Constraining Coulomb Corrections in Deep Inelastic Scattering with Positrons

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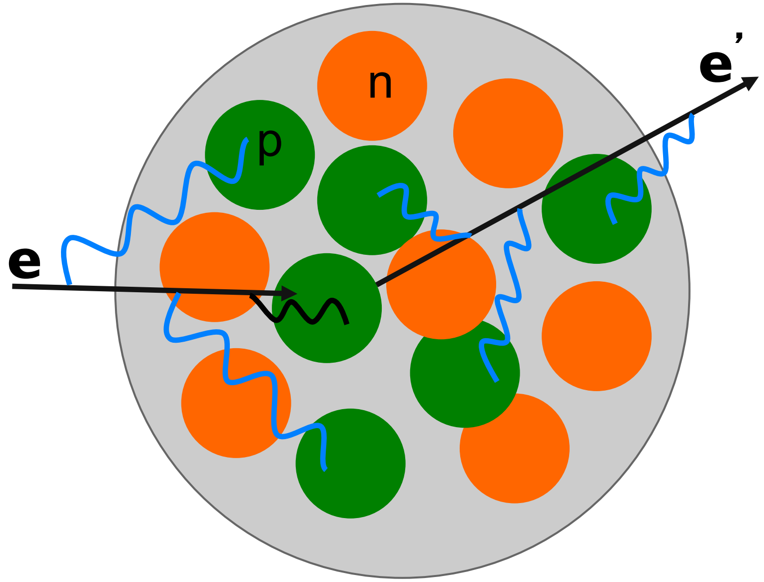
International Workshop on Physics with Positrons at Jefferson Lab
September 12-15, 2017

Heavy Nuclei and Coulomb Distortion



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
→ Important to remove/correct for apparent changes in the cross section due to Coulomb effects

In a very simple picture – Coulomb field induces a change in kinematics in the reaction

$E_e \rightarrow E_e + V_0$

$E_e' \rightarrow E_e' + V_0$

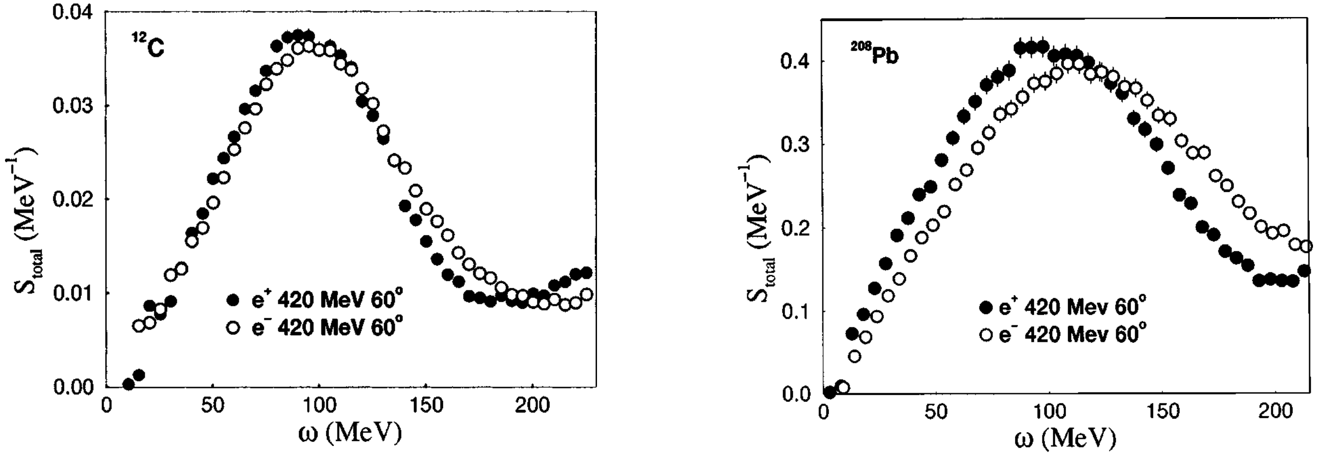
$V_0 = 3\alpha(Z-1)/2R$

↑

Electrostatic potential energy at center of nucleus

Coulomb Corrections in QE Processes

Importance of Coulomb Corrections in quasi-elastic processes well known



Gueye *et al.*, PRC60, 044308 (1999)

Distorted Wave Born Approximation calculations are possible – but difficult to apply to experimental cross sections

→Instead use Effective Momentum Approximation (EMA) tuned to agree with DWBA calculations

EMA: $E_e \rightarrow E_e + V_0$ $E_e' \rightarrow E_e' + V_0$ with "focusing factor" $F^2 = (1+V_0/E)$

$V_0 \rightarrow (0.7\text{-}0.8)V_0$, $V_0 = 3\alpha(Z-1)/2R$ V_0 = 10 MeV for Cu, 20 MeV for Au

[Aste et al, 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 → $-\frac{Z\alpha}{12}\frac{(Q^2)^2}{\nu^2}\frac{(E_e+E_e')}{E_e E_e'} < r >$
  - “For any reasonable kinematics, this is completely negligible”

