# Jeopardy Update

PAC 51
Jefferson Lab
July 24-28, 2023

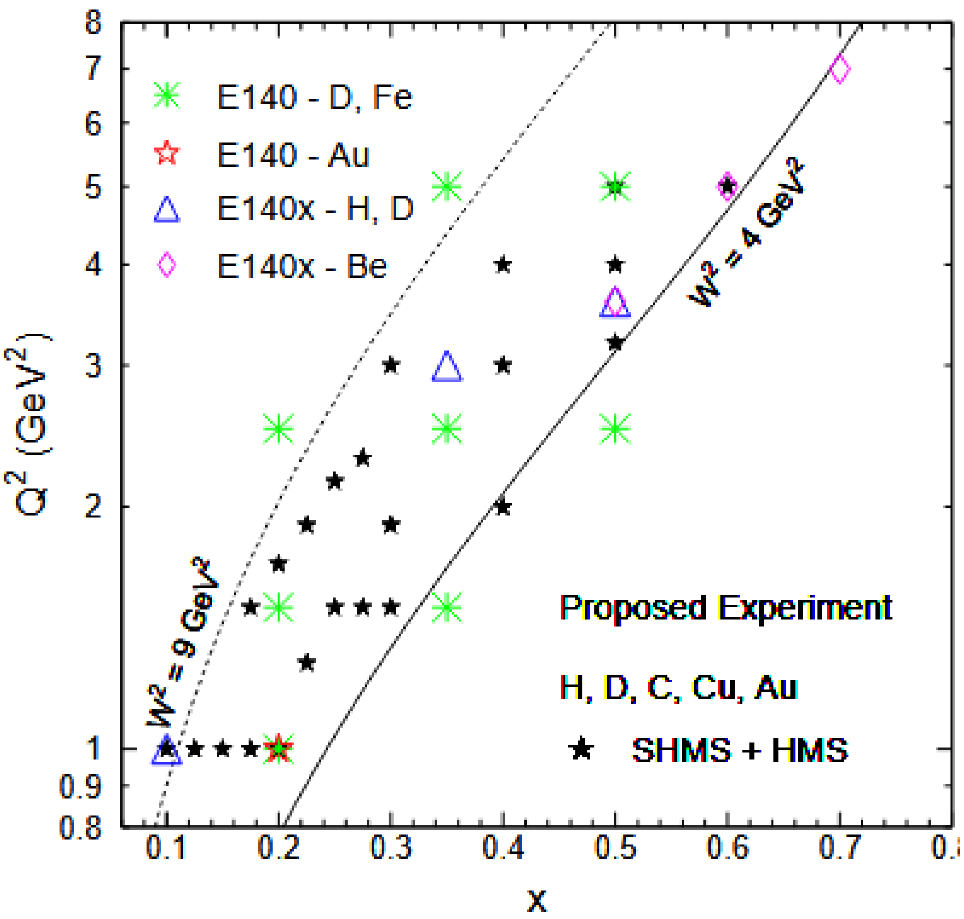
# E12-14-002: Precision Measurements and Studies of a Possible Nuclear Dependence of R

William Henry

Wednesday, July 26, 2023

# Experiment Overview

- Targets: H, D, C, Cu, Ag
- Beam Energies: 4.4, 5.5, 6.6, 7.7, 8.8, 11 GeV
- Equipment: Hall C SHMS and HMS
- Beam Time: 22 days
- Technique: Model independent Rosenbluth L/T separation
- Goal: To precisely measure and study the nuclear dependence of:
  - $R = {}^{\sigma_L}/_{\sigma_T}$
  - $R_A - R_D$
  - $R_D - R_P$
  - $F_1, F_2, F_L$



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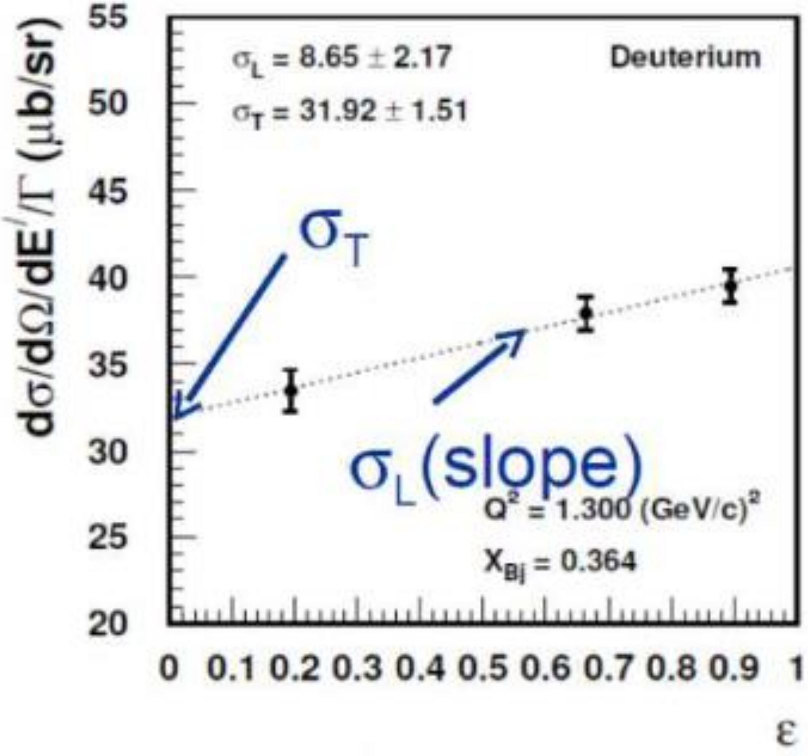
$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma\sigma_T(1+\varepsilon R)$$

