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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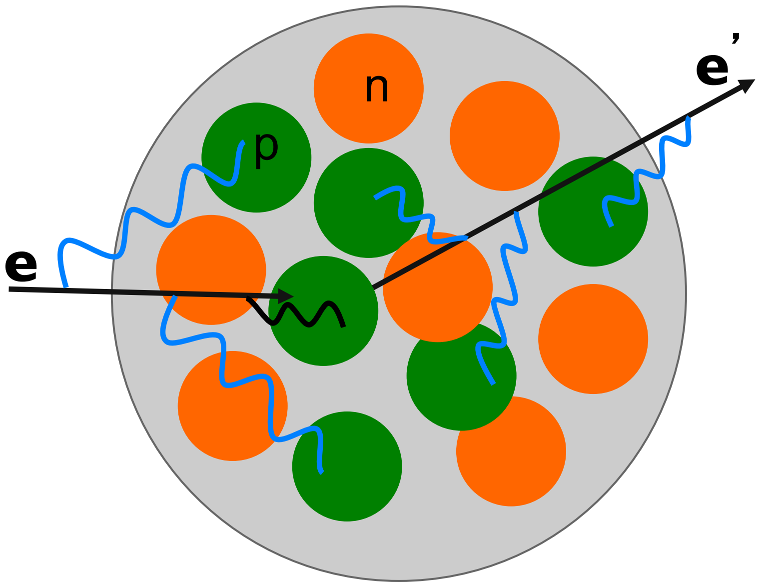
Jefferson Lab Positron Working Group Proposal

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

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

Effective Momentum Approximation (EMA)

$E_e \rightarrow E_e + V_0$

$E_e' \rightarrow E_e' + V_0$

$V_0 = 3\alpha Z/2R$ ⟵ Electrostatic potential energy at center of nucleus

Coulomb Corrections in QE Processes

- Importance of Coulomb Corrections in quasi-elastic processes well known – particularly relevant for measurements of Coulomb Sum Rule
- Distorted Wave Born Approximation calculations are most accurate – but difficult to apply to experimental cross sections
- Experiments instead use Effective Momentum Approximation (EMA)
  - Recent efforts dedicated to cross-checking EMA using DWBA → "Improved EMA"

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

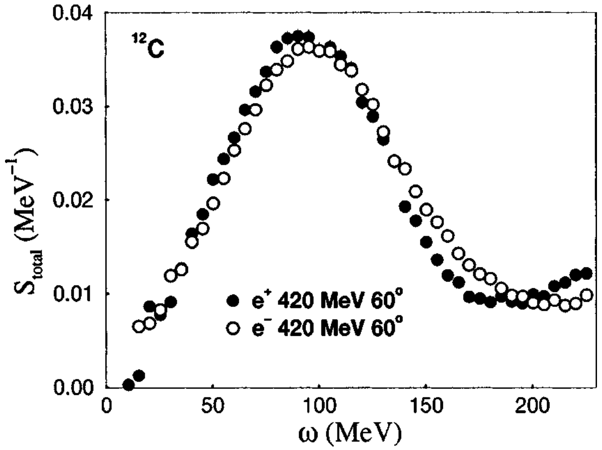
$V_0 \rightarrow (0.7\text{-}0.8)V_0$, $V_0=3\alpha(Z-1)/2R$

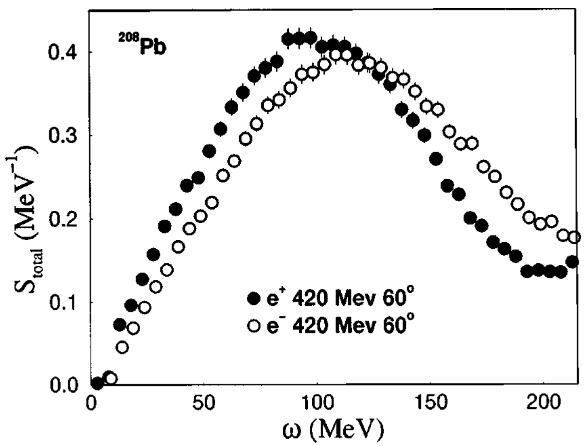
[Aste et al, Nucl. Phys. A, 806:191-215 (2008) Eur.Phys.J.A26:167-178,2005, Europhys.Lett.67:753-759,2004]

Comparisons of electron/positron scattering in QE have provided useful check of EMA

V_0 = 10 MeV for Cu, 20 MeV for Au

Gueye et al., PRC60, 044308 (1999)