- 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

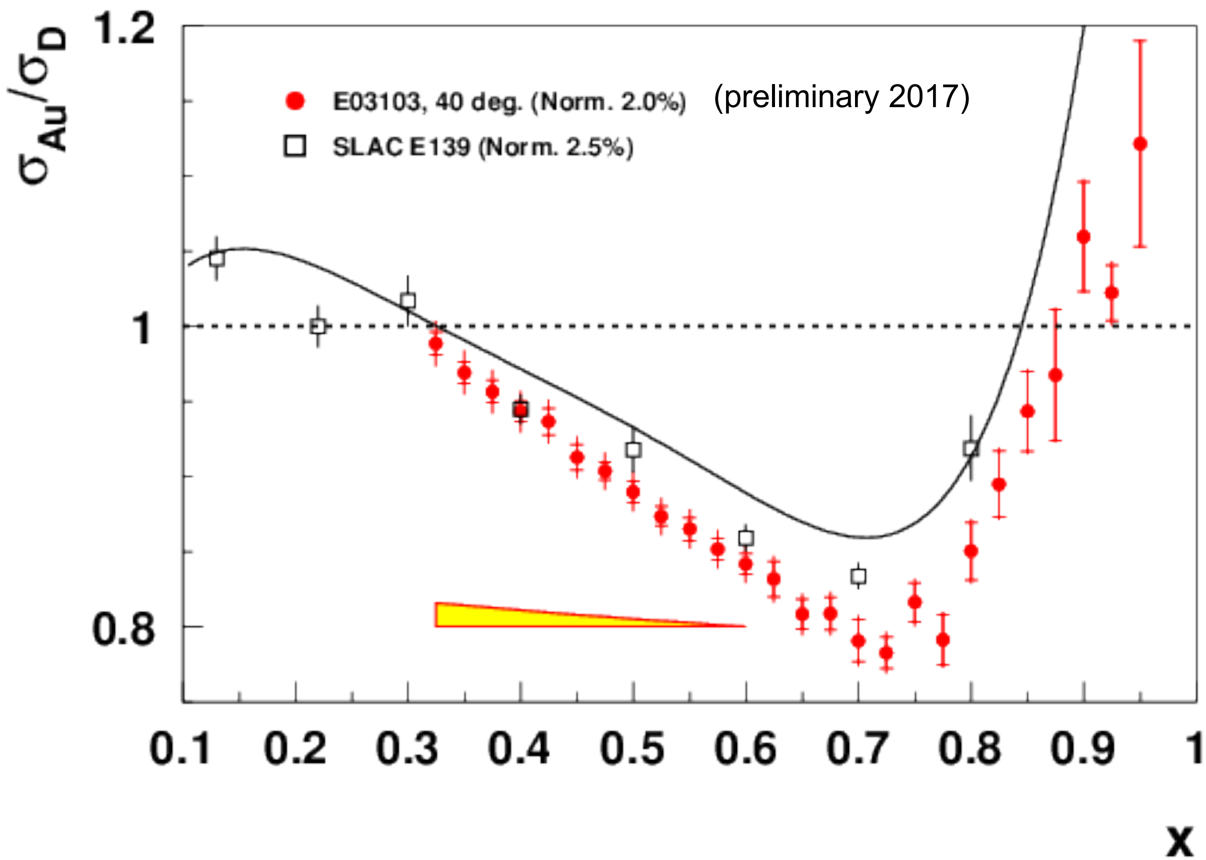
Application: EMC Effect

JLab E03-103 (6 GeV) measured σ_A/σ_D for light and heavy nuclei
→ Study modification of quark distributions in nuclei → *EMC effect*

σ_A/σ_D for Gold
A=197 Z=79

SLAC E-139
E_e ~ 8-25 GeV
E_e' ~4-8 GeV

JLab E03-103
E_e ~ 6 GeV
E_e' ~1-2 GeV



No Coulomb Corrections applied

Application: EMC Effect

Coulomb corrections significantly larger for JLab data → 5-10%, SLAC → 1-2%

σ_A/σ_D for Gold
A=197 Z=79

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

<u>JLab E03-103</u>
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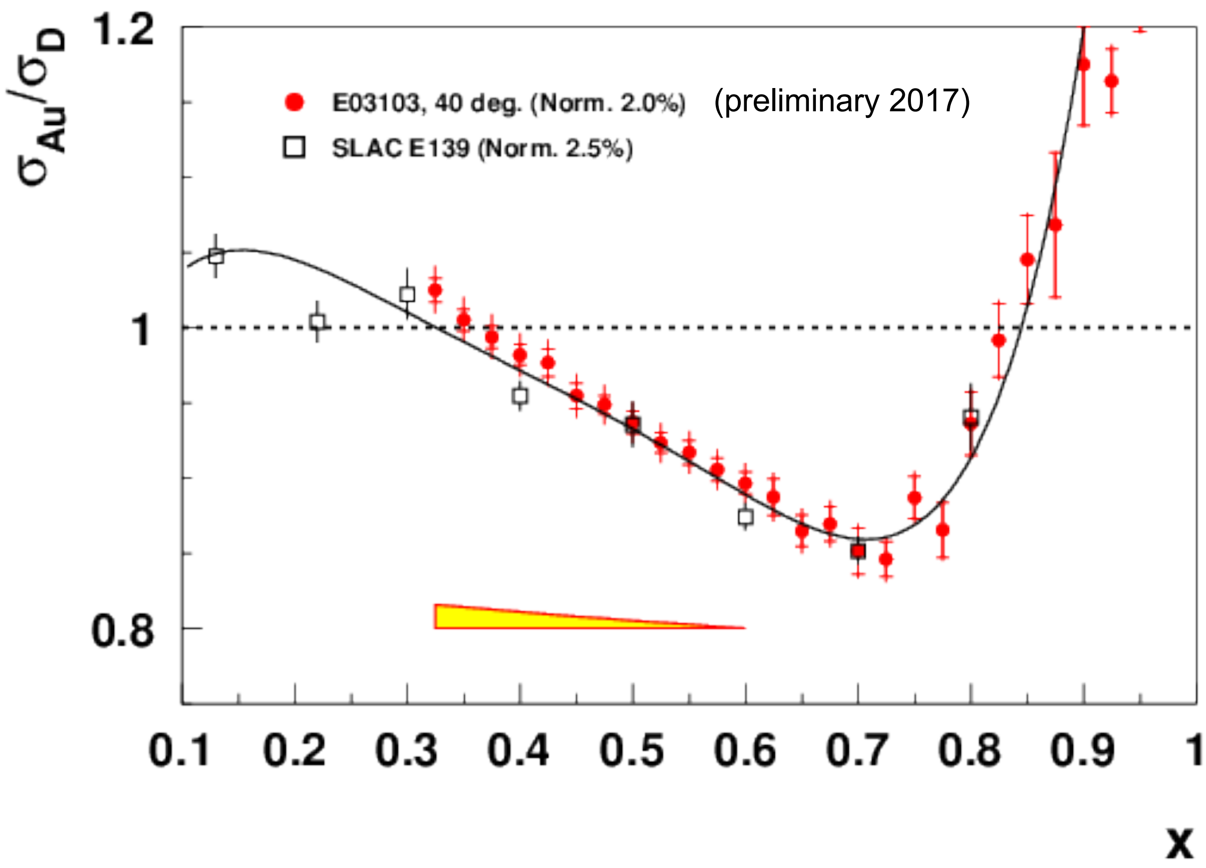


with Coulomb Corrections (both data sets)

Application: R_A-R_D

DIS/Inelastic cross section:

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2(E')^2}{Q^4\nu}\left[F_2(\nu,Q^2)\cos^2\frac{\theta}{2} + \frac{2}{M\nu}F_1(\nu,Q^2)\sin^2\frac{\theta}{2}\right]$$

