 1 1971.

[3] S Choi, J P Chen, and Z E Meziani. Precision Measurement of Longitudinal and Transverse Response Functions of Quasi-Elastic Electron Scattering in the Momentum Transfer Range 0.55 GeV/c ¡ q ¡ 0.9 GeV/c, 2005.

[4] J. Morgenstern and Z. E. Meziani. Is the Coulomb sum rule violated in nuclei? *Phys. Lett. B*, 515:269–275, 2001.

[5] P. Gueye et al. Coulomb distortion measurements by comparing electron and positron quasielastic scattering off C-12 and Pb-208. *Phys. Rev. C*, 60:044308, 1999.

[6] Andreas Aste and Jurg Jourdan. Improved effective momentum approximation for quasielastic (e,e-prime) scattering off highly charged nuclei. *EPL*, 67:753–759, 2004.

[7] Andreas Aste, Cyrill von Arx, and Dirk Trautmann. Coulomb distortion of relativistic electrons in the nuclear electrostatic field. *Eur. Phys. J. A*, 26:167–178, 2005.

[8] Andreas W. Aste. Coulomb distortion effects in quasi-elastic (e,e') scattering on heavy nuclei. *Nucl. Phys. A*, 806:191–215, 2008.

[9] J. Gomez et al. Measurement of the A-dependence of deep inelastic electron scattering. *Phys. Rev. D*, 49:4348, 1994.

[10] E. Calva-Tellez and D. R. Yennie. Coulomb Corrections to Deep Inelastic Electron or Muon Scattering From Nuclei. *Phys. Rev. D*, 20:105, 1979.

[11] J. Arrington et al. Measurement of the EMC effect in light and heavy nuclei. *Phys. Rev. C*, 104(6):065203, 2021.

[12] B. Z. Kopeliovich, A. V. Tarasov, and O. O. Voskresenskaya. Long range Coulomb forces in DIS: Missed radiative corrections? *Eur. Phys. J. A*, 11:345–356, 2001.

[13] O. Nachtmann. Final-state coulomb corrections to neutrino reactions. *Nucl. Phys. B*, 18:112–124, 1970.

[14] J. J. Aubert et al. The ratio of the nucleon structure functions $F2_n$ for iron and deuterium. *Phys. Lett. B*, 123:275, 1983.

[15] A Bodek and C Keppel. E04-001: Measurements of F_2 and R on Nuclear Targets in the Nucleon Resonance Region, 2004.

[16] S Malace, M E Christy, D Gaskell, C Keppel, P Solvignon, and H Szumilla-Vance. E12-14-002: Precision Measurements and Studies of a Possible Nuclear Dependence of R, 2014.

[17] S. Dasu et al. Measurement of kinematic and nuclear dependence of R = sigma-L / sigma-t in deep inelastic electron scattering. *Phys. Rev. D*, 49:5641–5670, 1994.

[18] M. Arneodo et al. The Q**2 dependence of the structure function ratio F2 Sn / F2 C and the difference R Sn - R C in deep inelastic muon scattering. *Nucl. Phys. B*, 481:23–39, 1996.

[19] Vadim Guzey, Lingyan Zhu, Cynthia E. Keppel, M. Eric Christy, Dave Gaskell, Patricia Solvignon, and Alberto Accardi. Impact of nuclear dependence of $R = \sigma_L/\sigma_T$ on antishadowing in nuclear structure functions. *Phys. Rev. C*, 86:045201, 2012.

[20] D. E. Wiser. Ph.D Thesis, University of Wisconsin-Madison, 1977.

[21] A. Karki. Ph.D Thesis, Mississippi State University, 2022.