PR12+23-003: Measurement of Deep Inelastic Scattering from Nuclei with Electron and Positron Beams to Constrain the Impact of Coulomb Corrections in DIS

Proposal to PAC 51

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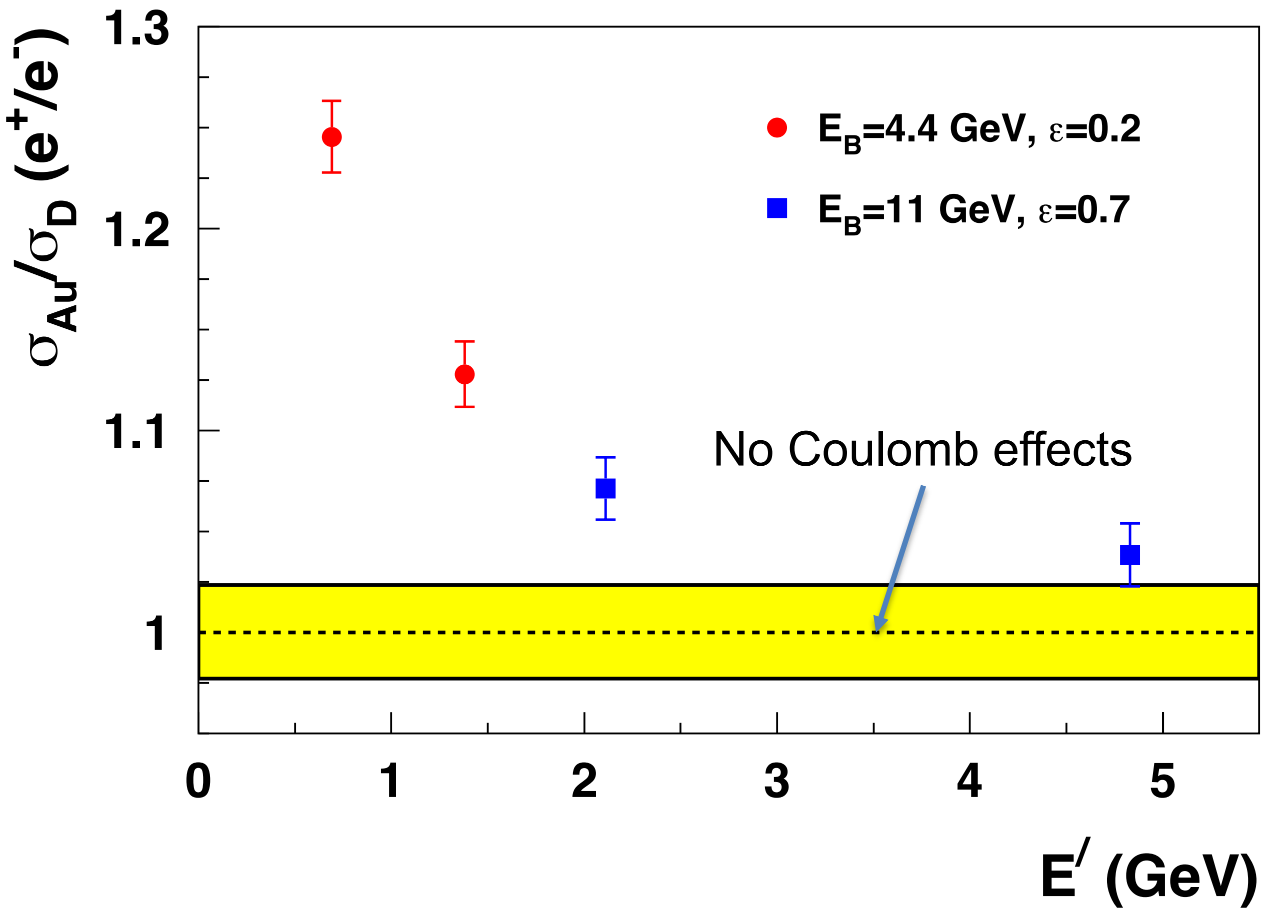
Jefferson Lab Positron Working Group Proposal

PR12+23-003: Coulomb Corrections in DIS

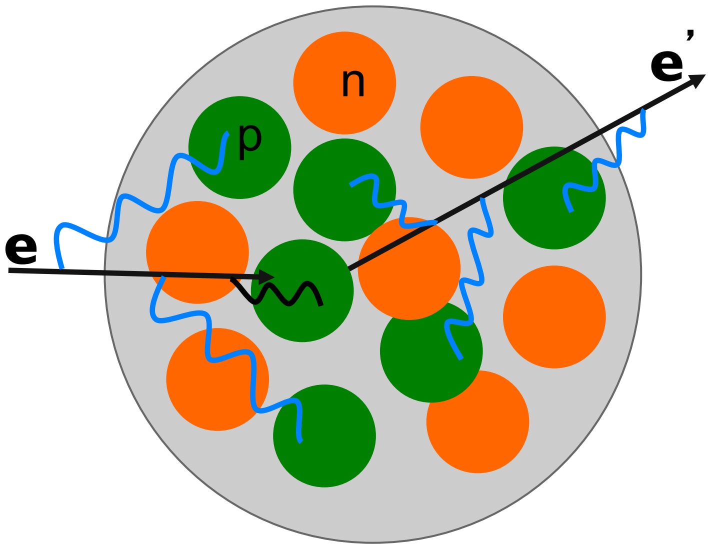
Goal: Directly measure the impact of Coulomb acceleration in heavy nuclei in DIS
→ Well-known effect in QE scattering
→ Little theoretical guidance for DIS
→ Potential impact on measurements of the EMC effect and nuclear dependence of $R=\sigma_L/\sigma_T$

Experiment: Measure cross section ratios for Au/D at with positron beam at 2 beam energies
→ Make direct comparison with electron data from E12-14-002



Beam time request: 9.3 days

Coulomb Distortion in Heavy Nuclei



Electrons scattering from nuclei can be accelerated/decelerated in the Coulomb field of the nucleus

→ This effect is in general **NOT** included in most radiative corrections procedures

→ *Note: Coulomb Corrections are perhaps more appropriately described in terms of multi-photon exchange, but Coulomb Corrections provide convenient shorthand*

- Well-known effect in QE scattering - relevant particularly for Coulomb sum rule
- Can be calculated in QE using DWBA → experimentalists use Effective Momentum Approximation (EMA) to apply corrections to data
- Recent efforts in comparing EMA with detailed DWBA calculations → "improved EMA"

$$E_e \to E_e + V_0 \qquad E_e' \to E_e' + V_0 \quad \text{with “focusing factor”} \; F^2 = (1+V_0/E_e)^2$$

$$V_0 \to (0.7\text{-}0.8)V_0, \quad V_0 = 3\alpha(Z-1)/2R$$

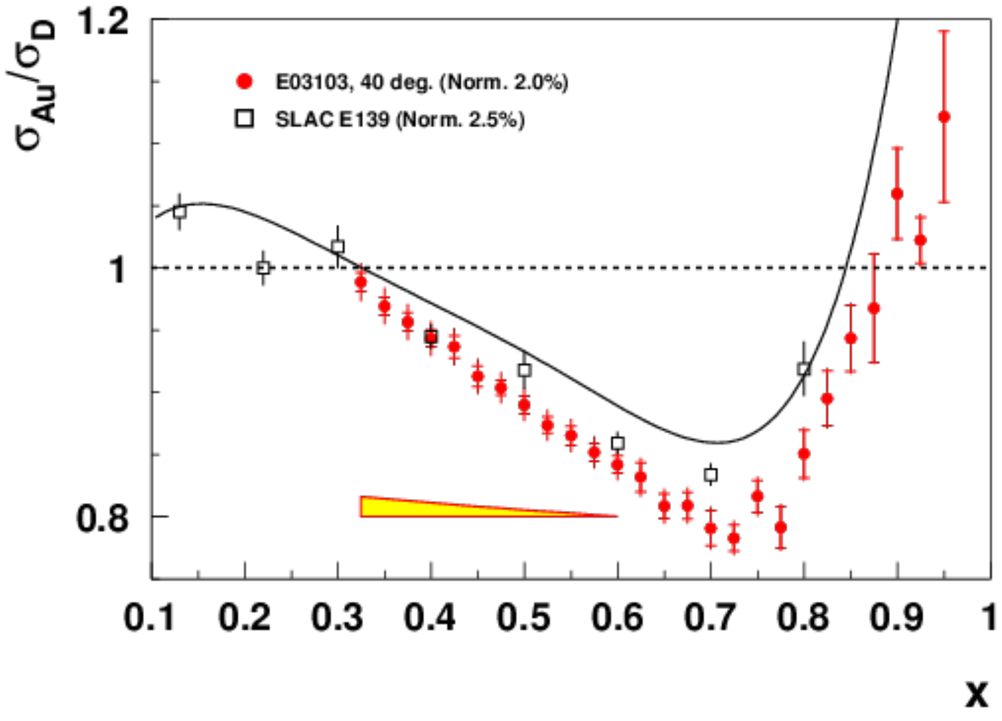
[Aste et al, Nucl. Phys. A, 806:191-215 (2008) Eur.Phys.J.A26:167-178,2005, Europhys.Lett.67:753-759,2004]