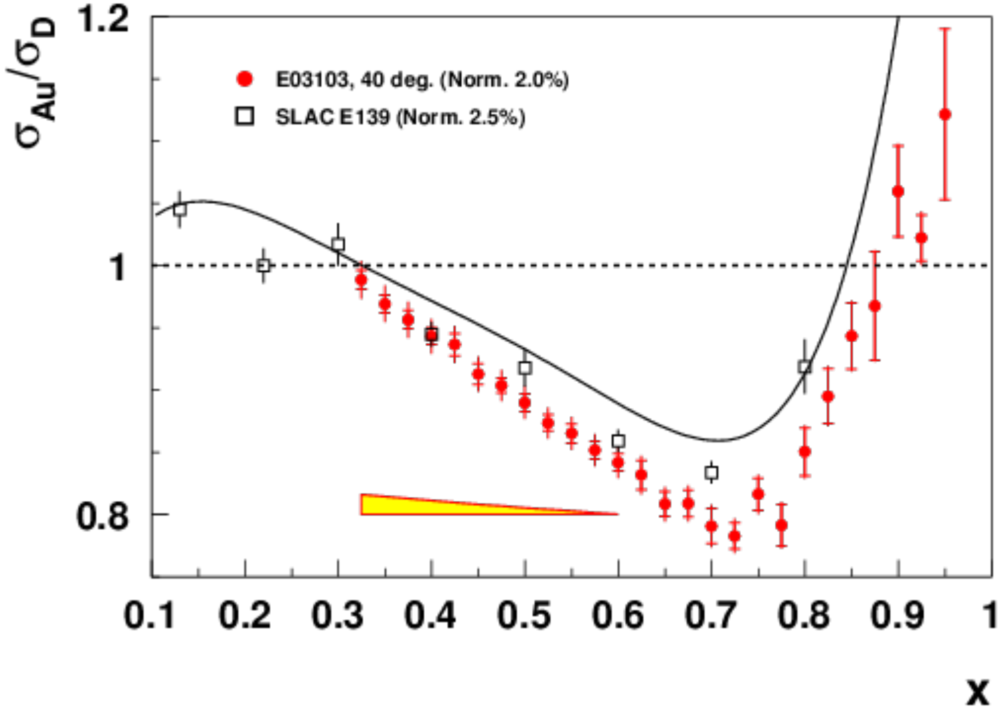


Coulomb Corrections in Inelastic Scattering

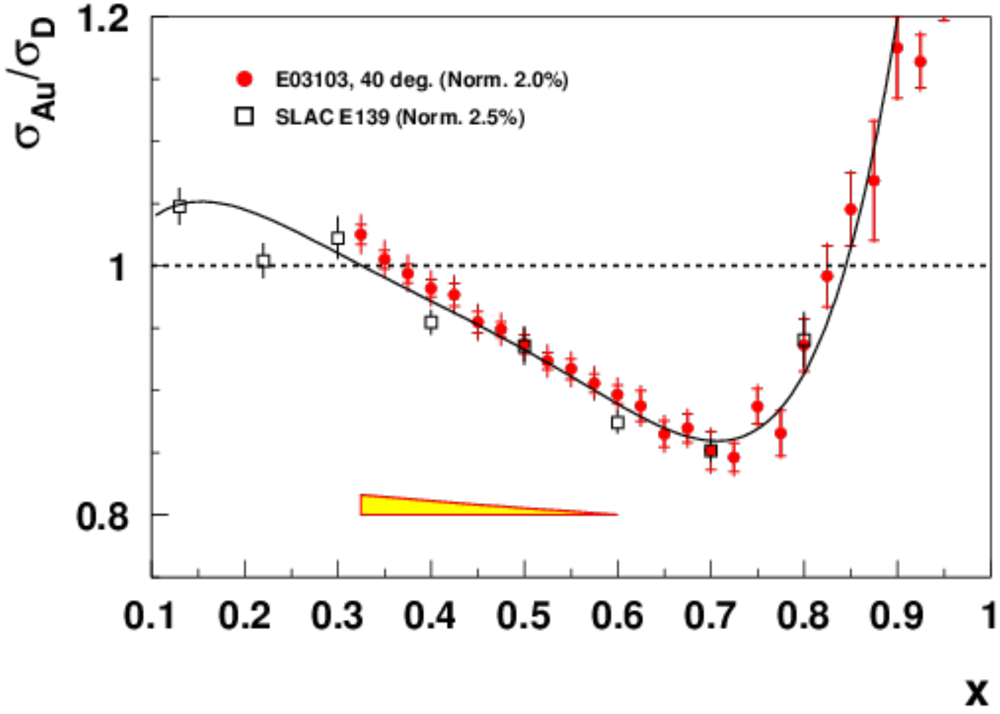
- E. Calva-Tellez and D.R. Yennie, Phys. Rev. D 20, 105 (1979)
  - Perturbative expansion in powers of strength of Coulomb field
  - Effect of order → $-\frac{Z\alpha}{12}\frac{(Q^2)^2}{\nu^2}\frac{(E_e+E_e')}{E_eE_e'} < r >$
  - “For any reasonable kinematics, this is completely negligible” → plugging 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 (both data sets)

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

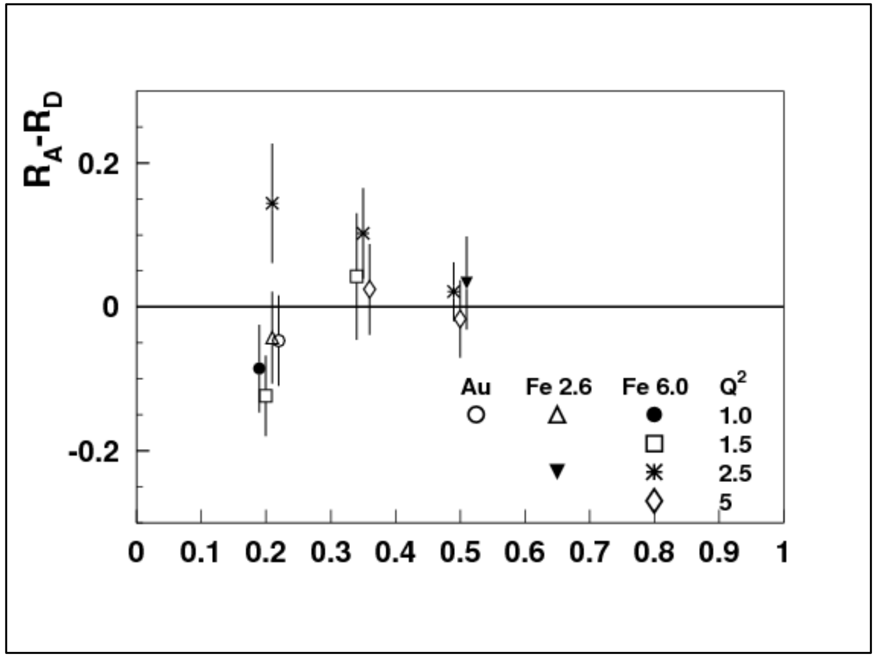
SLAC E-139
E_e ~ 8-25 GeV
E_e' ~4-8 GeV

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)]