$F_2(x) = \sum_i e_i^2 x q_i(x)$ ⟵ Quark distribution functions

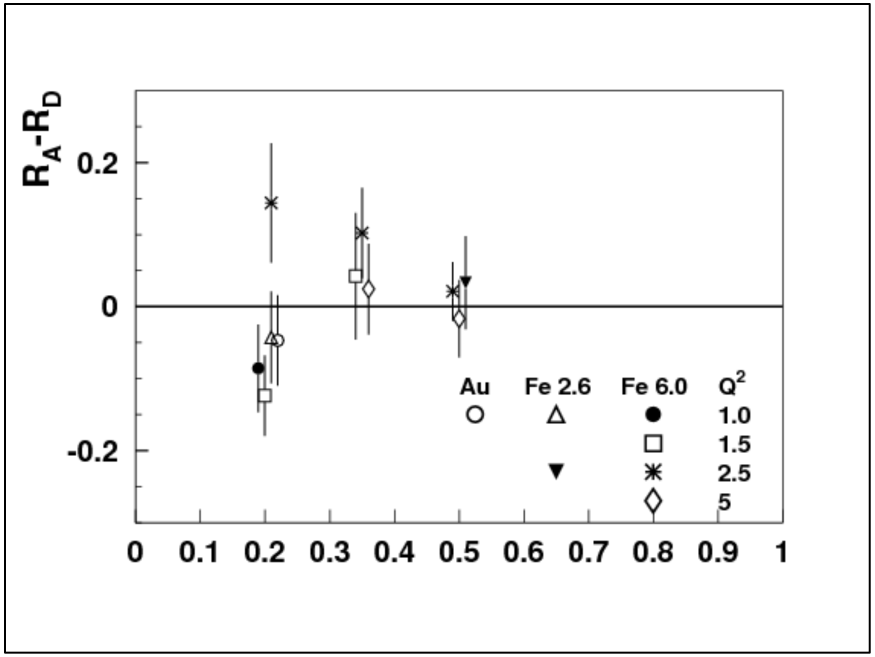
$$\frac{d\sigma}{d\Omega dE'} = \Gamma\left[\sigma_T(\nu,Q^2) + \varepsilon\sigma_L(\nu,Q^2)\right]$$

$F_1 \,\alpha\, \sigma_T$ F_2 linear combination of σ_T and σ_L

Measurements of EMC effect often assume $\boldsymbol{\sigma_A/\sigma_D = F_2^A/F_2^D}$
→ this is true if R=$\boldsymbol{\sigma_L/\sigma_T}$ is the same for A and D

SLAC E140 set out to measure R=$\boldsymbol{\sigma_L/\sigma_T}$ in deuterium and the nuclear dependence of R, i.e., measure R_A - R_D

R_A-R_D: E140 Re-analysis



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

E140 measured ε dependence of cross section ratios σ_A/σ_D for

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

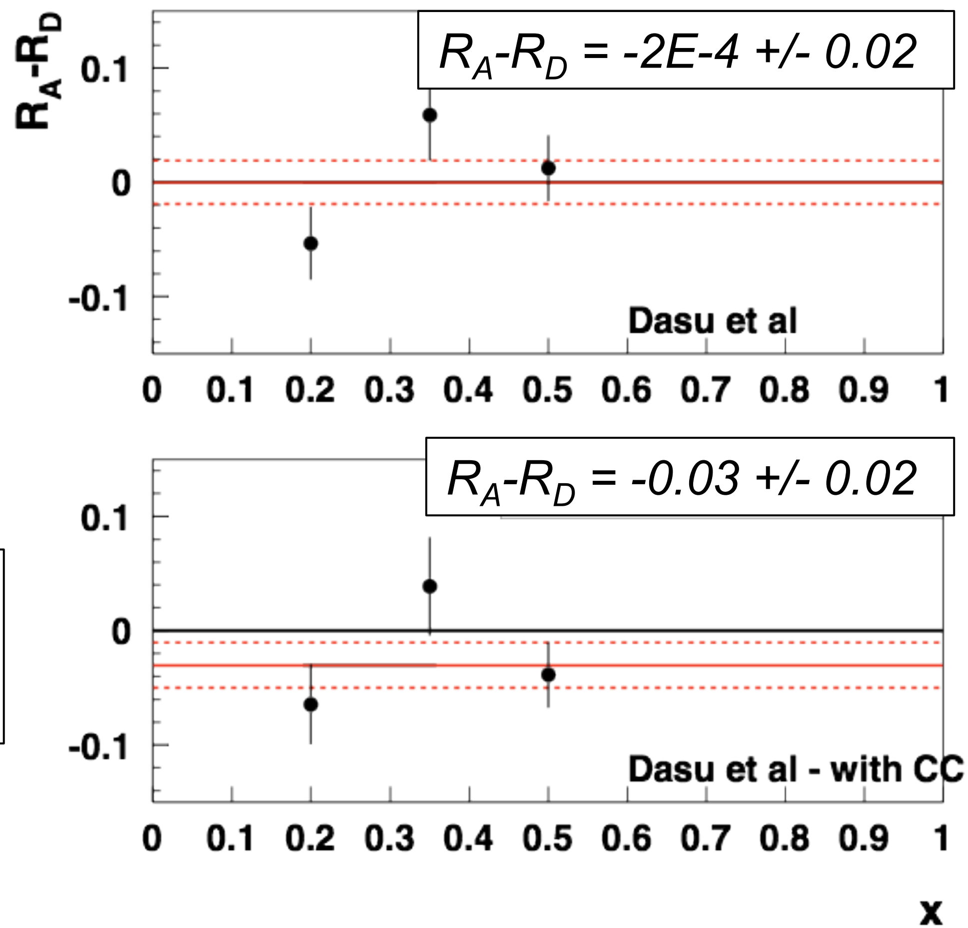
$R_A - R_D$ consistent with zero within errors

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**

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***

R_A-R_D at x=0.5

Interesting result from E140 re-analysis motivated more detailed study

→ *x=0.5*, *Q*²=*5* GeV²

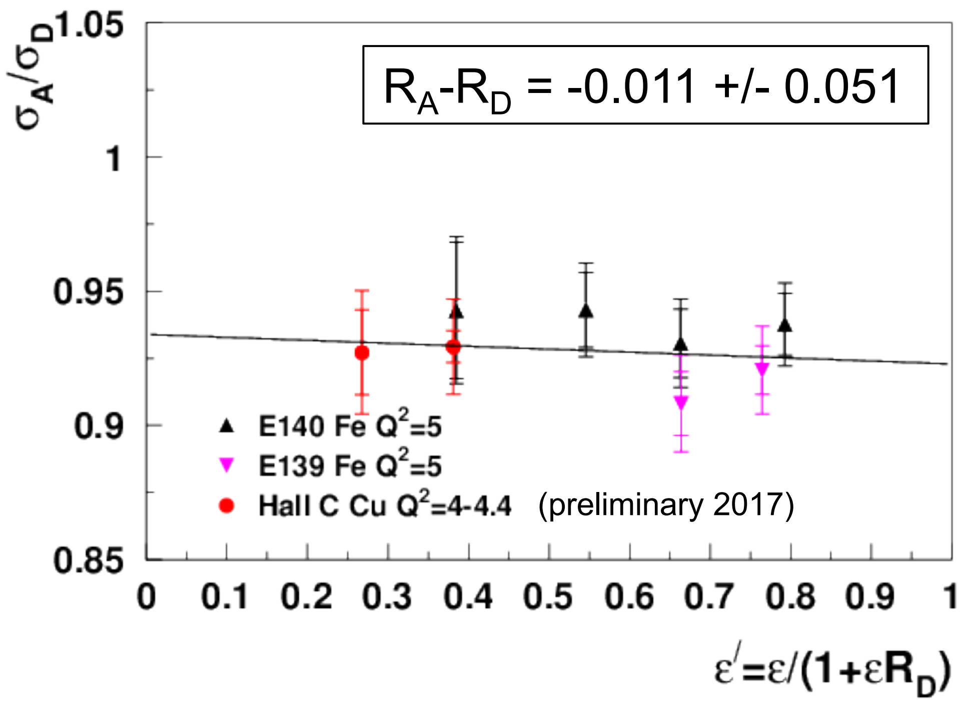
→ Include E139 Fe data

→ Include JLab data

Cu, Q^2=*4-4.4* GeV²

Normalization uncertainties between experiments treated as extra point-to-point errors