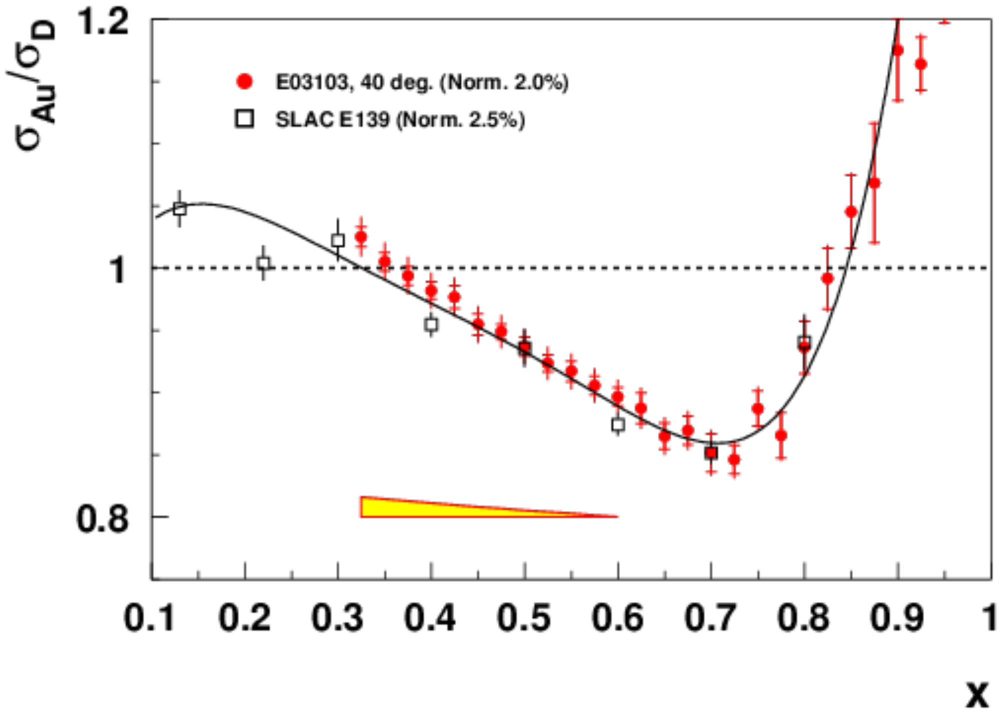
Coulomb Corrections in Inelastic Scattering

- E. Calva-Tellez and D.R. Yennie, Phys. Rev. D 20, 105 (1979)
  - Perturbative expansion in powers of strength of Coulomb field
  - Effect of order → $-\frac{Z\alpha}{12}\frac{(Q^2)^2}{\nu^2}\frac{(E_e+E_e')}{E_eE_e'} < r >$
  - "For any reasonable kinematics, this is completely negligible" → plugging in JLab/SLAC kinematics, this is not true!
- B. Kopeliovich et al., Eur. Phys. J. A 11, 345 (2001)
  - Estimates non-zero effect using Eikonal approximation → applies estimates to vector meson production, not DIS
- O. Nachtmann, Nucl. Phys. B 18, 112 (1970)
  - Coulomb Corrections for neutrino reactions
  - DWBA calculation that results in modifications to structure functions → "at most 5%" effects for energies > 1 GeV
  - Final state particle only, not directly applicable to electron/positron scattering

Impact of CC in DIS: EMC Effect

σ_A/σ_D for Gold (A=197, Z=79)





No Coulomb Corrections applied

With Coulomb Corrections

<u>JLab E03-103</u>
E_e ~ 6 GeV
E_e' ~1-2 GeV

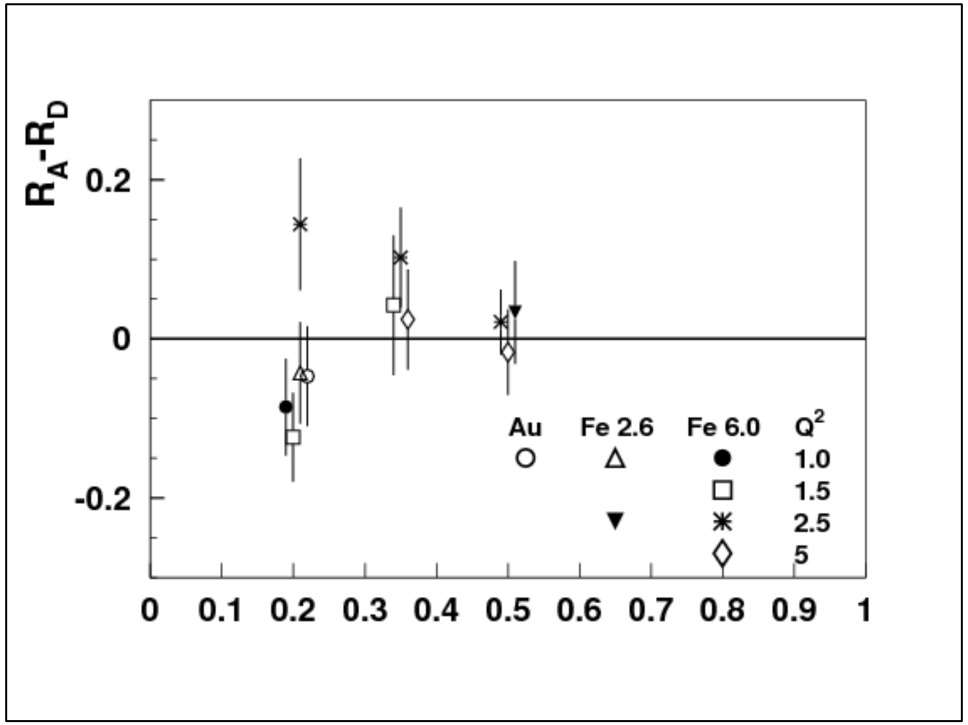
<u>SLAC E-139</u>
E_e ~ 8-25 GeV
E_e' ~4-8 GeV

Coulomb corrections larger for JLab data (5-10%), but still relevant for SLAC (few %)

Impact of CC in DIS: Nuclear Dependence of R

Nuclear dependence of $R=\sigma_L/\sigma_T$ can be extracted via measurement of ε dependence of σ_A/σ_D

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



[E140 Phys. Rev. D 49 5641 (1993)]

This method was used for SLAC E140

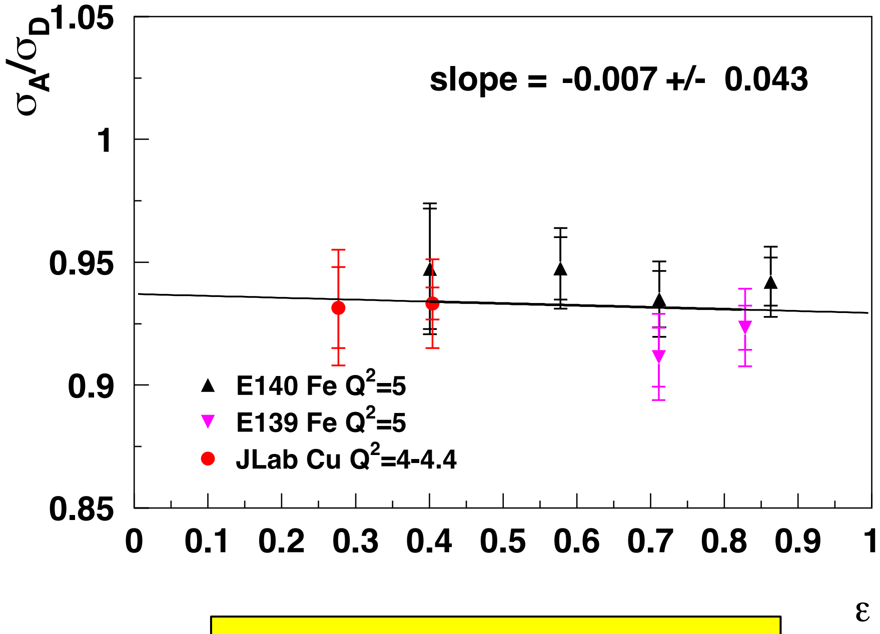
x=0.2, 0.35, 0.5
Q^2 = *1.0, 1.5, 2.5, 5.0* GeV²
Iron and Gold targets