<u>This method was used for SLAC E140</u>

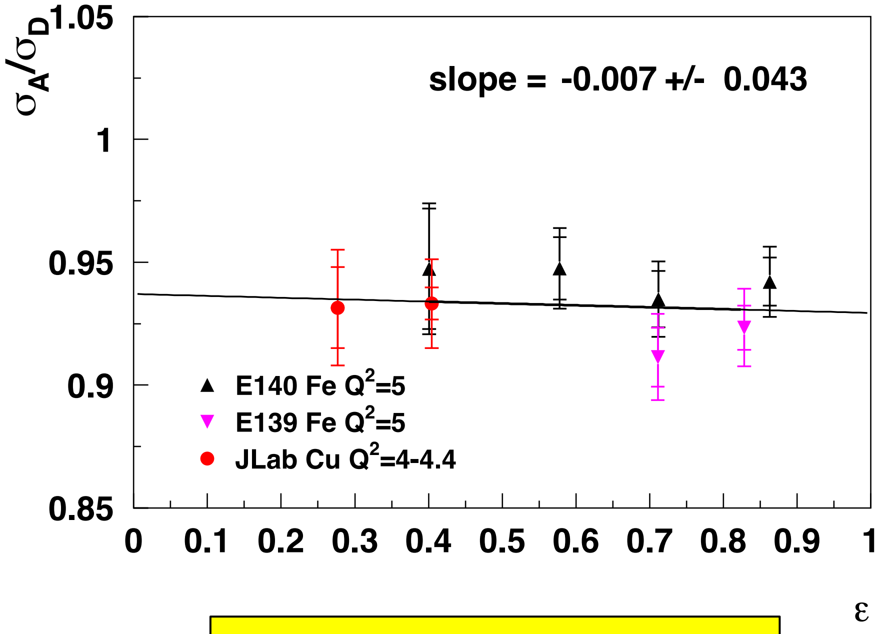
x=0.2, 0.35, 0.5
Q^2 = *1.0, 1.5, 2.5, 5.0* GeV^2
Iron and Gold targets