No Coulomb Corrections → combined analysis still yields R_A-R_D ~ 0



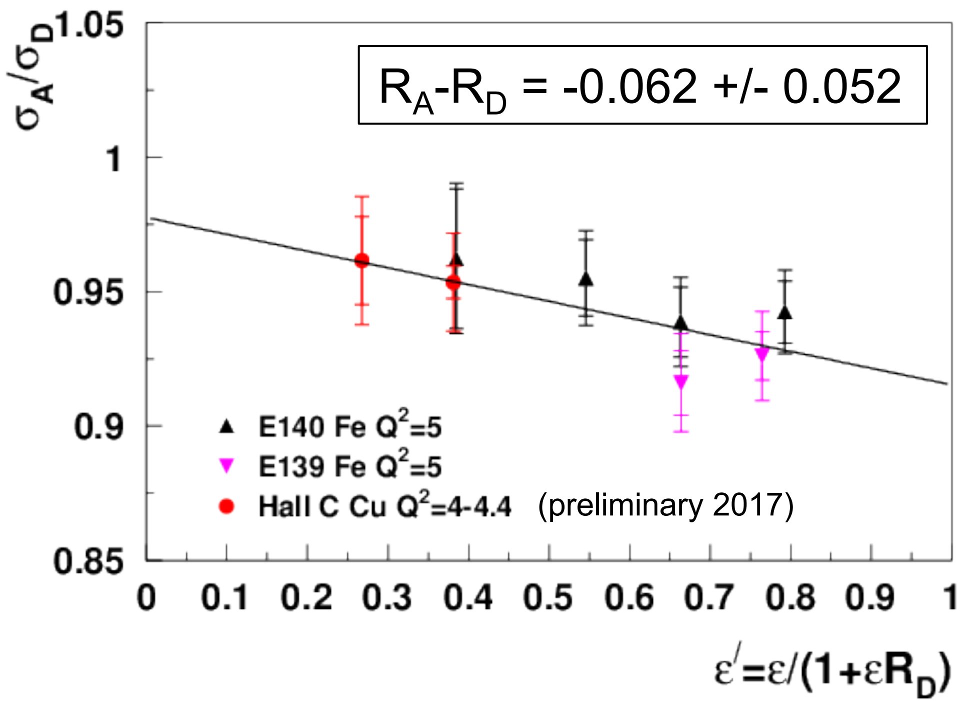
No Coulomb Corrections

R_A-R_D at x=0.5

Interesting result from E140 re-analysis motivated more detailed study
→ $x=0.5$, $Q^2=5$ GeV^2

→ Include E139 Fe data
→ Include JLab data
Cu, $Q^2=4\text{-}4.4$ GeV^2

Normalization uncertainties between experiments treated as extra point-to-point (between data sets) errors



with Coulomb Corrections

Application of Coulomb Corrections → R_A-R_D 1.2 σ from zero

R_A-R_D at Large x

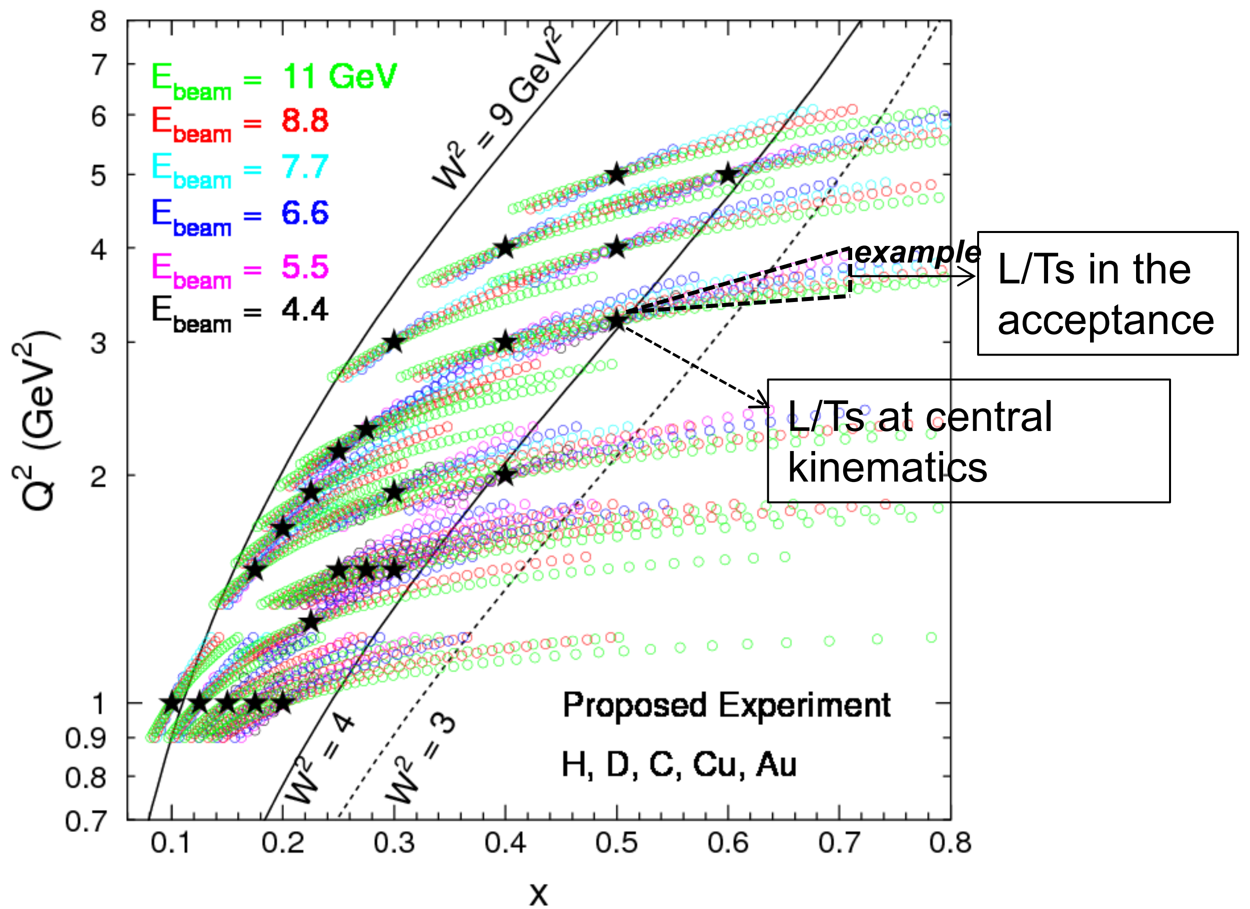
- Evidence is suggestive that R_A-$R_D < 0$ at large x
  - Effect is not large – depends on precision of the experimental data
  - Coulomb Corrections are crucial to observation/existence of this effect → CC has significant dependence on electron energy, varies between ε settings
- Implications of R_A-$R_D < 0$
  - F_1, F_2 not modified in the same way in nuclei
  - What does this mean for our understanding of the EMC effect?
  - Parton model: $R=4\langle K_T^2\rangle/Q^2$, $\langle K_T^2\rangle$ smaller for bound nucleons? [*A. Bodek, PoS DIS2015 (2015) 026*]
- **Additional data (dedicated measurement) in DIS region required**