$R_A - R_D$ consistent with zero within errors

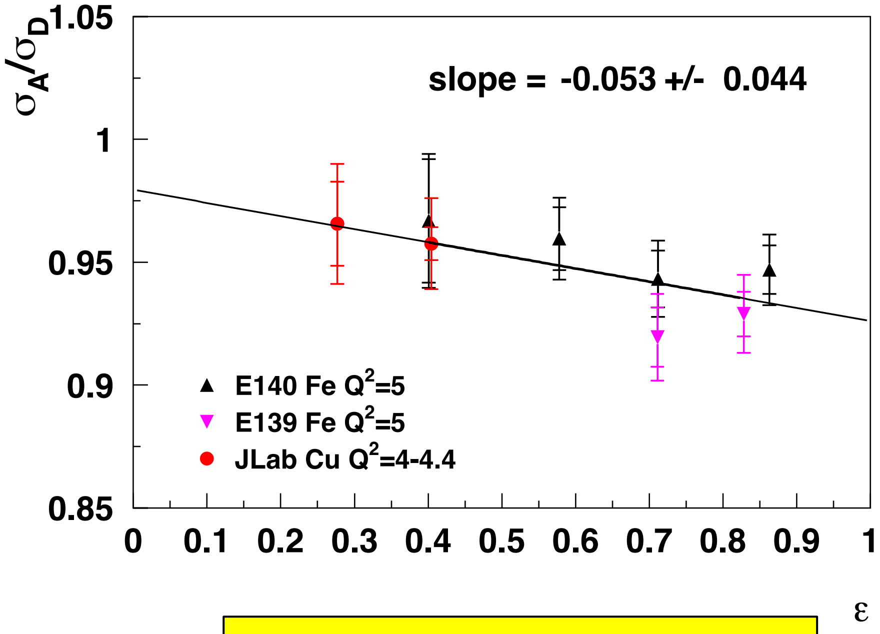
No Coulomb corrections were applied

Large ε data: E_e ~ *6-15* GeV E_e' ~ *3.6-8* GeV
Low ε data: E_e ~ *3.7-10* GeV **E_e' ~ 1-2.6 GeV**

Impact of CC in DIS: Nuclear Dependence of R



No Coulomb Corrections



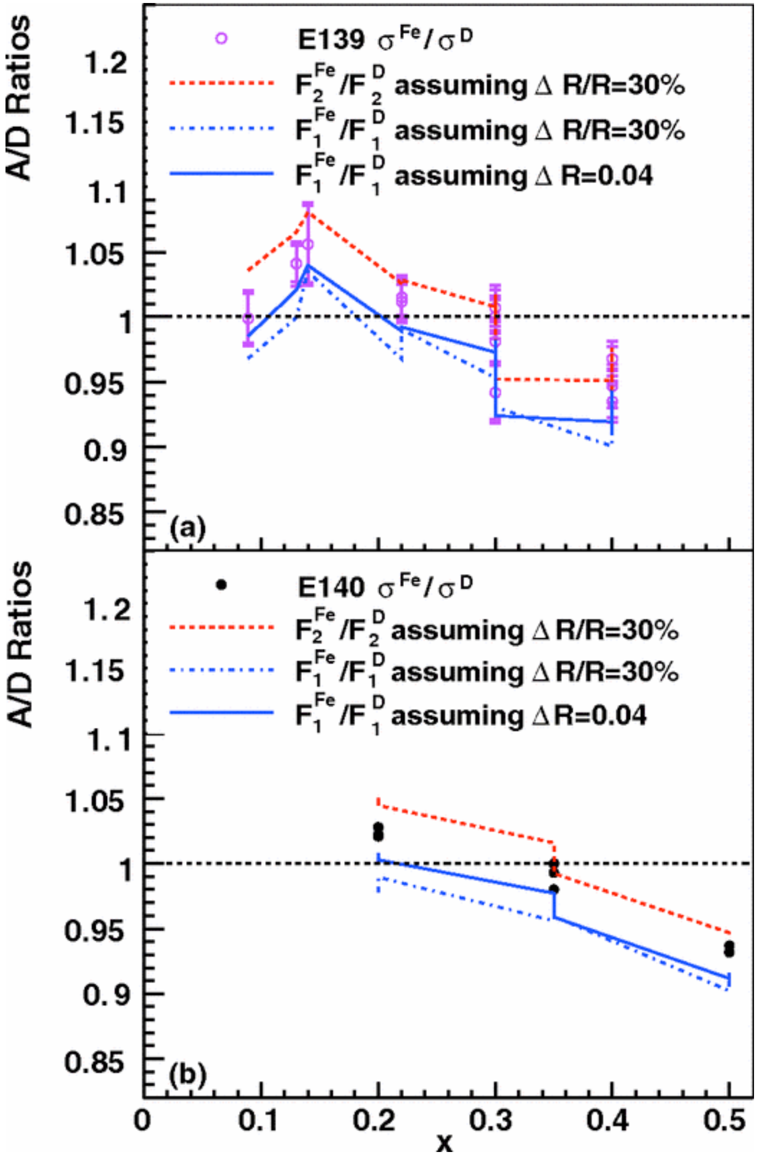
with Coulomb Corrections

PRC 104(6):065203, 2021

Combined analysis of SLAC E139, E140 and JLab 6 GeV data for Fe/Cu at $x=0.5$, $Q^2 \sim 5\ GeV^2$