$R_A - R_D$ consistent with zero within errors

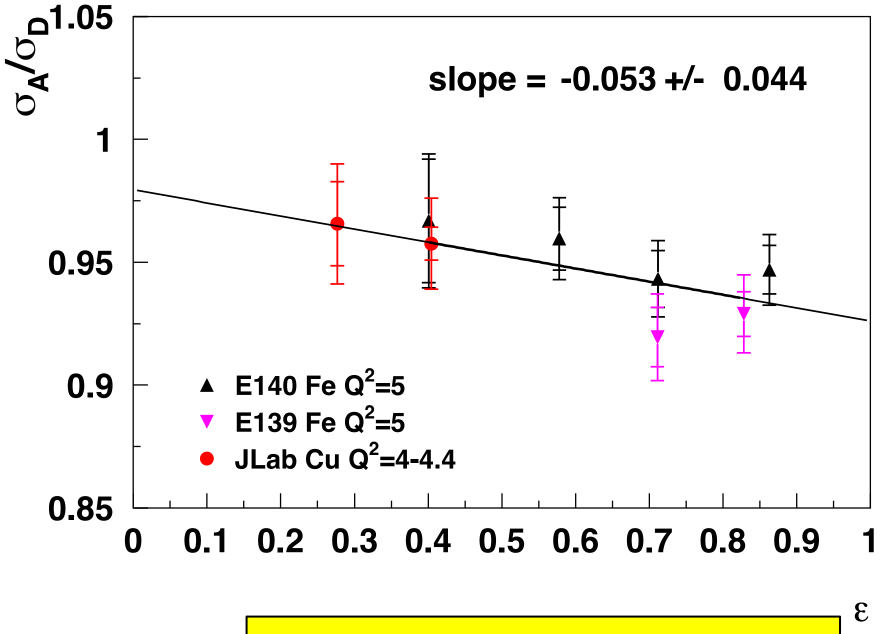
No Coulomb corrections were applied

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**

Impact of CC in DIS: Nuclear Dependence of R



No Coulomb Corrections



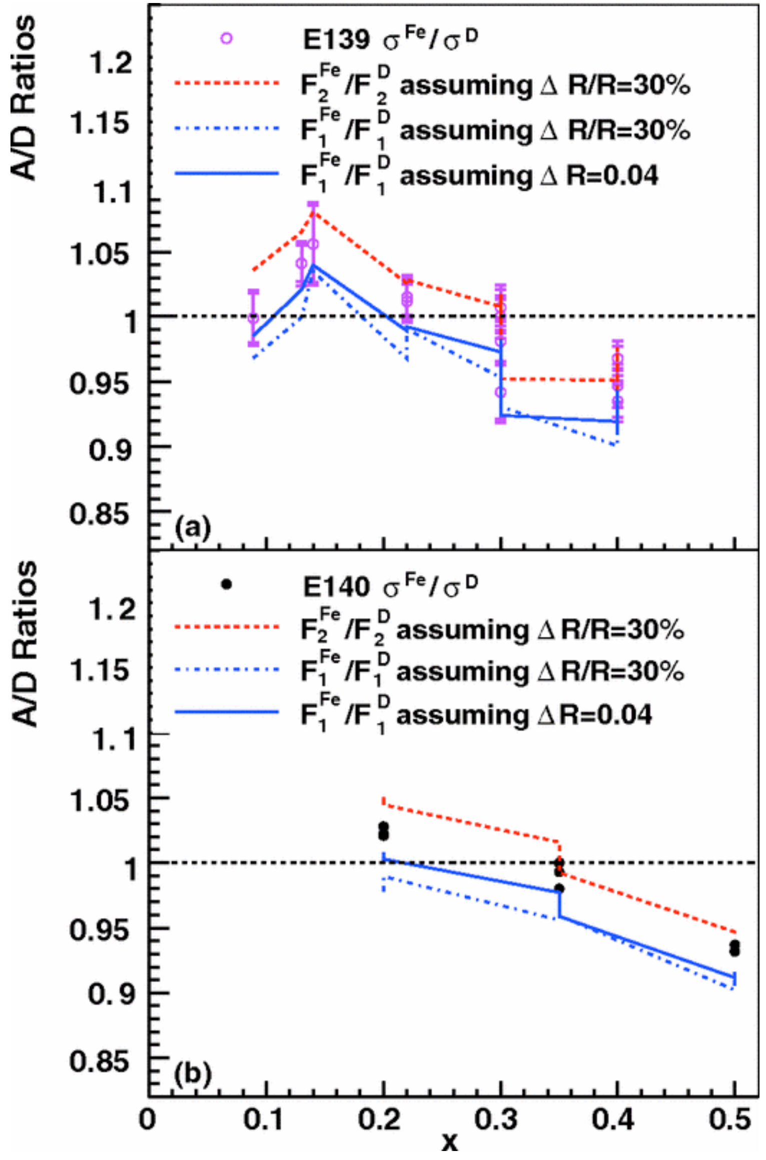
with Coulomb Corrections

PRC 104(6):065203, 2021

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

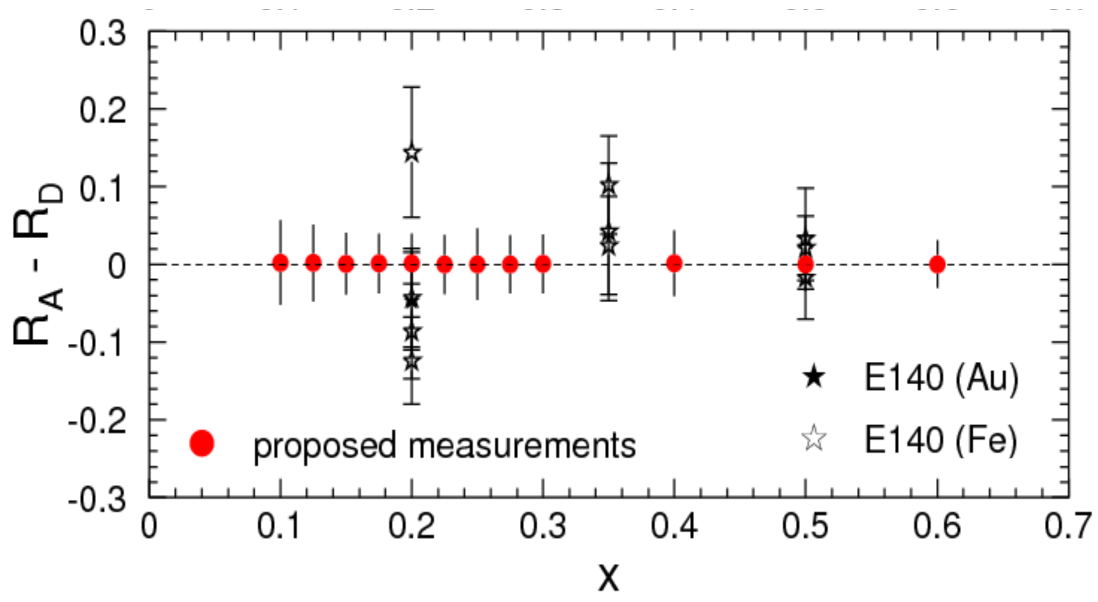
Consequences of non-zero R_A-R_D

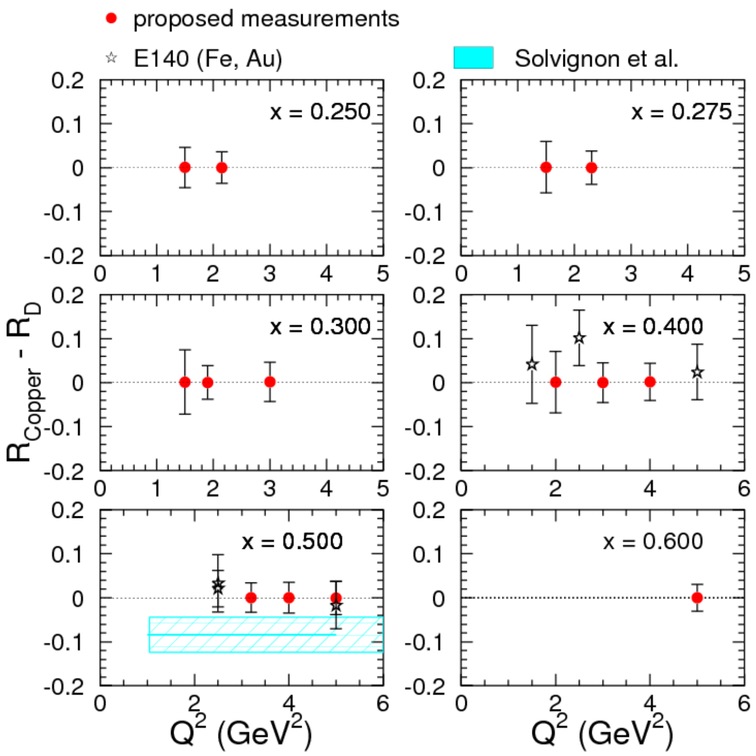
- Several hints that R_A-R_D not zero
  - Effect is not large – depends on precision of the experimental data
  - Coulomb Corrections are crucial to observation/existence of this effect → CC has significant dependence on electron energy, varies between ε settings
- Implications of non-zero R_A-R_D
  - F_1, F_2 not modified in the same way in nuclei → impact on EMC effect?
  - Anti-shadowing a longitudinal photon effect?
  - Parton model: $R=4\langle K_T^2\rangle/Q^2$, $\langle K_T^2\rangle$ 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