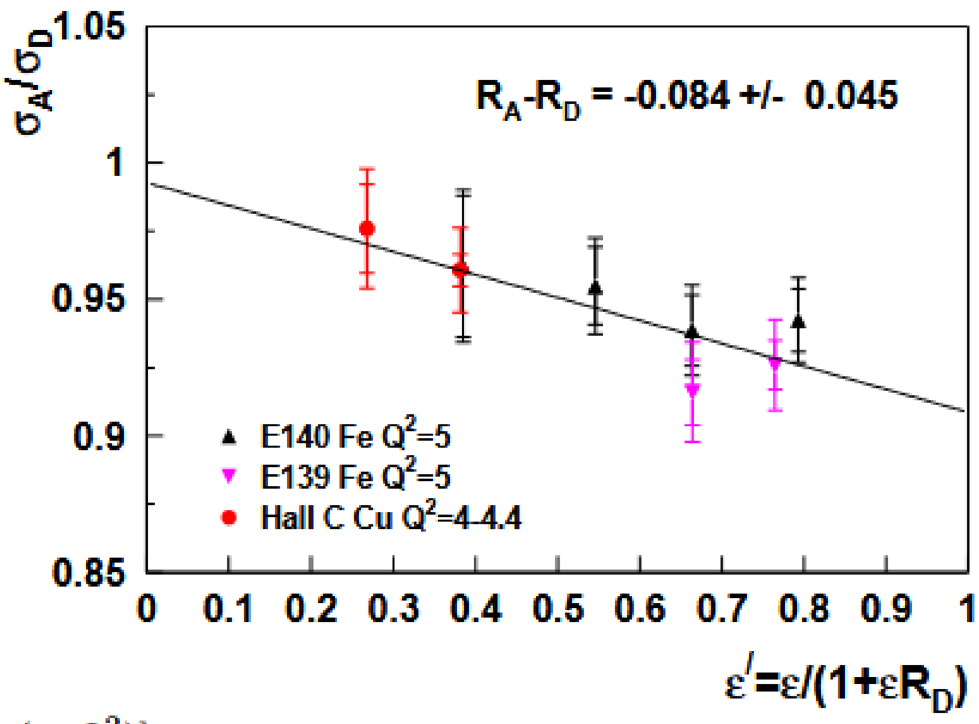
$$\Gamma = \frac{\alpha}{2\pi^2 Q^2}\frac{E'}{E}\frac{K}{1-\epsilon}, K = \nu(1-x) \qquad \epsilon = \left[1 + 2\left(1+\frac{\nu^2}{Q^2}\right)\tan^2\frac{\theta}{2}\right]^{-1}$$



# Experimental Overview

- Aim: To determine the nuclear dependence and to precisely measure:
  - $R = \sigma_L / \sigma_T$
  - $R_A - R_D$
  - $R_D - R_P$
  - $F_1, F_2, F_L$

$$\frac{\sigma_A}{\sigma_D} = \frac{F_1^A}{F_1^D}\left[1 + \frac{\epsilon}{1+\epsilon R_D}(R_A - R_D)\right]$$




$$F_L(x,Q^2) = \frac{2xKM}{4\pi^2\alpha}\sigma_L(x,Q^2)$$

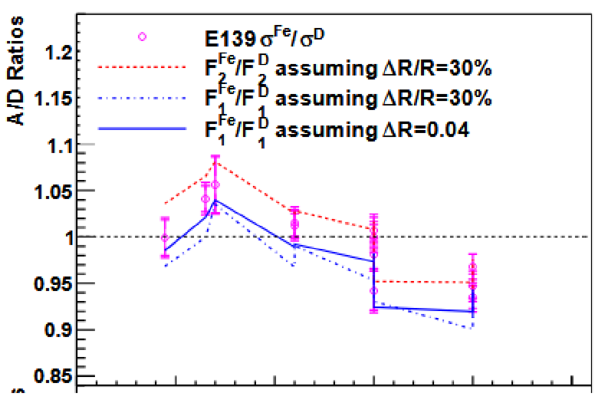
$$F_1(x,Q^2) = \frac{KM}{4\pi^2\alpha}\sigma_T(x,Q^2)$$

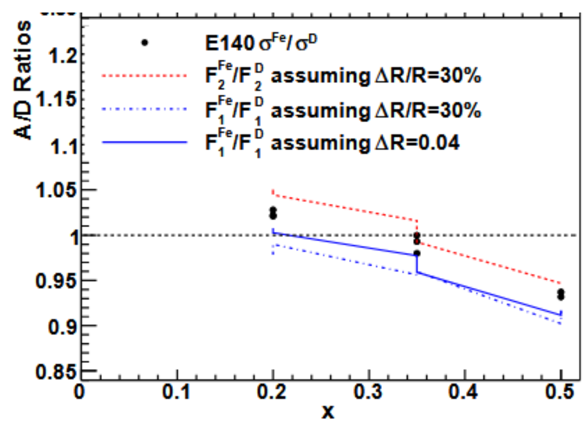
$$F_2(x,Q^2) = \frac{K}{4\pi^2\alpha}\frac{\nu}{(1+\nu^2/Q^2)}[\sigma_T(x,Q^2) + \sigma_L(x,Q^2)]$$