JLab Experiment 12-14-002

Precision Measurements and Studies of a Possible Nuclear Dependence of $R=\sigma_L/\sigma_T$

[S. Malace, M.E. Christy, D. Gaskell, C. Keppel, P. Solvignon]

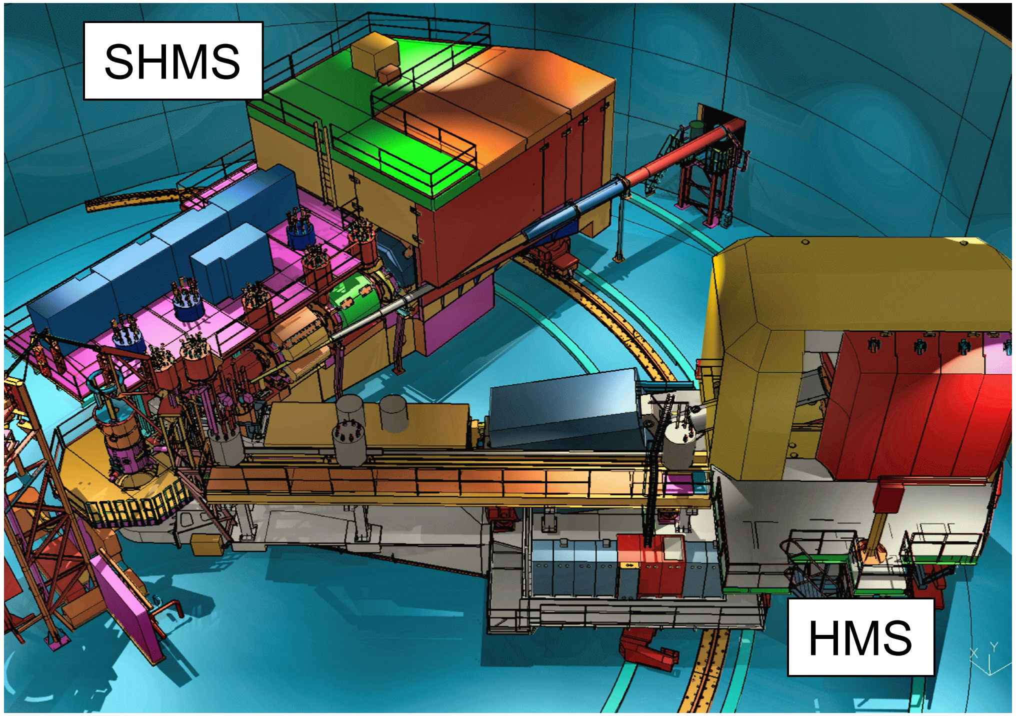
Measurements of nuclear dependence of structure functions, R_A-R_D via direct L-T separations



Detailed measurements of *x* and Q^2 dependence for Copper target

→ A dependence at select kinematics using C and Au

E12-14-002 Experimental Hall C



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

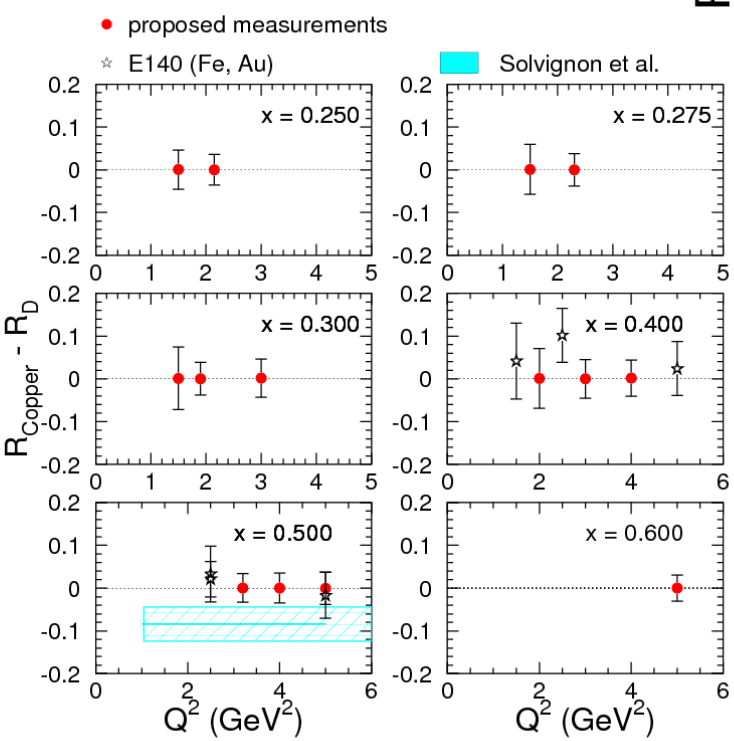
SHMS:
dΩ ~ *4* msr, P_0= *1 – 11 GeV/c*
ϑ_0=*5.5 to 40 degrees*
e ID via heavy gas Cerenkov and calorimeter

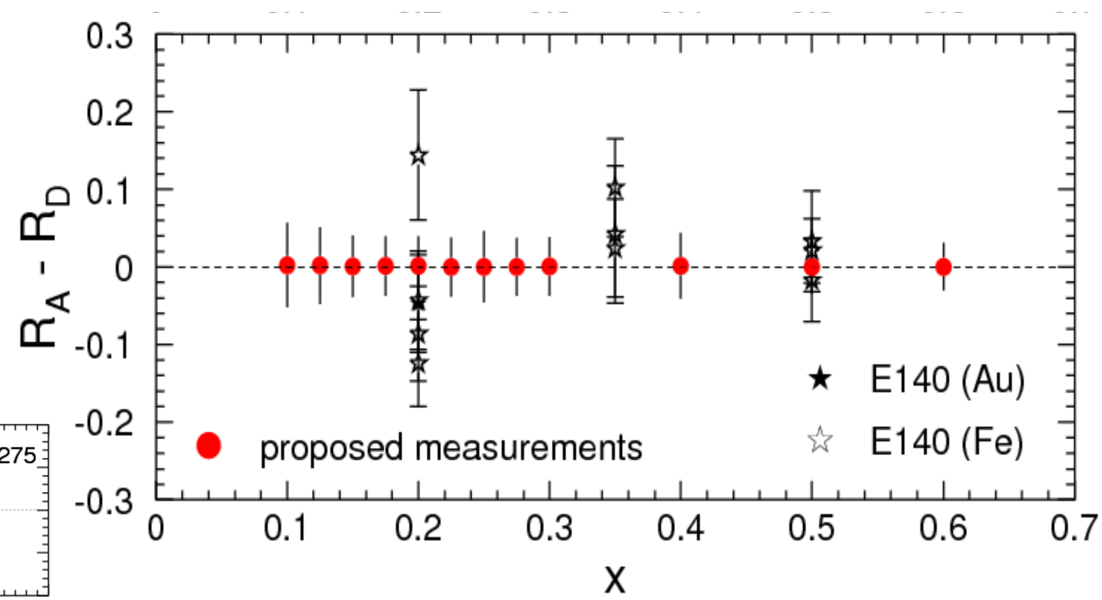
Excellent control of point-to-point systematic uncertainties required for precise L-T separations
→ Ideally suited for focusing spectrometers