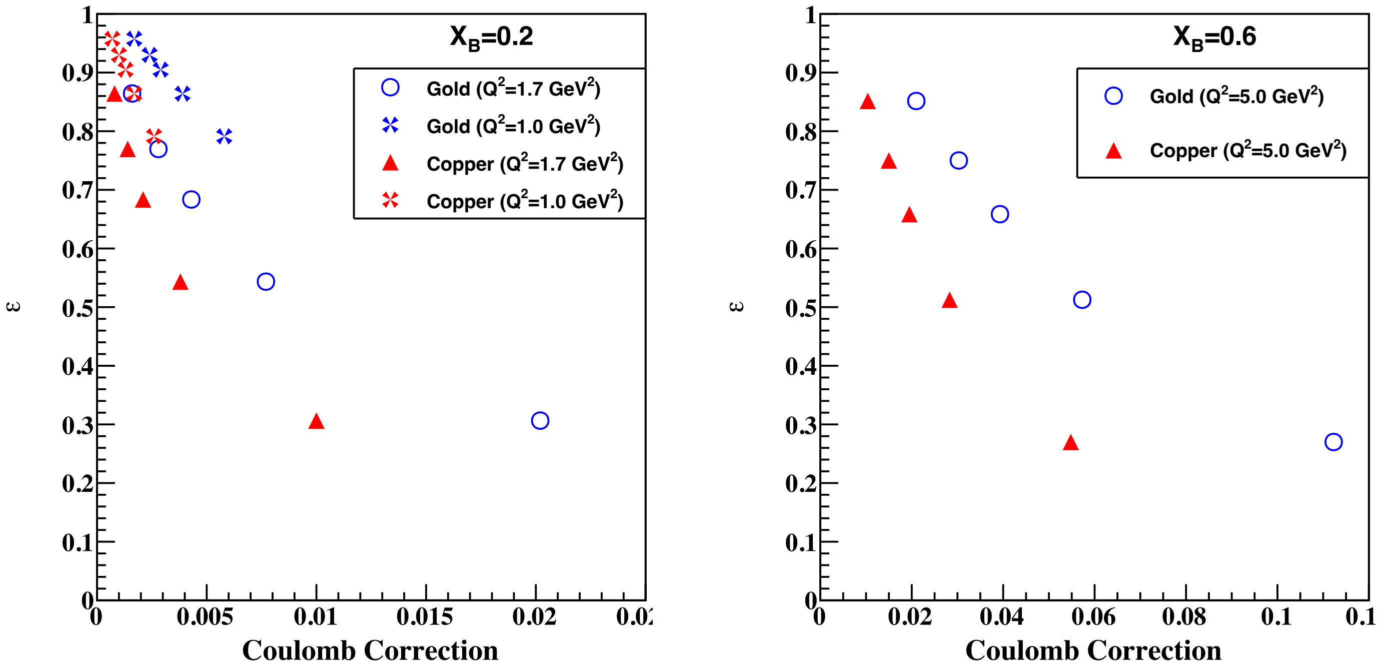
- Precision Measurements and Studies of a Possible Nuclear Dependence of $R=\sigma_L/\sigma_T$
  [S. Alsalmi, M.E. Christy, D. Gaskell, W. Henry, S. Malace, D. Nguyen, T.J. Hague, P. Solvignon]
- Measurements of nuclear dependence of structure functions, R_A-R_D via direct L-T separations





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

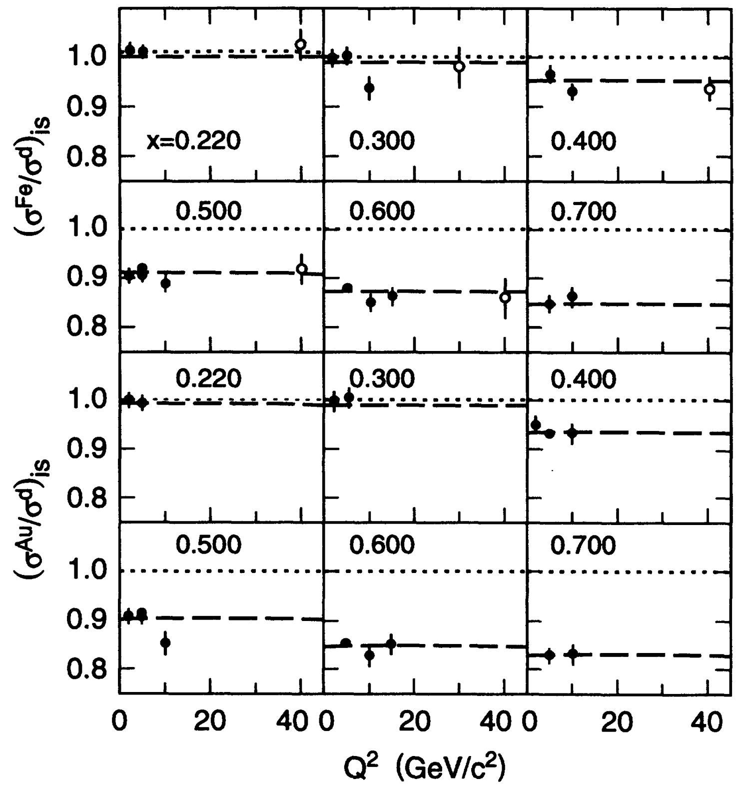
Coulomb corrections can be tested by measuring target ratios at fixed ***x*** and **ε**
→ Varying Q^2 allows us to change E and E' and hence size of CC