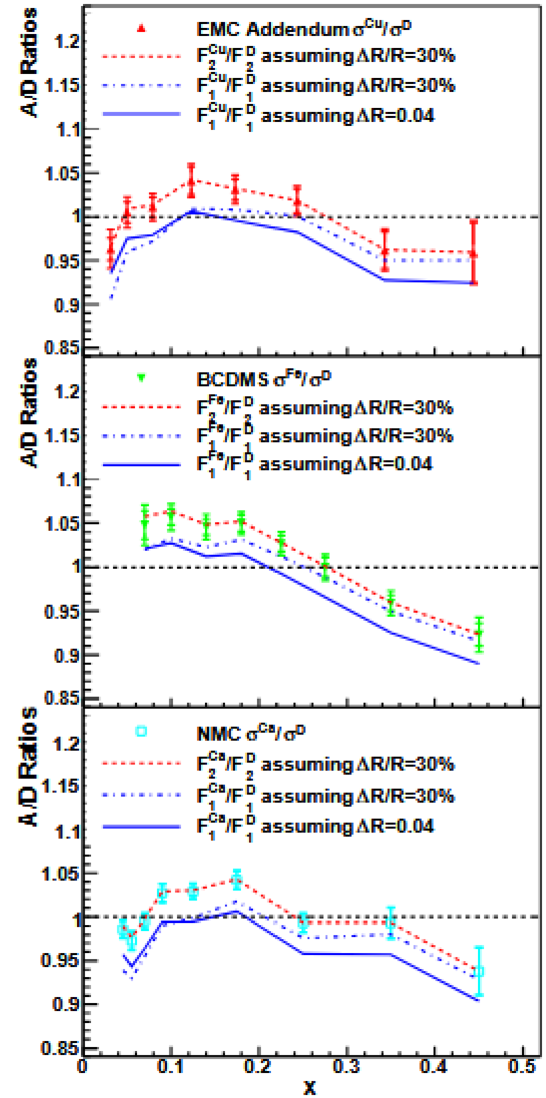
You need to know R to accurately extract F2!

# Motivation

- The impact of a non-zero ΔR for the antishadowing region on $F_1$ and $F_2$
- Anti-shadowing disappears for $F_1$, remains for $F_2$
- Is $F_L$ responsible for the antishadowing region?
- ΔR = .04 and 30% base on NMC $R_{Sn}$-$R_C$

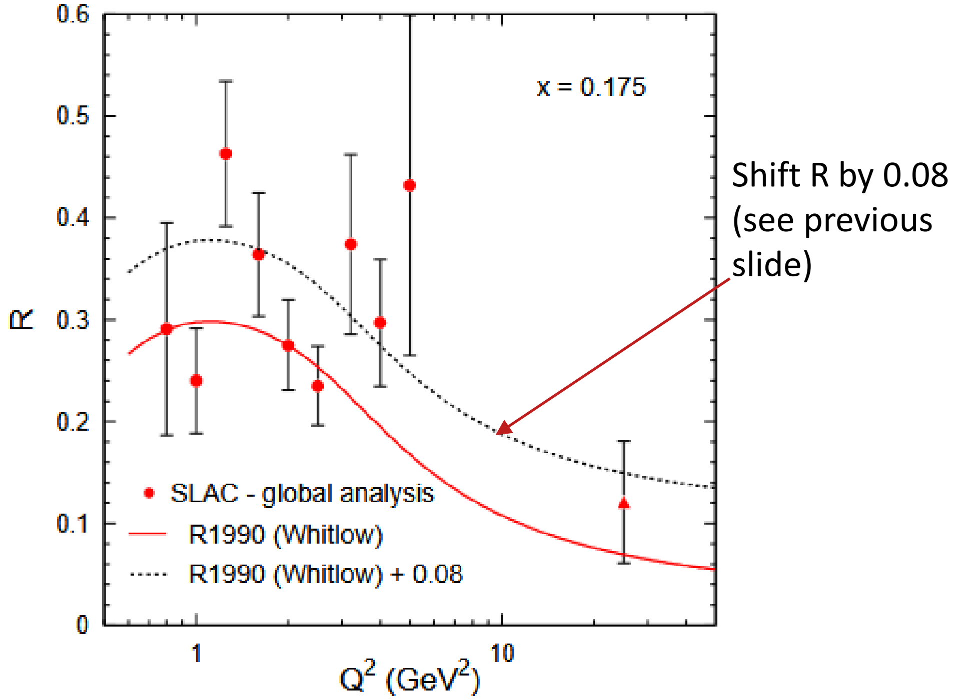


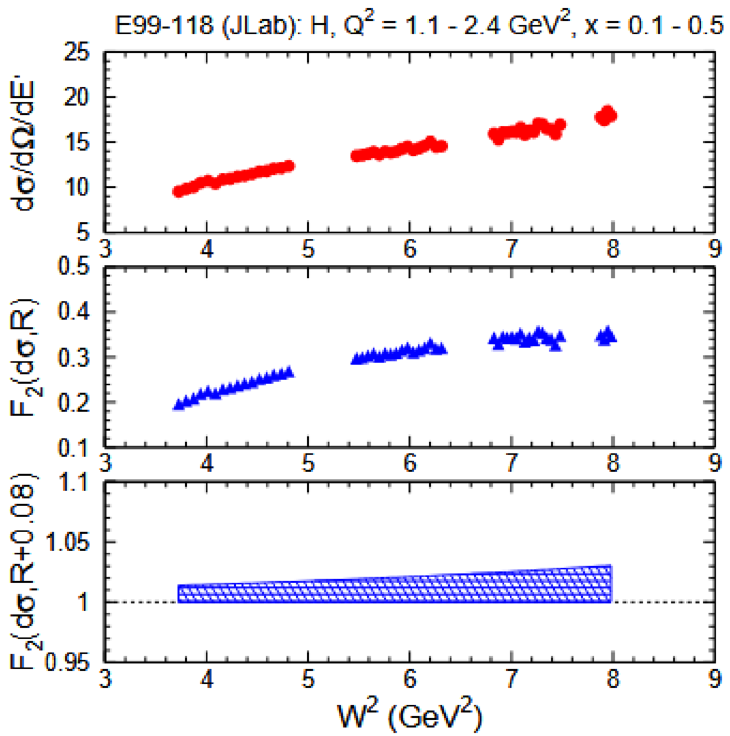




V.Guzey et al., PRC 86 045201 (2012)