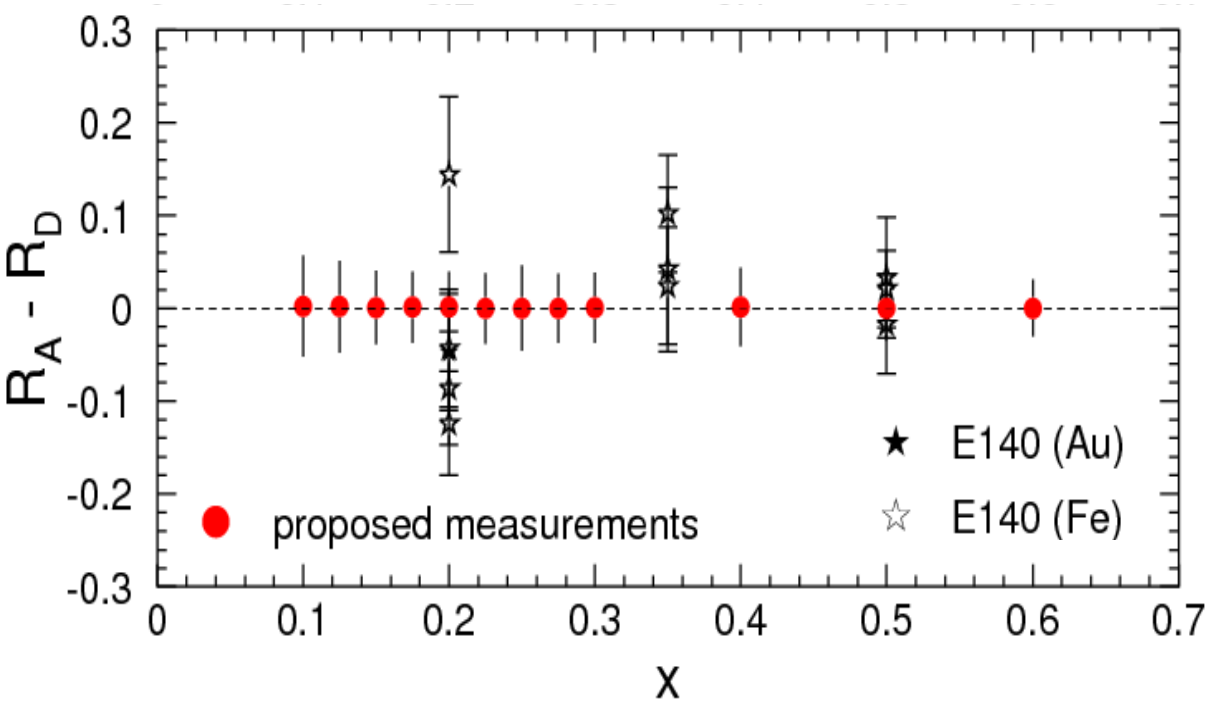
Consequences of non-zero R_A-R_D

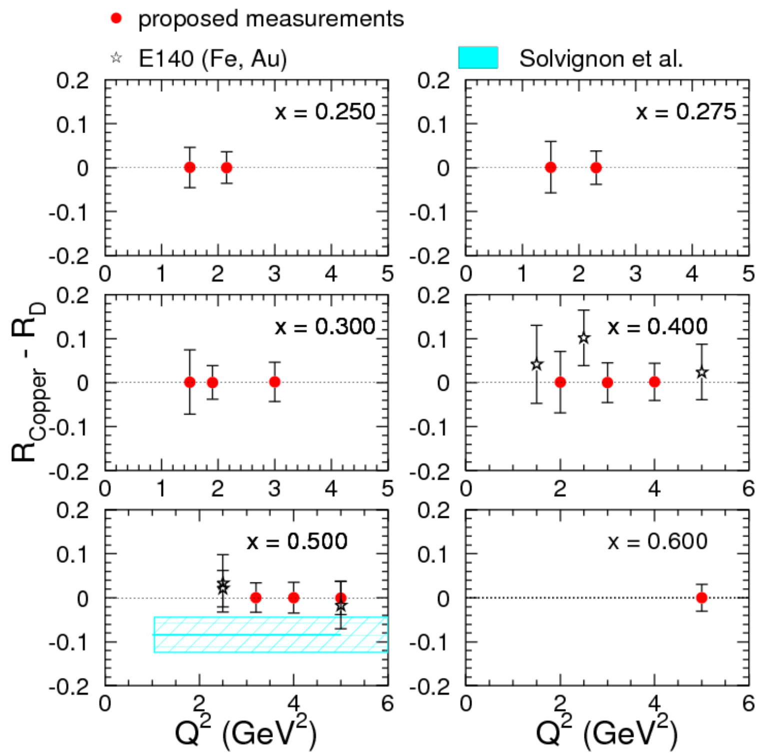
- Several hints that R_A-R_D not zero
  - Effect is not large – depends on precision of the experimental data
  - Coulomb Corrections are crucial to observation/existence of this effect
- Implications of non-zero R_A-R_D
  - F_1, F_2 not modified in the same way in nuclei → impact on EMC effect?
  - Anti-shadowing a longitudinal photon effect?
  - Parton model: $R=4<k_T^2>/Q^2$, $<k_T^2>$ smaller for bound nucleons? [*A. Bodek, PoS DIS2015 (2015) 026*]
  - Explored in some detail in Phys. Rev. C, 86:045201, 2012
- New, precision data required → E12-14-002



Connection to E12-14-002

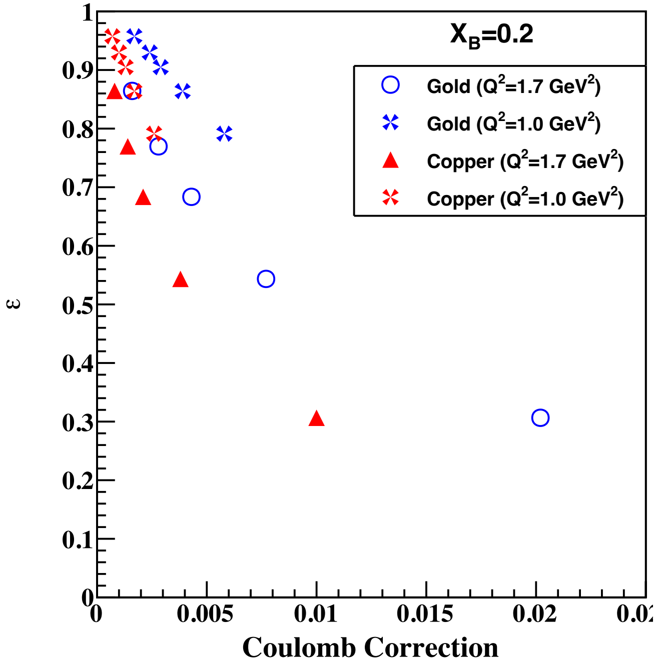
- Precision Measurements and Studies of a Possible Nuclear Dependence of $R=\sigma_L/\sigma_T$
  [S. Alsalmi, M.E. Christy, D. Gaskell, W. Henry, S. Malace, D. Nguyen, T.J. Hague, P. Solvignon]
- Measurements of nuclear dependence of structure functions, R_A-R_D via direct L-T separations

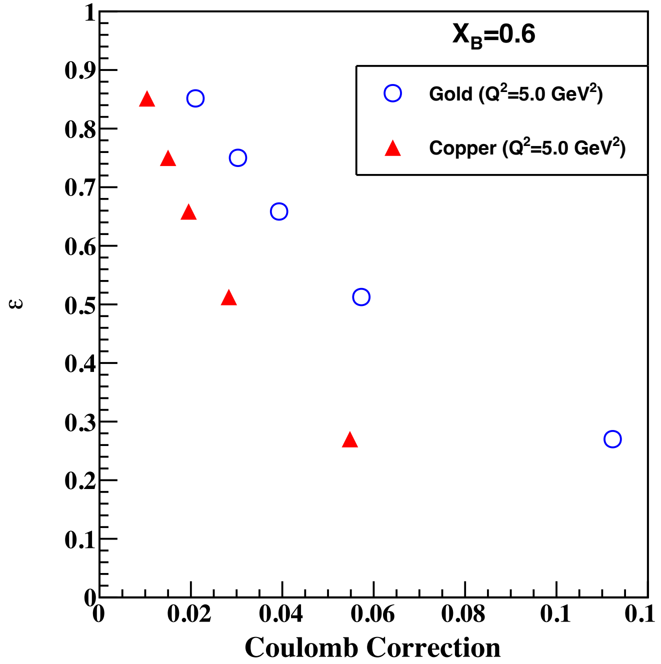




Depends critically on correct application of Coulomb Corrections

E12-14-002 and Coulomb Corrections





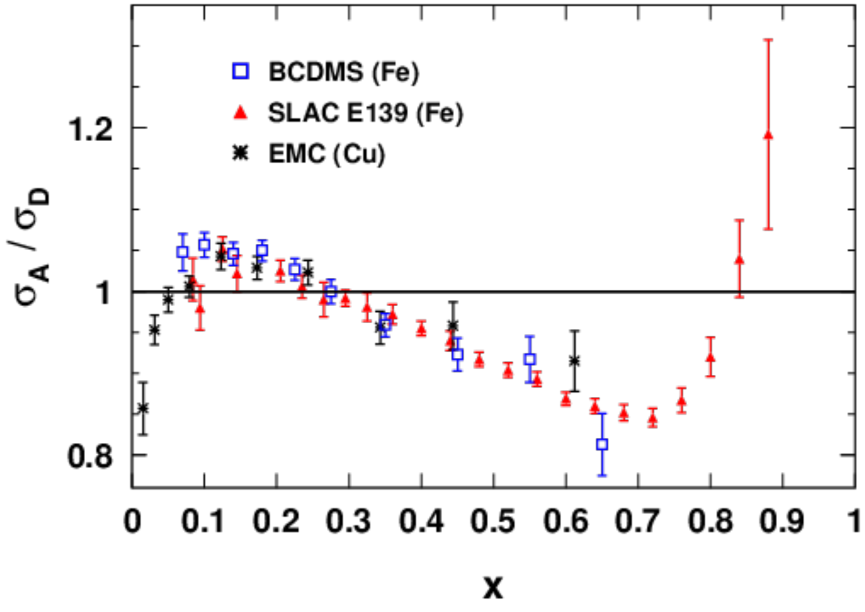
Coulomb corrections a key systematic issue for E12-14-002

→ L-T separations require varying epsilon. Smaller epsilon corresponds to smaller beam energies and scattered electron momenta → larger Coulomb corrections
→ Size of Coulomb correction highly correlated with the very effect we are trying to study
→ Need robust tests to verify CC magnitude and epsilon dependence

Testing Coulomb Corrections with Electrons

Coulomb corrections can be tested by measuring target ratios at fixed ***x*** and **ε**
→ Varying Q^2 allows us to change E and E' and hence size of CC