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

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

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

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



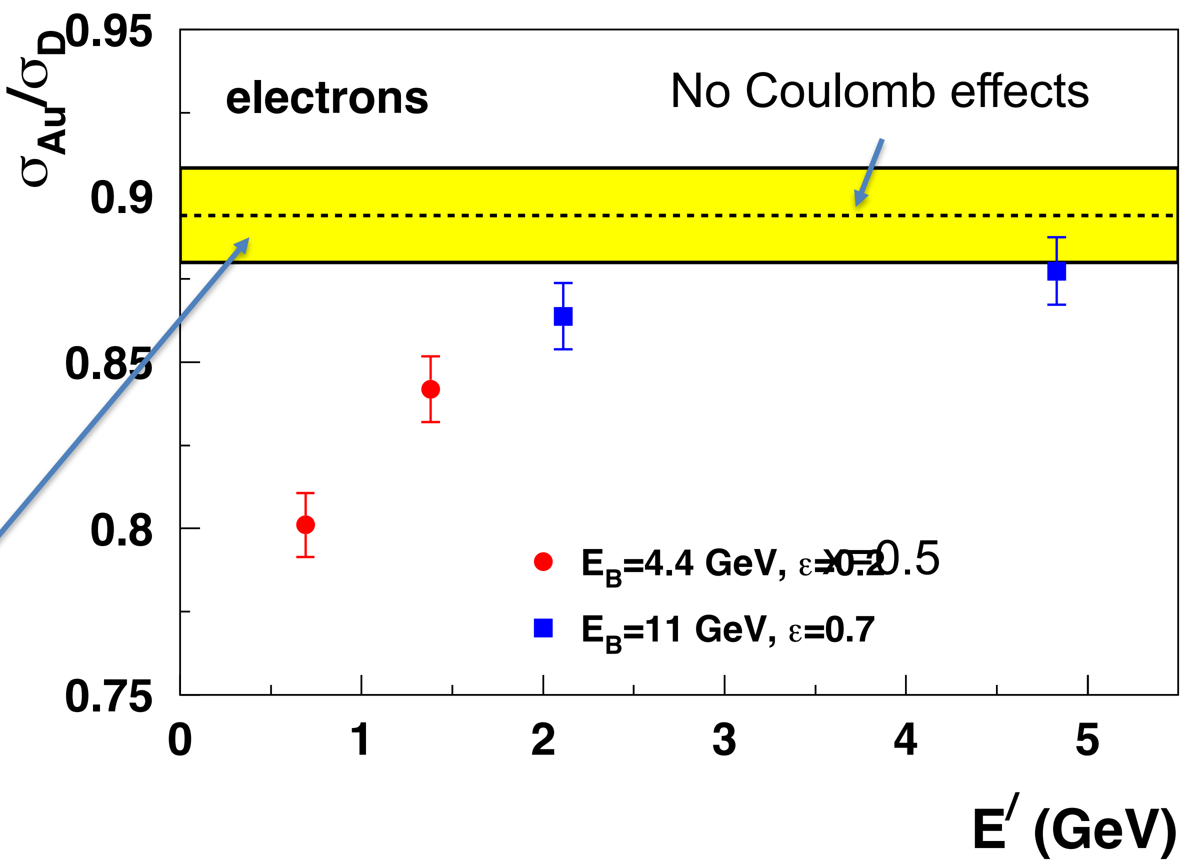
E12-14-002 Coulomb Corrections Test

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

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



Testing Coulomb Corrections with Positrons

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

Key questions:

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 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

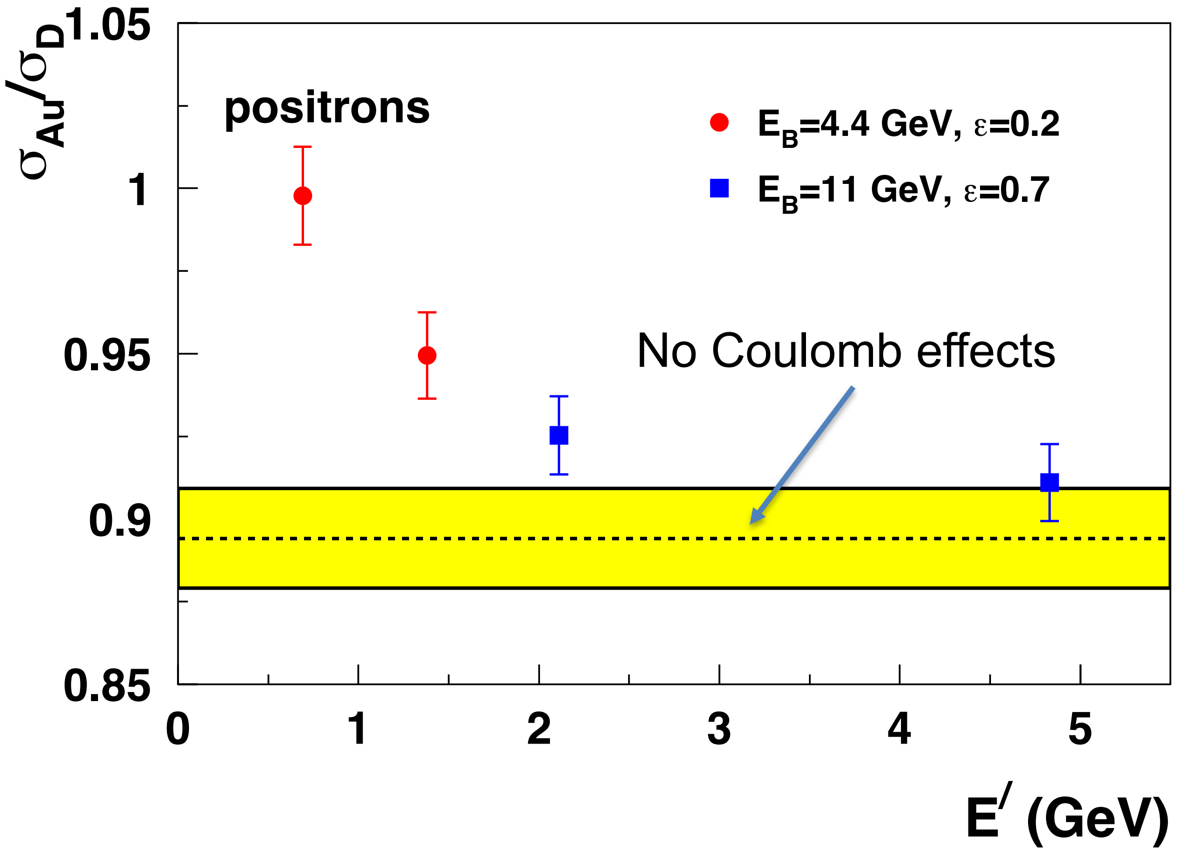
Source	$\delta R/R$ (%) point-to-point	$\delta R/R$ (%) scale
Spectrometer momentum	-	$< 0.1\%$
Beam energy	-	$< 0.1\%$
θ_{spec}	-	$< 0.1\%$
Charge	0.35%	-
Target Boiling	-	$< 0.1\%$
Total dead time	0.15%	0.14%
Detector efficiency	0.11%	-
Charge Symmetric Background	0-1%	-
Radiative Corrections	0.55%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