# Motivation




$$\Delta R = 0.08 \longrightarrow \Delta F_2 = 4\ \%$$

- Our lack of knowledge of R results in uncertainties of structure functions
- If one assumes a change in R of 0.08 (dashed line), F2 changes by 4%
- EMC effect is ~15%, this 4% can contribute ~30% uncertainty on this “well-known” effect
- R1990 and R1998 have together have 1,790 citations!!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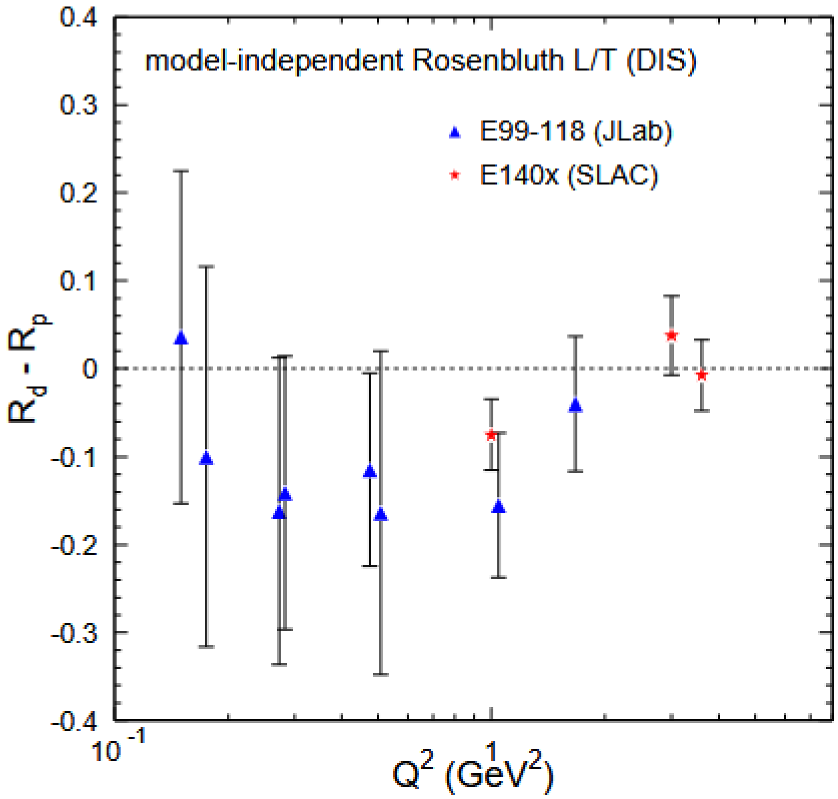
# Motivation




- R1990 assumes $R_d$=$R_p$
- The only published model independent measurements of $R_d$-$R_p$ in DIS at low to moderate Q2 are from E140x and E99-118
- $R_d$-$R_p$ =-0.054 +/- 0.029 (E99-118, PRL 98, 142301 (2007))
- $R_d$-$R_p$ =-0.042 +/- 0.018 (E99-002, PRC 97, 045204 (2018))
- A common assumption when extracting structure function from cross section ratios is $R_d = R_p$

$$\frac{\sigma_d}{\sigma_p} = \frac{F_2^d}{F_2^p} \quad only\ if \quad R_d = R_p$$