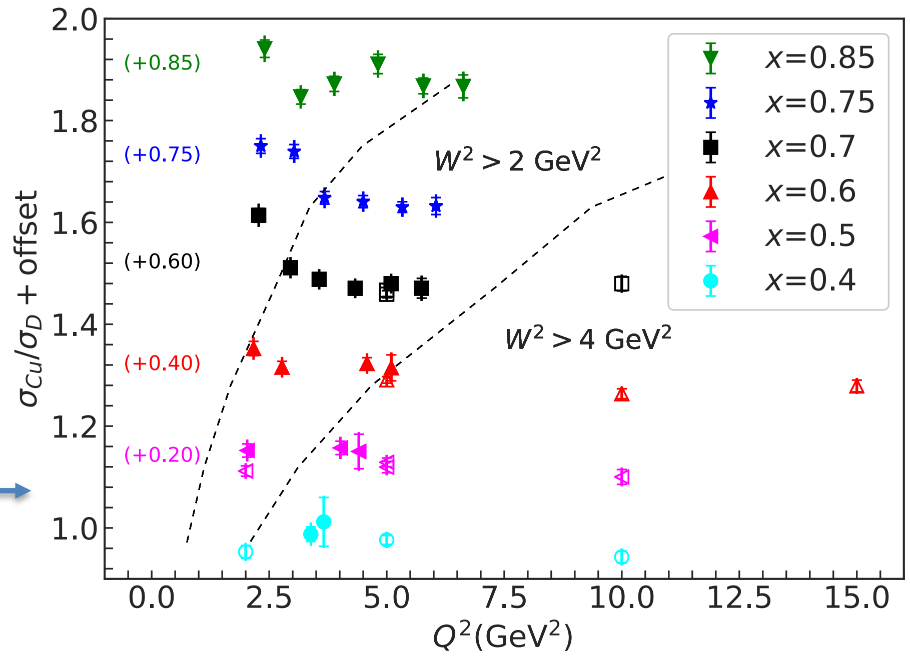
Fixed ***x*** required due to EMC effect



Fixed **ε** eliminates potential dependence on R_A-R_D

$$\frac{\sigma_A}{\sigma_D} = \frac{F_2^A(1+\epsilon R_A)(1+R_D)}{F_2^D(1+R_A)(1+\epsilon R_D)}$$

EMC effect measurements have shown little or no dependence on Q^2

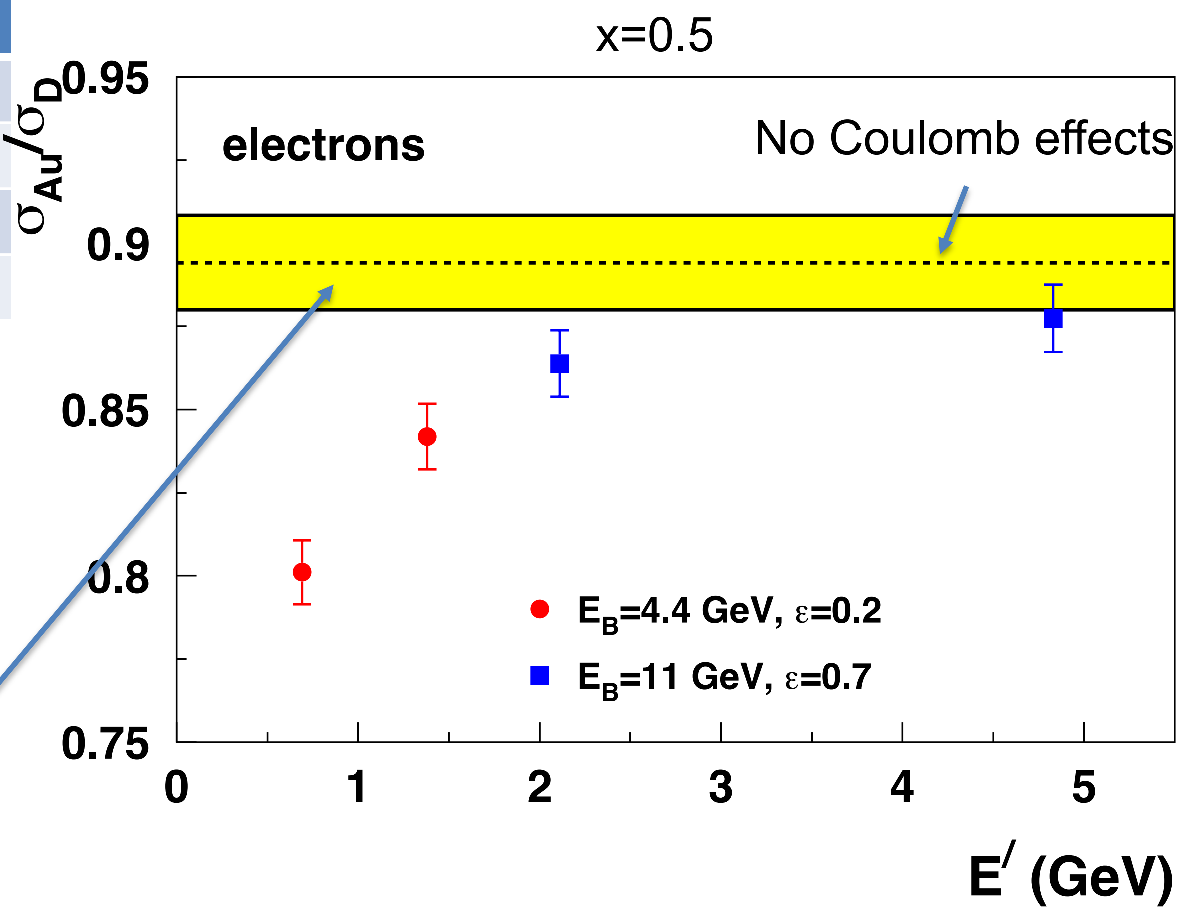


E12-14-002 Coulomb Corrections Test

CC test will measure precise Au/D ratios in HMS
→ 2 shifts (16 hours) at 60 μA

ε	Q^2 (GeV^2)	E (GeV)	E' (GeV)	θ (deg.)	$C_{Coulomb}$
0.2	3.48	4.4	0.69	64.6	11.6%
0.2	9.03	11.0	1.38	45.5	6.2%
0.7	2.15	4.4	2.11	27.9	3.5%
0.7	5.79	11.0	4.83	19.0	1.9%

Gold and Deuterium targets at fixed x=0.5



Normalization uncertainty → dominated by gold and LD2 target thicknesses

Testing Coulomb Corrections with Positrons

Positron beam at JLab an excellent opportunity for studying Coulomb Corrections in DIS

<u>Key questions:</u>

1. Are Coulomb Corrections relevant for DIS?
   - For QE scattering effects have been clearly observed experimentally – consensus that CC are required
   - “Makes sense” that they should be needed for DIS, but proof is needed
2. Is the Improved Effective Momentum Approximation (EMA) adequate/appropriate for DIS?
   - EMA has been checked/optimized in QE scattering via comparisons to DWBA calculations
   - Equivalent calculations for DIS appear to be more challenging and perhaps model dependent

Coulomb Corrections Test with Positrons

Will perform CC test w/positrons at same kinematics as E12-14-002

→ Will allow **direct** comparison of electrons and positrons

→ Polarization not required, assume current of 1 μA available

→ Magnetic focusing spectrometers desirable for excellent PID, good control of acceptance

→ Target ratios (Au/D) minimize uncertainty in e+/e- comparison – less sensitive to absolute measurement of beam current

  → Nucleon-level beam-charge sensitive effects will cancel in target ratios

→ Use of thicker targets will partially offset lower beam currents, but will introduce some differences in radiative corrections and charge symmetric backgrounds

LD2: 4 cm → 10 cm

Au: 2% RL → 6% RL

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

Statistics goals: LD2: 50k, Au: 25k

Systematic Uncertainties

Systematic uncertainties for this experiment will be similar to E12-14-002, with some exceptions

1. BCM calibrations → typically use Unser, but will need to use Faraday Cup in injector (or new Hall C FC) due to low current. Impact minimal due to ratio
2. Radiative corrections → slightly larger due to thicker targets
3. Charge symmetric backgrounds → slightly larger due to thicker targets