Perform L-T separations using same spectrometer for all ε points as much as possible

JLab Experiment 12-14-002

Experiment will study R_A-R_D in both the EMC effect and anti-shadowing regions





Projections shown at central kinematics only; enhanced coverage by adding L/Ts from spectrometers acceptance

Overlap previous L-T separated data but will extend to both smaller and larger *x*

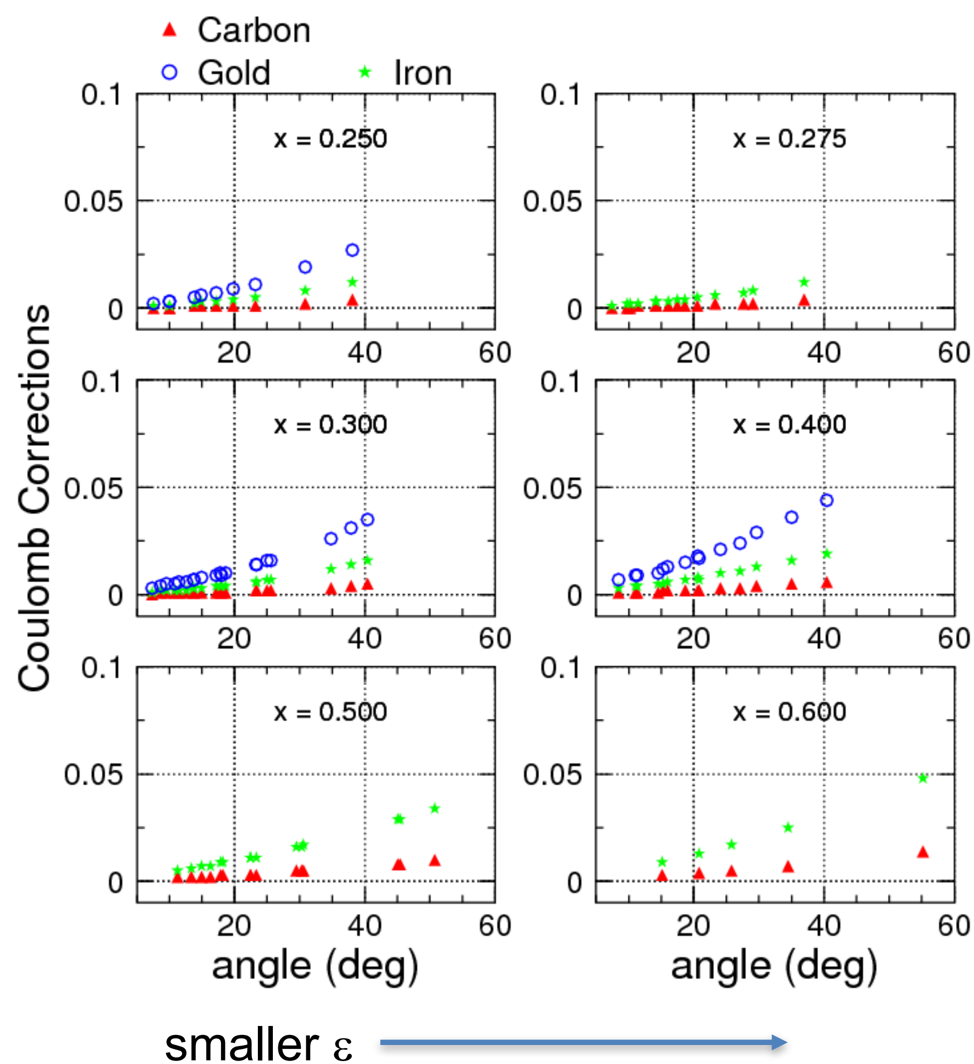
E12-14-002 and Coulomb Corrections

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

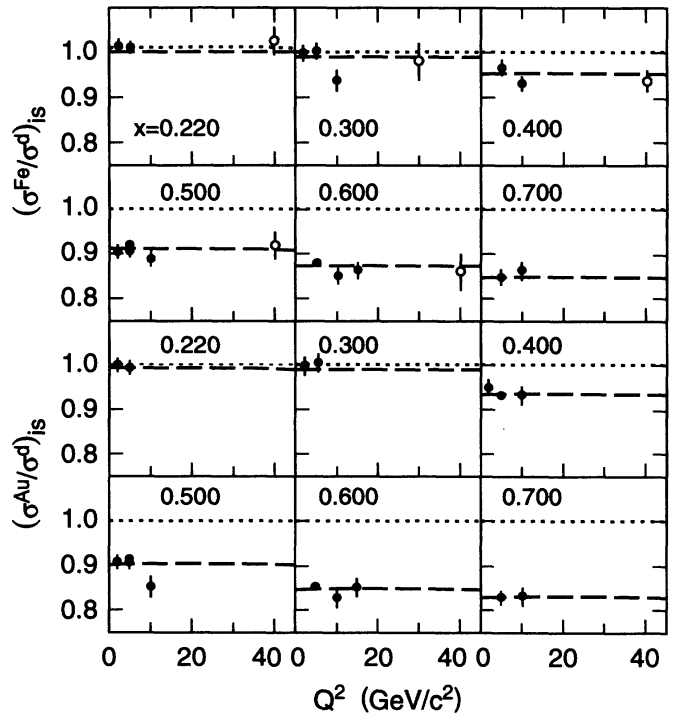
Coulomb corrections can be tested by measuring target ratios at fixed ***x*** and **ε**
→ Varying Q^2 allows us to change E/E' and hence size of CC

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

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

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

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



E12-14-002 Coulomb Corrections Test

Gold target x=0.5

ε	Q^2 (GeV^2)	E (GeV)	E' (GeV)	θ (deg.)	W (GeV)	$C_{Coulomb}$
0.2	3.48	4.4	0.69	64.6	2.08	11.6%
0.2	9.03	11.0	1.38	45.5	3.10	6.2%
0.7	2.15	4.4	2.11	27.9	1.74	3.5%
0.7	5.79	11.0	4.83	19.0	2.58	1.9%