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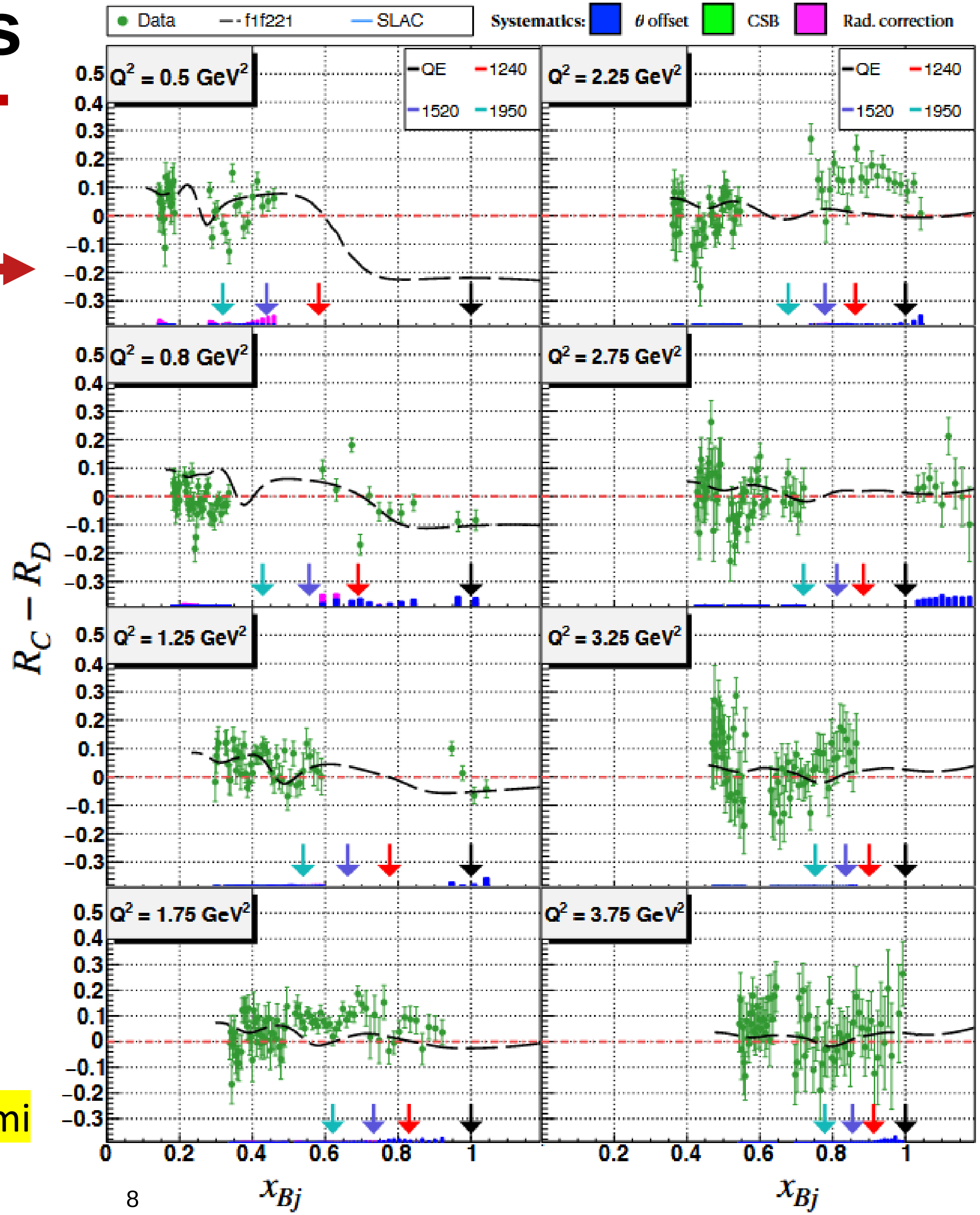
# New 6 GeV Results

$R_{Carbon}$ - $R_{Deuteron}$

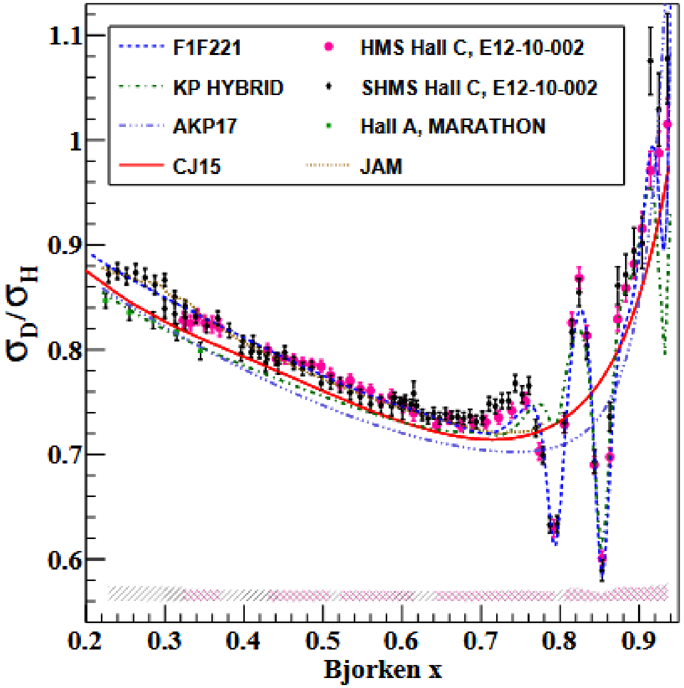
- New 6 GeV Hall C results which focused on resonance region
- Results implies $R_C$-$R_D$ > 0 (larger Q2 clearly not zero)
- Recall R is ~ (0.2 - 0.3) so $\Delta R = 0.1$ is BIG
- $R_C$ - $R_d$ > 0 which is opposite as was found in previous experiments (see slide 4)