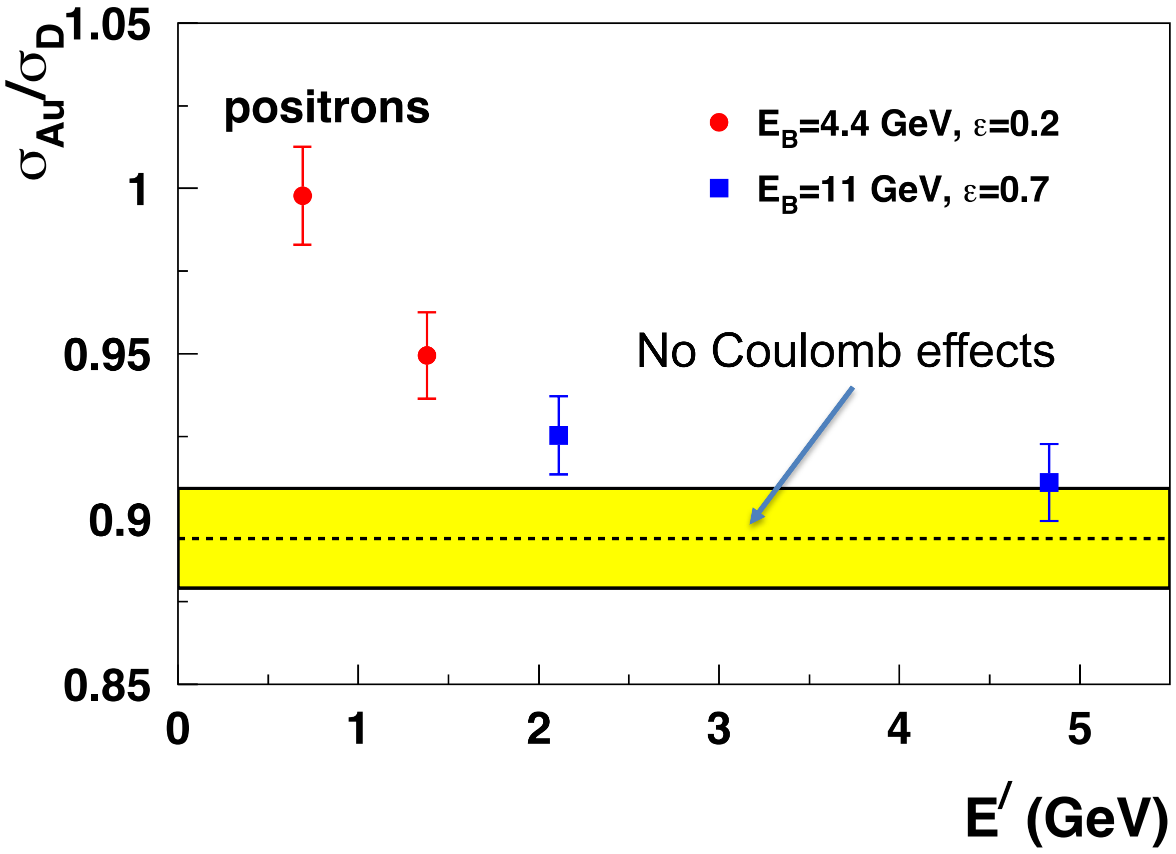
Source	$\delta R/R$ (%) point-to-point	$\delta R/R$ (%) scale
Spectrometer momentum	-	$< 0.1\%$
Beam energy	-	$< 0.1\%$
θ_{spec}	-	$< 0.1\%$
Charge	0.35%	-
Target Boiling	-	$< 0.1\%$
Total dead time	0.15%	0.14%
Detector efficiency	0.11%	-
Charge Symmetric Background	0-1%	-
Radiative Corrections	0.55%	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%

Coulomb Corrections Test w/Positrons

- HMS only (compatible with DVCS installation)
- Beam current = 1 μA
- 10 cm LD2 target, 6% RL Au target
- Total beam time on target = 159.9 hours = 6.7 days

Additional time required for:
→ Kinematic changes (7 hours)
→ Pass change (8 hours)
→ Target wall backgrounds (9.1 hours)
→ Charge symmetric backgrounds (39.3 hours)

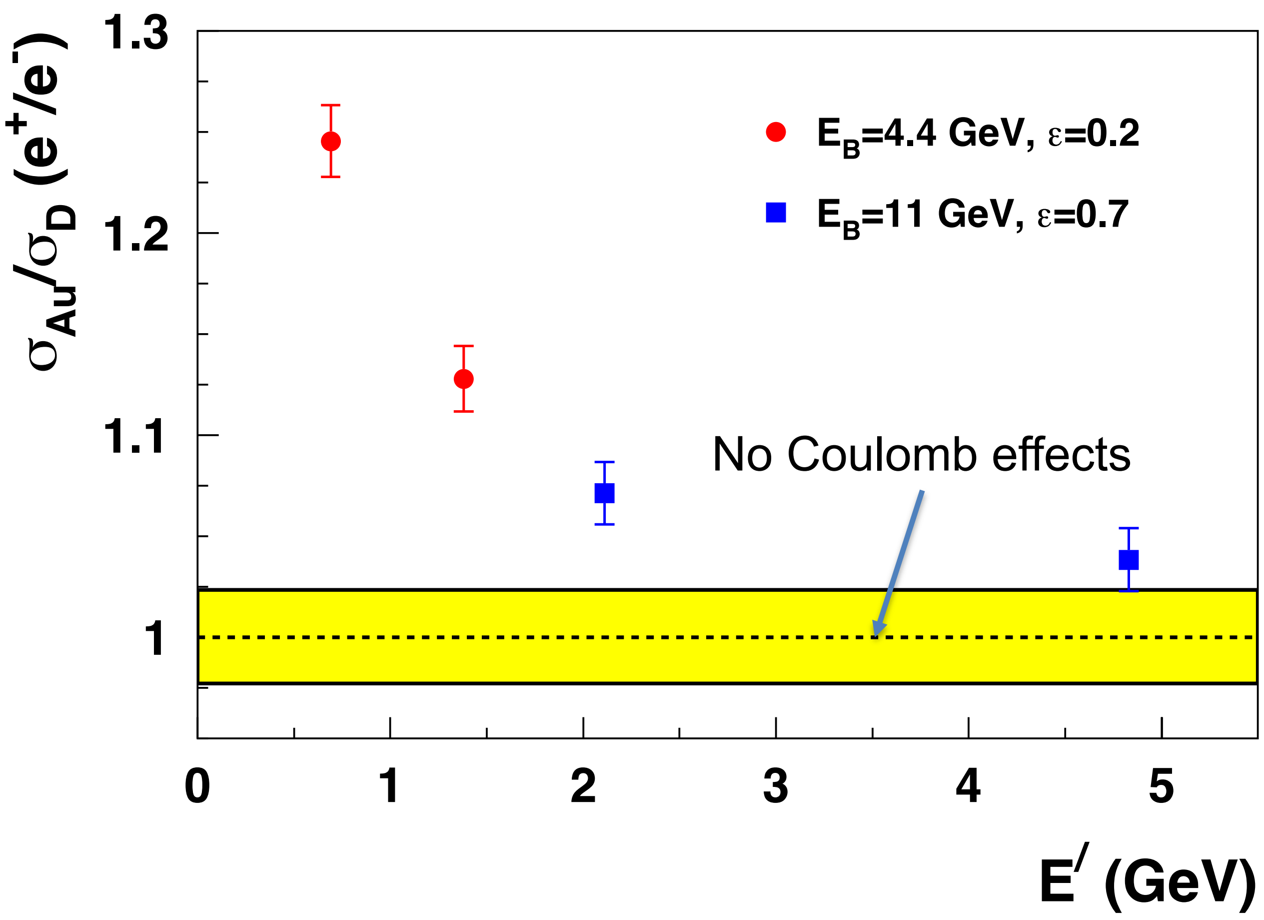
Total time requested = 223.3 hours (9.3 days)



Coulomb Corrections Test: Electrons and Positrons

Cleanest measurement of CC from super-ratio for e+/e-:
→ Insensitive to assumptions in electron/positron-only CC test