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

Statistics goals: 100k events for deuterium, 50k for gold
→ 0.55% uncertainty in ratio (statistics)
→ Effect is potentially large at these kinematics, but want to test to high precision to minimize contribution to point-to-point uncertainties

E12-14-002 Coulomb Corrections Test

Gold and Deuterium targets x=0.5

ε	Q^2 (GeV^2)	E (GeV)	E' (GeV)	θ (deg.)	W (GeV)	$C_{Coulomb}$
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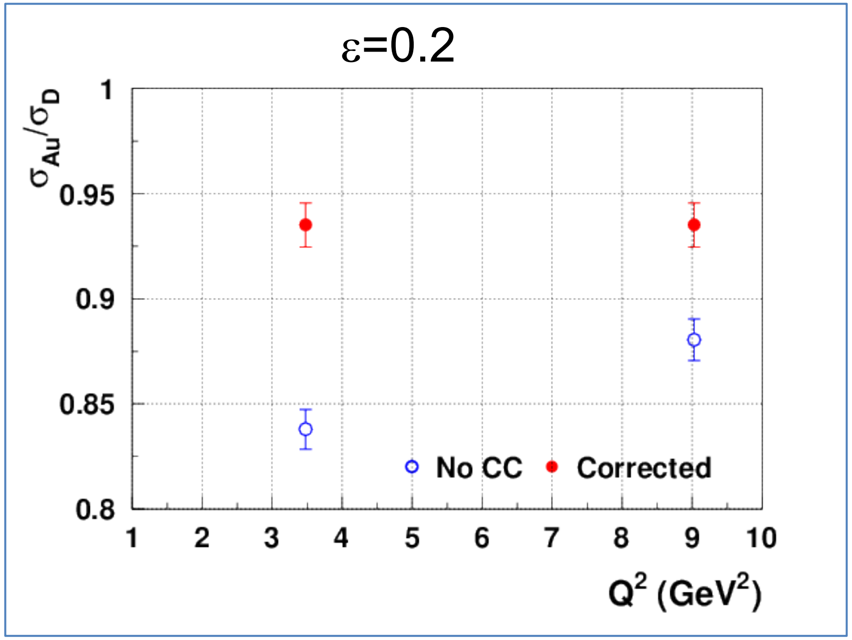

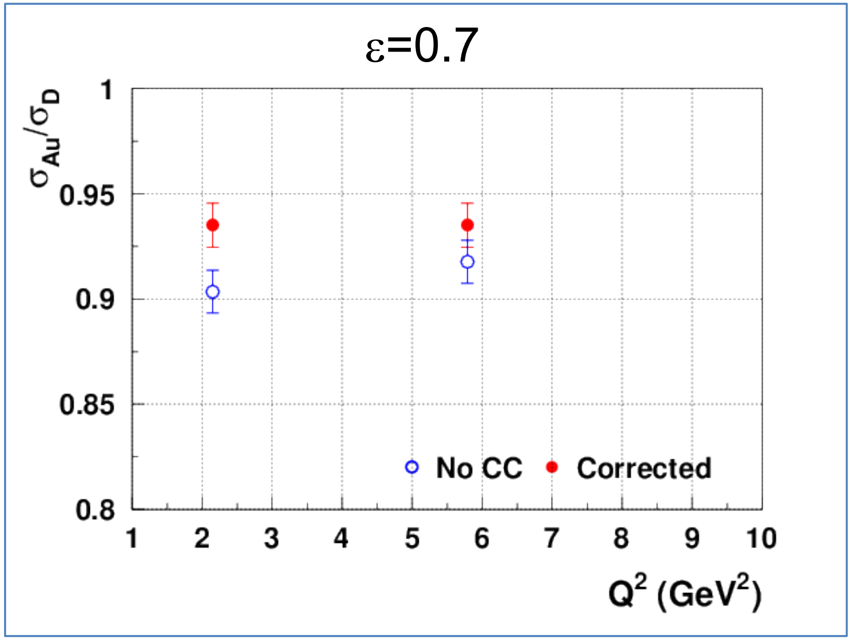

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Assume point-to-point uncertainty ~ 1% - normalization uncertainty not shown

Testing Coulomb Corrections with Positrons

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

Key questions:

1. Are Coulomb Corrections even relevant for DIS?
   - For QE scattering effects have been clearly observed experimentally – clear consensus that CC are required
   - "Makes sense" that they should be needed for DIS, but not a proof
2. Is the 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

E12-14-002 Coulomb Corrections Test with Positrons

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0.7	2.15	4.4	2.11	27.9	1.74	-3.5%
0.7	5.79	11.0	4.83	19.0	2.58	-1.9%

Assume CC for positrons = 1/CC for electrons.
In EMA:
$E_e \rightarrow E_e + V_0$ (e-)
$E_e \rightarrow E_e - V_0$ (e+)

Starting point for CC test w/positrons: E12-14-002 CC test kinematics
→ Polarization not required, so currents ~1 μA hopefully available
→ Magnetic focusing spectrometers still 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

Assuming same statistics goals as electron kinematics (100k deuterium, 50k gold) would take 60 * 16 hours = 960 hours → 40 days

Can use thicker targets, etc., but this would improve things by about a factor of 4 → more modest statistics goals are still useful