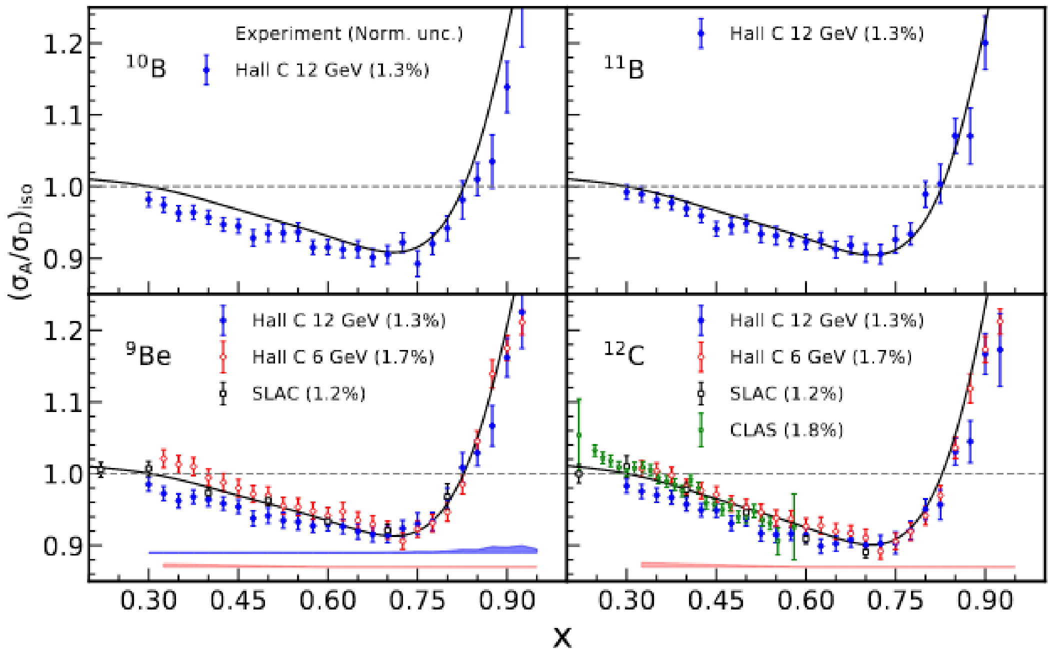

Analysis by Sheren Alsalmi

# Experience with SHMS in 12 GeV Era

“F2 in Hall C” E12-10-002

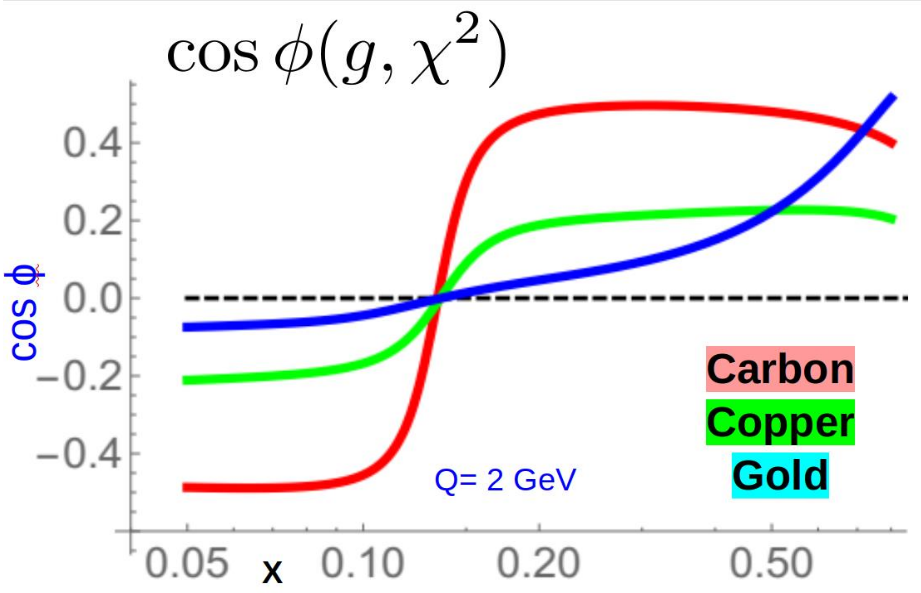



“EMC in Hall C” E14-10-002




- The commissioning experiments, F2 and EMC, provided experience using the new SHMS
- The E12-14-002 analysis will closely follow a similar analysis roadmap
- Point to point systematics are well understood
- Experiment is ready to run

# Impact studies using nCTEQ




gluon sensitivity vs. nuclear A

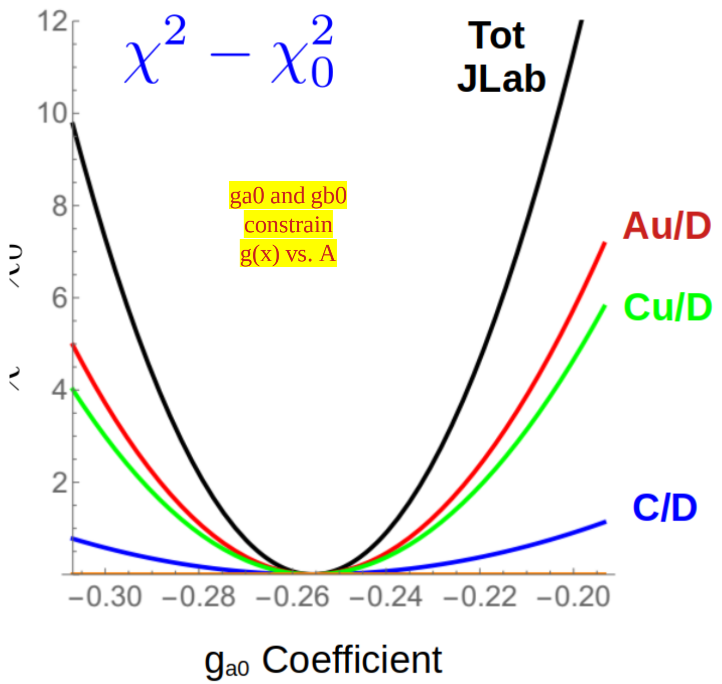
$$\cos\phi[X,Y] = \frac{\sum_{i_{pdf}} \left(X^{(+)}_{i_{pdf}} - X^{(-)}_{i_{pdf}}\right)\left(Y^{(+)}_{i_{pdf}} - Y^{(-)}_{i_{pdf}}\right)}{\sqrt{\sum_{i'_{pdf}} \left(X^{(+)}_{i'_{pdf}} - X^{(-)}_{i'_{pdf}}\right)^2}\sqrt{\sum_{i''_{pdf}} \left(Y^{(+)}_{i''_{pdf}} - Y^{(-)}_{i''_{pdf}}\right)^2}},$$

This shows the cosine correlation between the gluon and the JLab data as a function of x for Q=2 GeV. This shows the differing influence of the data across the kinematic range, and for the different nuclear A values.