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



Summary

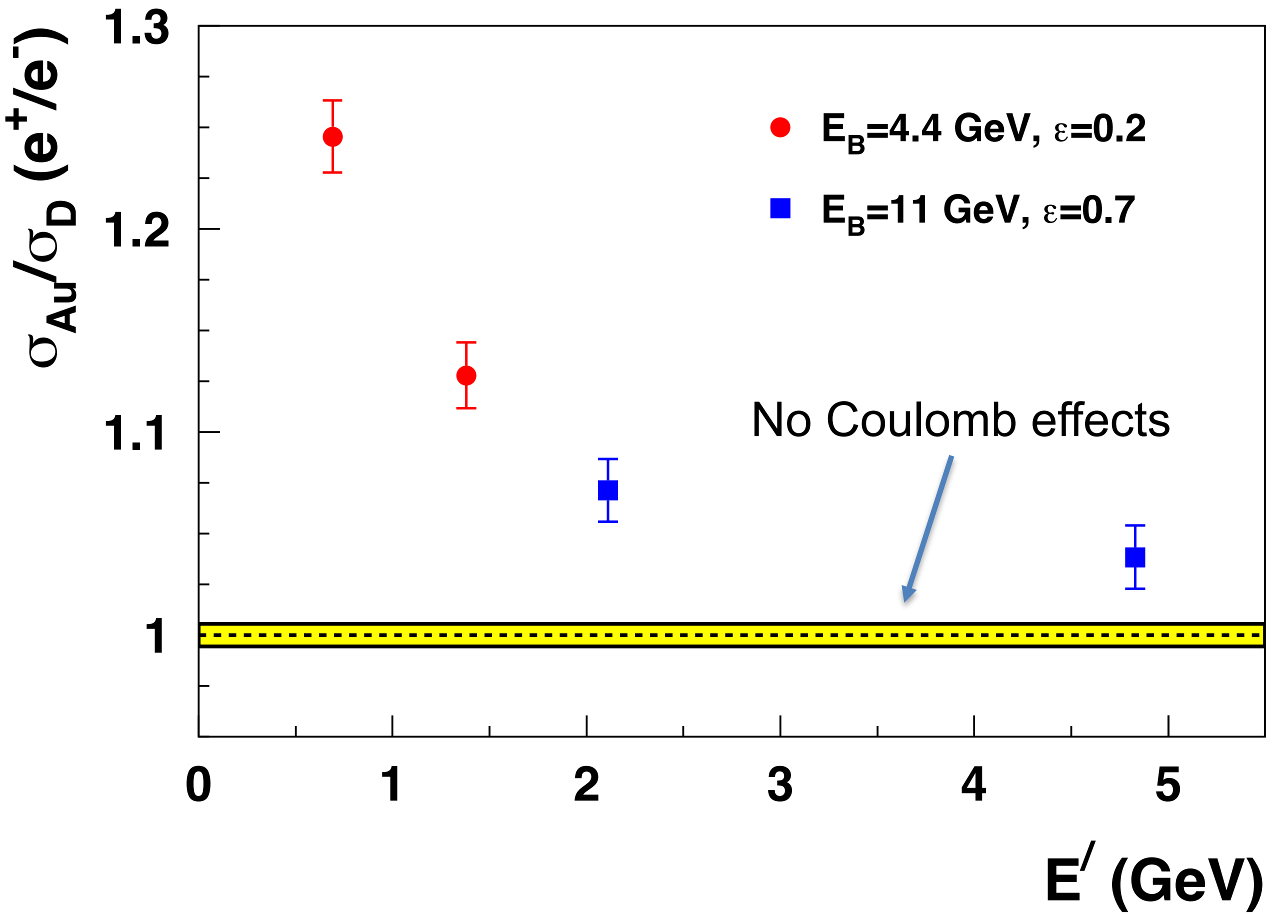
- This experiment will make a definitive test of Coulomb Corrections in DIS in 9.3 days
  - Coulomb corrections an important systematic for measurements of nuclear dependence of *R*
  - Important ramifications for our understanding of the EMC effect
- Use of target ratios (σ_A/σ_D) allows one to compare electron and positron results directly without requiring rapid switching between electron and positron beams
  - Desirable to have beam energy the same as much as possible
- Coulomb corrections also relevant for other reactions
  - Hadronization studies: $e+A \rightarrow e'+\pi+X$
  - $x>1$, $A(e,e')$ at large Q^2
  - Color transparency: $A(e,e'p)/H(e,e'p)$

EXTRA

Coulomb Corrections Test: Electrons and Positrons

Cleanest measurement of CC from super-ratio for e+/e-:
→ Insensitive to assumptions in electron/positron-only CC test

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



Electron and Positron data taken during same run period → smaller normalization uncertainty

→ Extra day of beam-on-target for electron running

Response to TAC Comments

Hall C plans to develop a low power Faraday Cup (FC) for the positron program to monitor the beam current at the +-0.1% level. The Unser monitor is essentially useless at 1 muA, and in the 12 GeV era, injector FC measurements mentioned in the proposal would be invasive for as many as 3 other halls. Furthermore, it would be a great challenge to not only transport a relatively large positron beam of 1 muA but verify that the scrape-off during transport was less than 1%. A FC in Hall C will dramatically reduce potential systematic errors in charge normalization for a Hall C positron program.

The development of a Faraday Cup for use during the positron running in Hall C would be a great benefit for this experiment and the positron program as a whole. However, we would like to argue that for this experiment, the Faraday Cup would not strictly be required. We only need a rough idea of the BCM gain and offset since we will not be measuring absolute cross sections, just cross section ratios between targets at a given energy. We will use the same beam current for both targets, so we only need to make sure that the BCMs are stable for the duration of a given measurement. This can be accomplished by comparing the response of the 5 different BCMs in Hall C (3 in one temperature controlled enclosure, and 2 further downstream).

Response to TAC Comments

Beam time request is only for positrons, but an additional 1 day with an electron beam would allow for a direct comparison of e+ to e- with the same targets and apparatus, thus reducing an expected 1.21% systematic error in the ratio of gold to deuterium. This is particularly important for the significance of the high epsilon data, where the Coulomb corrections in Table I are smaller. Initial estimates from the positron working group for how long it takes to switch from e- to e+ or the reverse were about 1 week, but in a recent memo the prospect of a 1 day switchover time is thought to be feasible after further study.

In the event that the positron-to-electron switchover time were indeed reduced to a single day, we would definitely like to run the experiment with both positrons and electrons to reduce the systematic uncertainty as noted above.

Response to TAC Comments

This proposal is designed to cleverly check Coulomb corrections on a previously approved proposal. In a Taylor series expansion of the perturbations to the cross section, the two important terms are proportional to (V/Ee) and (V/Ee'). An experiment designed to more generally constrain Coulomb corrections – i.e., determining the effective value of "V" - might also include e+ and e- measurements at a beam energy of 8.8 GeV, for example. (Especially at epsilon = 0.7, where the significance of the 11 GeV point in Table 1 may be marginal.)

It is not clear that additional running at 8.8 GeV would benefit this experiment. The run plan was explicitly designed to make measurements at high beam energy (11 GeV) and larger scattered electron momentum (>2 GeV) where Coulomb Corrections are projected to be small, and to make measurements where the Coulomb corrections are projected to be large, at lower beam energy (4.4 GeV) and scattered electron momenta. In the context of the size of the estimated Coulomb Correction, an intermediate beam energy would not increase the lever arm of the measurement and would have limited impact on a possible fit of the effective potential.

Theory Review

This proposal aims to measure Coulomb corrections in Deep Inelastic Scattering (DIS) with large nuclei and validate existing formalisms based on the Effective Momentum Approximation (EMA). The main component of this proposal is the utilization of the positron beam at JLab, that will enable a direct measurement of the size of these corrections, especially from forming ratios of positron to electron cross sections. Together with the Jeopardy proposal E12-14-002, which conducts similar measurements with an electron beam, it is thus possible to powerfully investigating Coulomb effects in DIS. Even higher precision data can be expected with a short electron beam run with the proposed settings, and can test for alternatives to the EMA formalism.

The proposal has a broad range of physics areas of impact including tests of the EMA framework, input for nuclear effects in the resonance region for neutrino experiments and studies of EMC effects with longitudinal photons.

The motivations for this proposal are strong and we encourage the full realization of these measurements.

Charge Symmetric Backgrounds

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

Radiative Corrections

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

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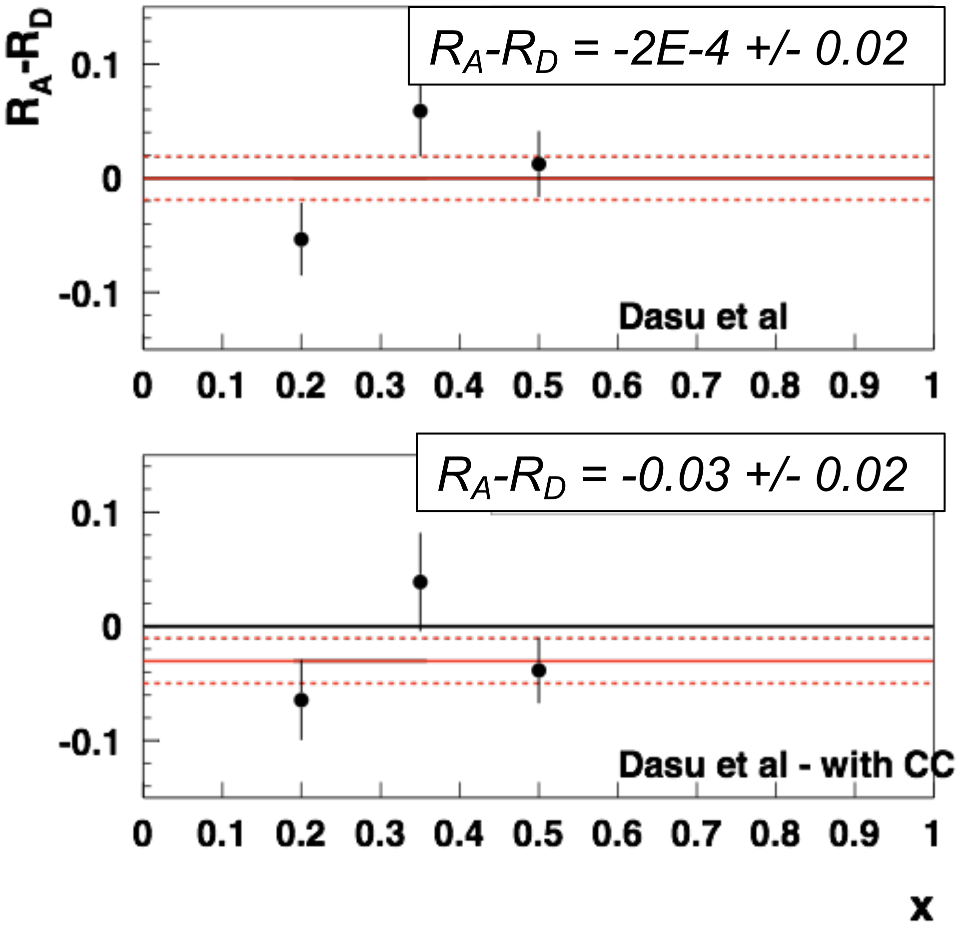
Jefferson Lab Positron Working Group Proposal