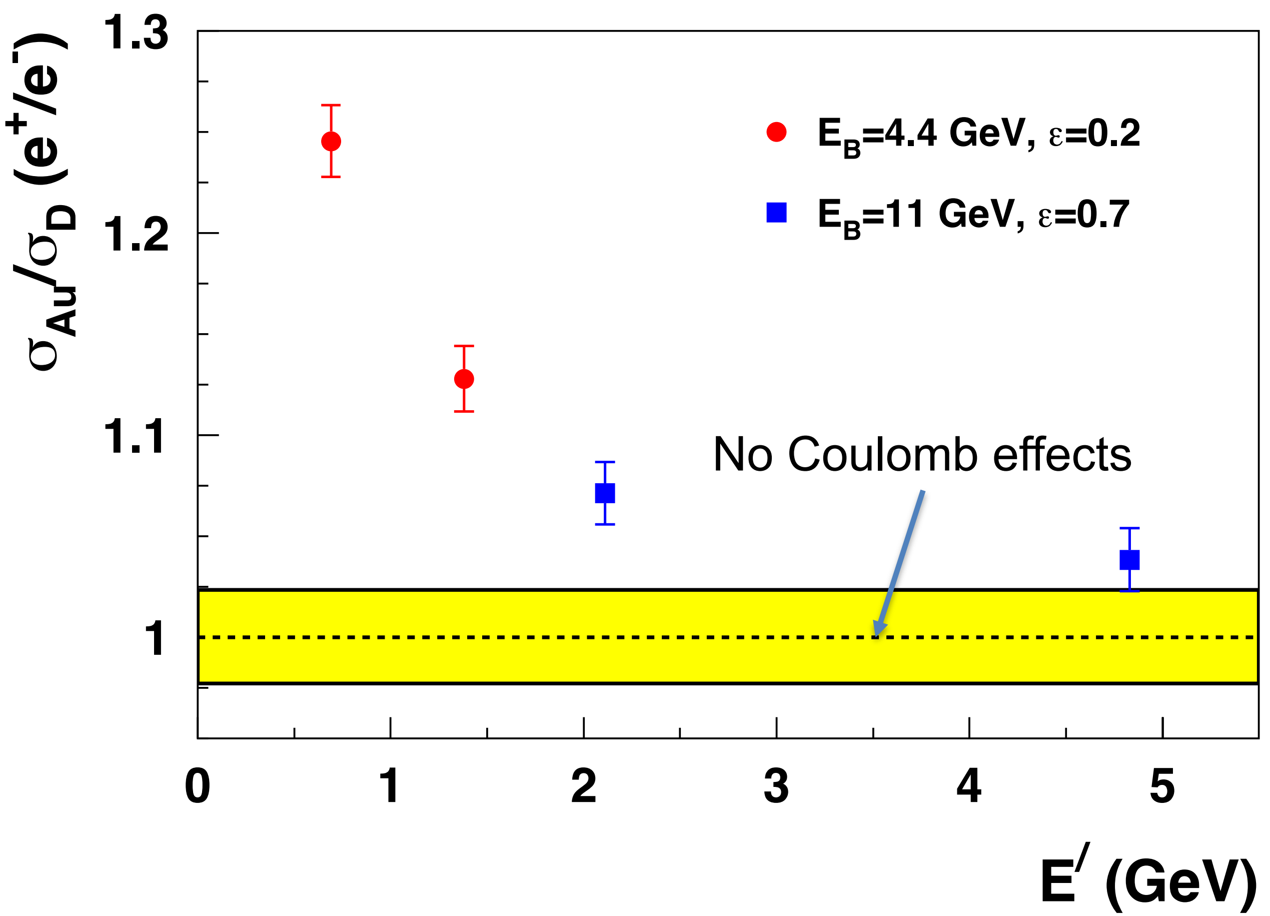
Total time requested = 223.3 hours (9.3 days)



E12-14-002 Coulomb Corrections Test w/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 → e'+π+X
  - *x*>1, *A(e,e')* at large Q^2
  - Color transparency: A(e,e'p)/H(e,e'p)

EXTRA

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

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 $R=\sigma_L/\sigma_T$ is the same for A and D