E12-14-002 Coulomb Corrections Test w/Positrons

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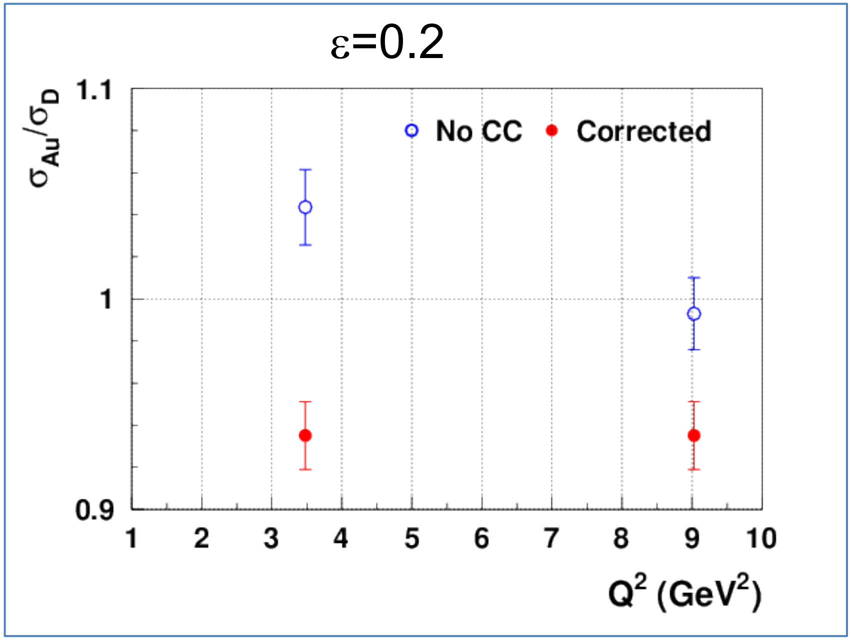
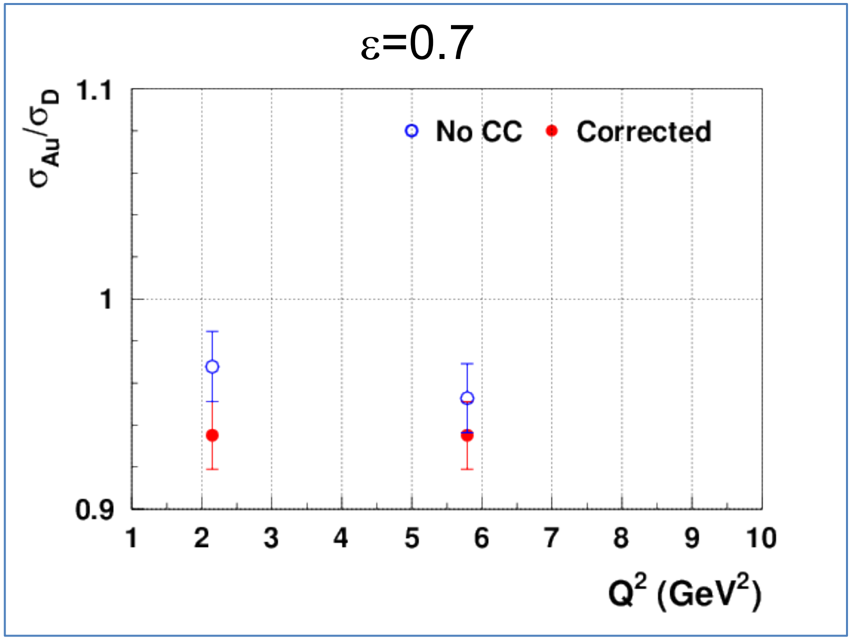
0.7	5.79	11.0	4.83	19.0	2.58	-1.9%

Assuming 1 μA, 10k for all settings and targets → 7 days



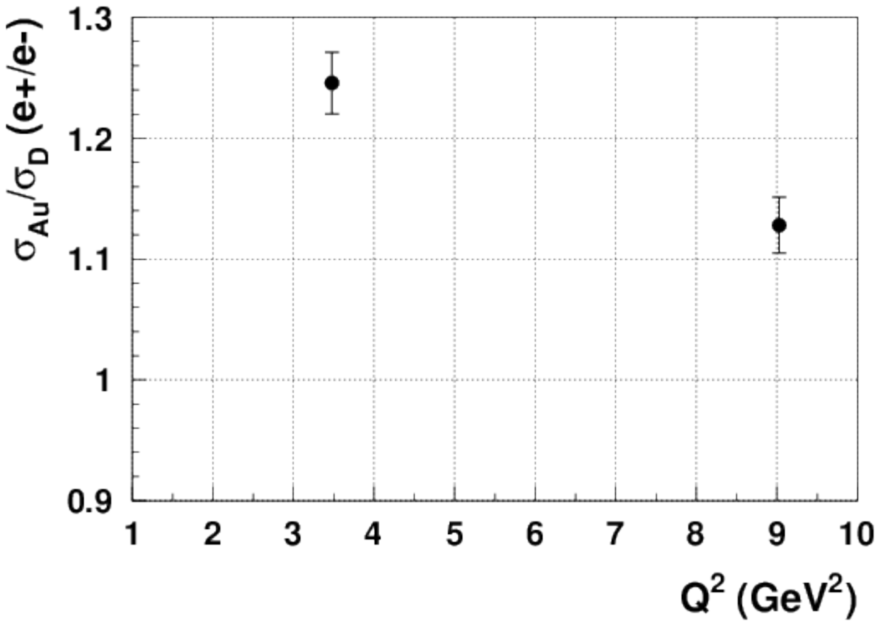


E12-14-002 Coulomb Corrections Test w/Positrons

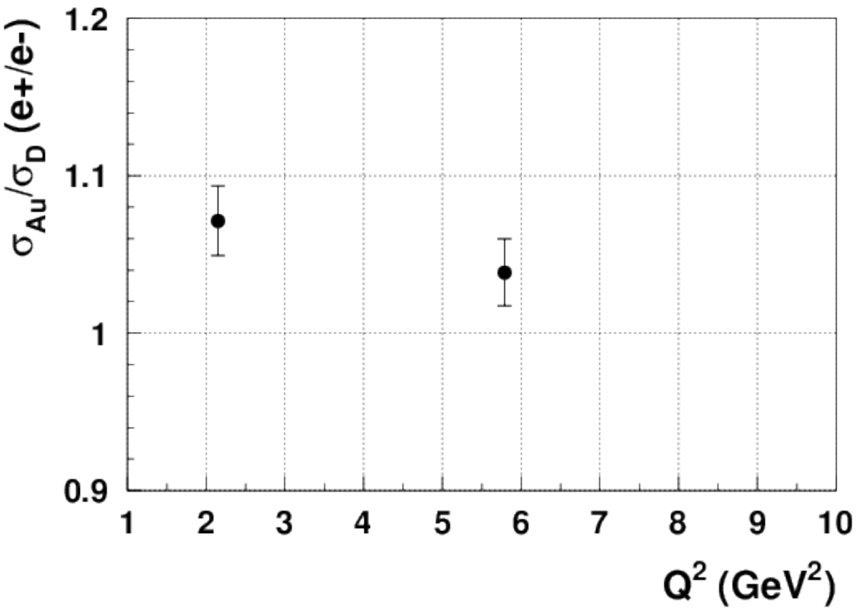
Clearest sign of CC from super-ratio for e+/e-:

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

ε=0.2



ε=0.7



Additional Coulomb Correction Studies

- More studies could be carried out to further elucidate Coulomb Corrections and provide data to test models (EMA)
  - More targets
    - Light target like carbon would provide useful calibration point where impact of CC expected to be small
    - Another heavy target (like iron or copper) would help verify/quantify *Z* dependence of effect and correction
  - More kinematics
    - Would be helpful to reproduce a couple E12-14-002 L-T separations with positrons to obtain a full extraction of R_A-R_D
    - Example: x=0.5, Q^2=3 and Q^2=5 GeV^2

Summary

- An unpolarized positron beam with currents ~ 1μA would allow precise studies of the relevance and size of Coulomb Corrections in DIS from nuclei
- An experiment could be performed in about 2-4 weeks of beam time that would use a subset of the kinematics from E12-14-002
- Use of target ratios (A/D) allows one to compare electron and positron results directly without requiring rapid switching between electron and positron beams
  - Main requirement is to have beam energy the same as much as possible
- Verification (or not) of the validity of the EMA for DIS has important implications for the nuclear dependence of structure functions, in particular R_A-R_D at large x
- Coulomb corrections also relevant for other reactions
  - Hadronization studies: e+A → e'+π+X
  - x>1, A(e,e') at large Q^2
  - Color transparency: A(e,e'p)/H(e,e'p)