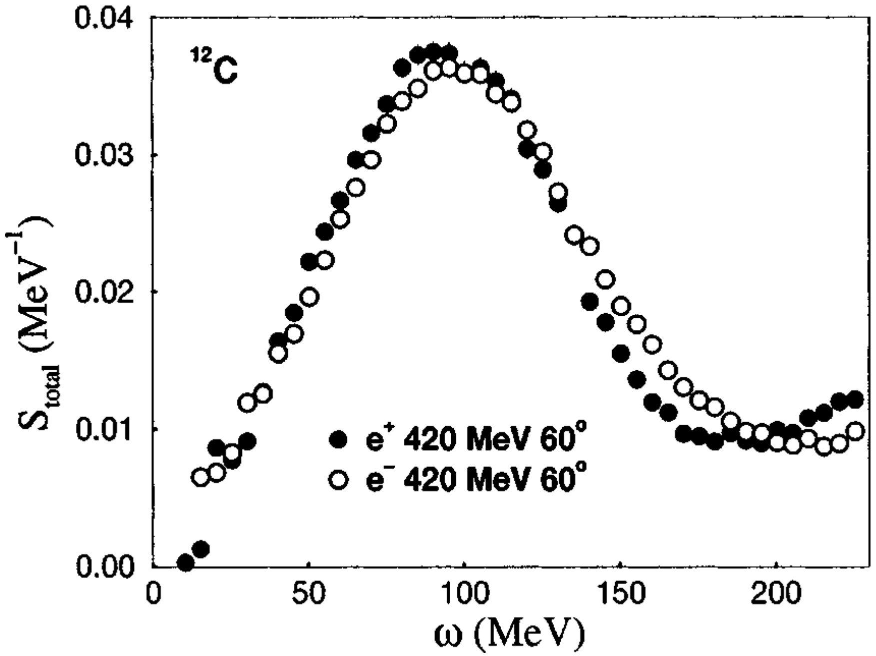
R_A-R_D: E140 Re-analysis

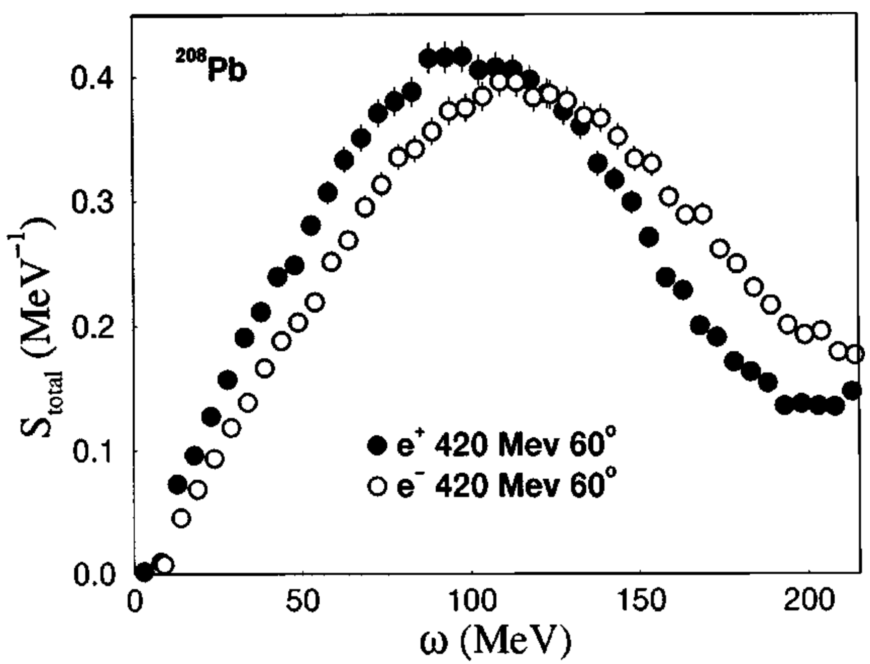
Re-analyzed E140 data using Effective Momentum Approximation for published “Born”-level cross sections
→ Total consistency requires application to radiative corrections model as well



Including Coulomb Corrections yields result 1.5 σ from zero when averaged over x

Electron-Positron Comparisons in QE Scattering

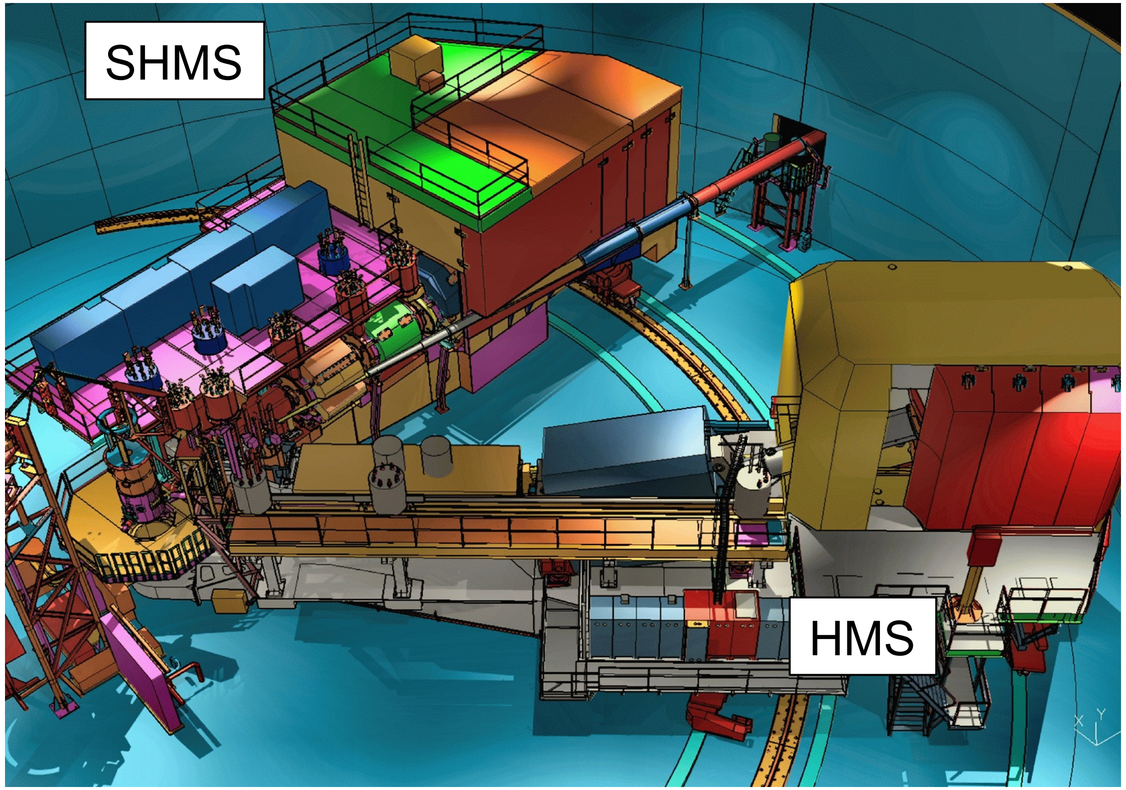




Gueye et al., PRC60, 044308 (1999)

- Comparisons of electron and positron scattering have been performed in QE scattering
- Were used to fit V_0 in context of EMA
- V_0 = 10 MeV for Fe, 20 MeV for Fe

Hall C: HMS and SHMS



Spectrometers

HMS:
dΩ ~ *6* msr, P_0= *0.5 – 7 GeV/c*
θ_0=*10.5 to 80 degrees*
e ID via calorimeter and gas Cerenkov

SHMS:
dΩ ~ *4* msr, P_0= *1 – 11 GeV/c*
θ_0=*5.5 to 40 degrees*
e ID via heavy gas Cerenkov and calorimeter

Excellent control of point-to-point systematic uncertainties