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

J. Caylor, S. Covrig, D. Gaskell (spokesperson), W. Henry (spokesperson),
D. Jones, D. Mack, M. McCaughan
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J. Arrington, T. J. Hague, S. Li, E. Sichtermann
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Cameron Cotton
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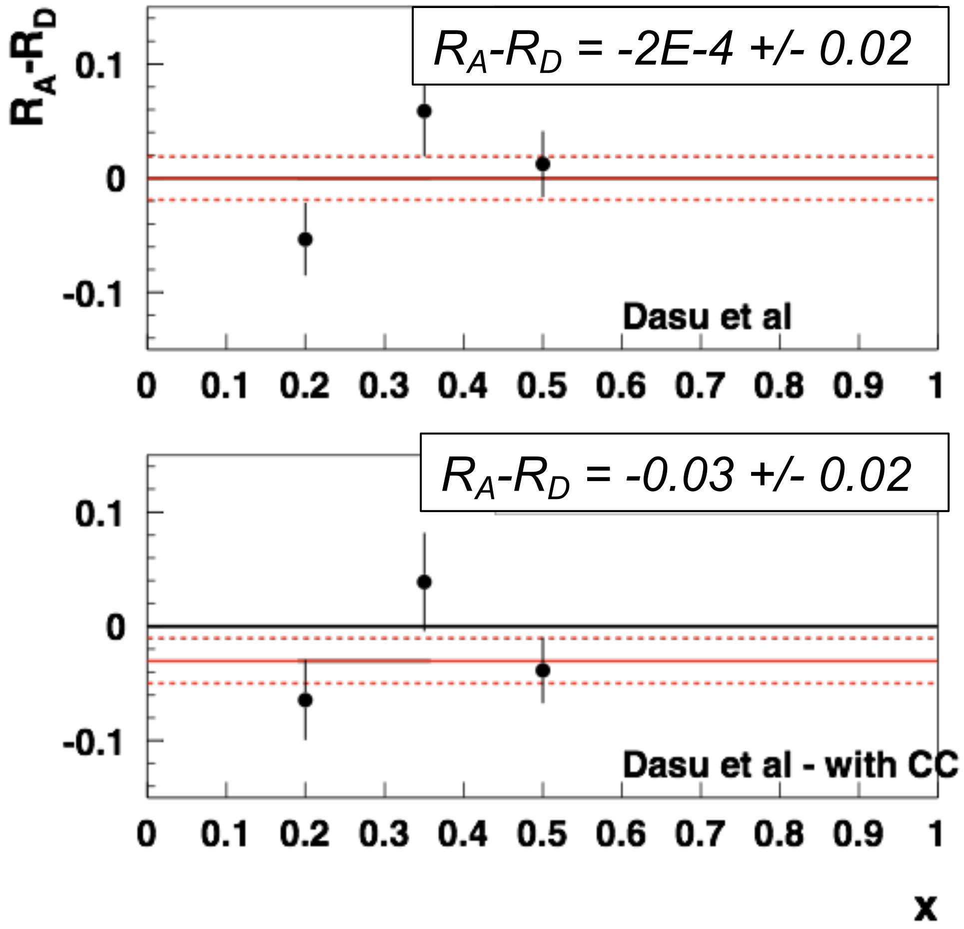
Department of Natural Sciences, Virginia Union University

Jefferson Lab Positron Working Group Proposal

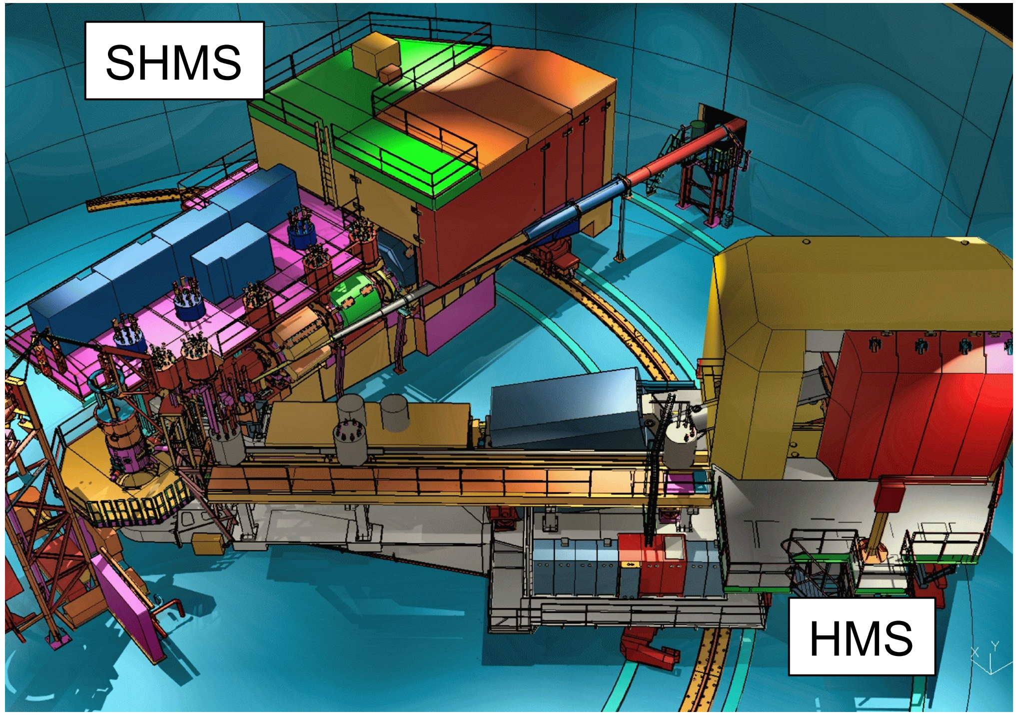
R_A-R_D: E140 Re-analysis

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***

Hall C: HMS and SHMS



Spectrometers

HMS:
$d\Omega \sim 6$ msr, $P_0 = 0.5 - 7$ *GeV/c*
$\theta_0 = 10.5$ *to 80 degrees*
e ID via calorimeter and gas Cerenkov

SHMS:
$d\Omega \sim 4$ msr, $P_0 = 1 - 11$ *GeV/c*
$\theta_0 = 5.5$ *to 40 degrees*
e ID via heavy gas Cerenkov and calorimeter

Excellent control of point-to-point systematic uncertainties