Work done by: Fred Olness, Tomas Jezo, Aleksander Kusina & Karol Kovarik for nCTEQ

# Impact studies using nCTEQ

This shows the chi2 scans of the ga0 coefficient which, in part, controls the momentum fraction of the nuclear gluon component. The total of the JLab experiments yields between 10 and 15 units of chi2. For comparison, recall the nCTEQ15 tolerance was delta-chi2 of 35, and these scans run over approximately 50 units of chi2. Thus these experiments can help constrain the gluon across different nuclear A values.




$$x\, g_i^{p/A}(x, Q_0) = g_0\, x^{g_1} (1-x)^{g_2} e^{g_3 x} (1 + e^{g_4} x)^{g_5}$$

$$g_0(A) = g_{p0} + g_{a0} (1 - A^{-g_{b0}})$$

$$\sigma_{red} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

$$Y_+ = 1 + (1-y)^2$$

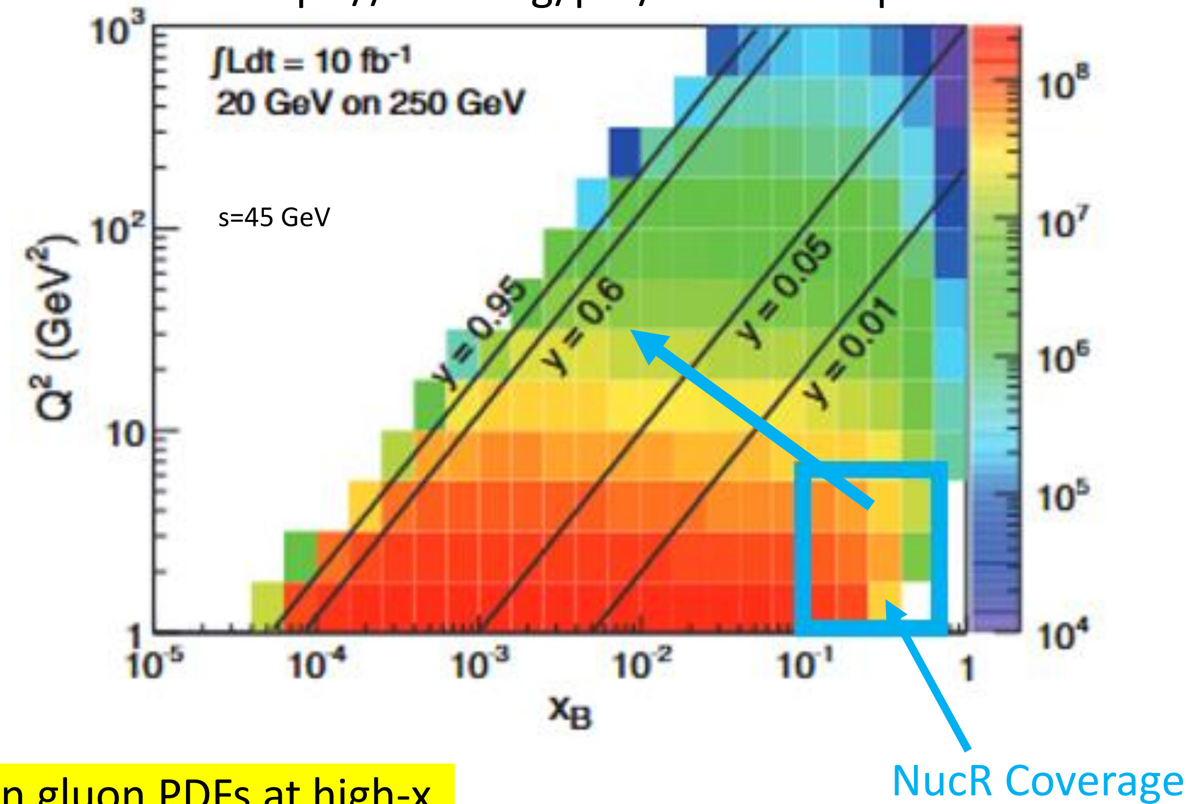
$$F_L = \alpha_S \left[ c_g \otimes g(x) + c_q q(x) \right]$$

Provides key information on the gluon at intermediate x vs. nuclear A

Work done by: Fred Olness, Tomas Jezo, Aleksander Kusina & Karol Kovarik for nCTEQ

# Impact studies using nCTEQ

https://arxiv.org/pdf/1212.1701.pdf




- Information on gluon PDFs at high-x, low Q2 provides insight into low-x, high Q2 EIC kinematics.

Provides key information on the gluon at intermediate x vs. nuclear A

# Workforce

## Spokespeople

Sheren Alsalmi (King Saud's University)
Eric Christy (JLab)
Dave Gaskell (JLab)
Bill Henry (JLab)
Simona Malace (JLab)
Tyler Hague (LBNL)
Dien Nguyen (JLab/UTenn)

- Since E12-14-002 approval, the spokespeople have undergone some changes. New Members
- Thesis students and shift takers will be provided by Univ. of Tennesse and possibly King Saud's Univ.
- Current collaboration has extensive experience in L/T separations, EMC experiments, precision measurements, Hall C, radiative corrections and target ratio type analysis

Bill Henry

# Summary

wmhenry@jlab.org

- E12-14-002 will precisely measure and study the nuclear dependence of R, $R_A$-$R_d$, $R_d$-$R_p$, $F_L$, $F_1$, and $F_2$
- A nuclear dependence of R could shine new light on the origin of the anti-shadowing region and EMC effect
- Precision structure function from cross section measurements require precise (and non-existent) measurements of R
- Measurements of FL can provide constraints on the gluon PDFs
- Successful commissioning of the SHMS, new results from the "F2" and "EMC", and a team experienced in Hall C demonstrate the readiness of this experiment to run
- Hall C is the only place that can achieve this kind of measurement using the precision focusing spectrometers

Bill Henry
wmhenry@jlab.org

# Closing Remark

| | Proposal | Status | Hall | Title | Spokesperson | Institutions | Beam days | Rating | PAC | |
|---|---|---|---|---|---|---|---|---|---|---|
| | E12-14-002 | A | C | Precision Measurements and Studies of a Possible Nuclear Dependence of R | S. Malace*<br>M. Christy<br>D. Gaskell<br>C. Keppel<br>P. Solvignon-Slifer<br>H. Szumila-Vance | JLab<br>JLab<br>JLab<br>JLab<br>U of NH<br>JLab | 22 | B 😥 | 40 | Paper - pdf |

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# BACK UPS

| Source | Point-to-point Uncertainty ($x \leq 0.6$) | | |
|---|---|---|---|
| | E12-10-002 | E12-10-008 | **E12-14-002** |
| Spectrometer momentum | $< 0.1\%$ | $< 0.1\%$ | $< 0.1\%$ |
| Beam energy | $< 0.1\%$ | $< 0.1\%$ | $< 0.1\%$ |
| $\theta_{spec}$ | $< 0.1\%$ | $< 0.1\%$ | $< 0.1\%$ |
| Charge | 0.1-0.6% | 0.35% | $< 0.1\%$ |
| Target Boiling | 0-0.2% | - | 0.1% |
| Total dead time | 0.0-1.0% | 0.15% | 0-0.5% |
| Detector efficiency | 0.1% | 0.11% | 0.1% |
| Charge Symmetric Background | 0-1.4% | 0.13% | 0.1-0.7% |
| Pion contamination | 0.1-0.3% | - | 0.15% |
| Radiative Corrections | 0.6% | 0.55% | 0.6% |
| Acceptance | 0.0-0.3% | 0.5% | 0.5% |
| Total | 0.6-2.0% | 0.7% | **0.8-1.3%** |

# Two Photon Exchange Effects

## Experimental constraints on non-linearities induced by two-photon effects in elastic and inelastic Rosenbluth separations

V. Tvaskis,[1,2] J. Arrington,[3] M. E. Christy,[1] R. Ent,[2] C. E. Keppel,[1,2] Y. Liang,[1,4] and G. Vittorini[5]

[1]*Hampton University, Hampton VA 23668, USA*
[2]*Thomas Jefferson National Accelerator Facility, Newport News, VA 23602, USA*
[3]*Argonne National Laboratory, Argonne, IL 60439, USA*
[4]*American University, Washington, D.C. 20016*
[5]*Eckerd College, St Petersburg, FL 33711*

(Dated: October 18, 2018)

The effects of two-photon exchange corrections, suggested to explain the difference between measurements of the proton elastic electromagnetic form factors using the polarization transfer and Rosenbluth techniques, have been studied in elastic and inelastic scattering data. Such corrections could introduce $\varepsilon$-dependent non-linearities in inelastic Rosenbluth separations, where $\varepsilon$ is the virtual photon polarization parameter. It is concluded that such non-linear effects are consistent with zero for elastic, resonance, and deep-inelastic scattering for all $Q^2$ and $W^2$ values measured.

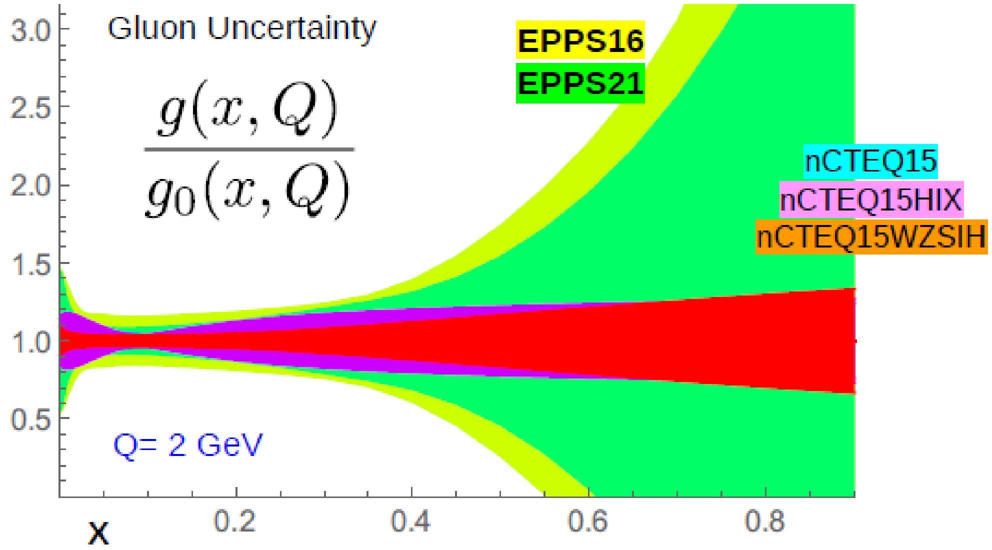
### VI. CONCLUSION

We have searched for possible two-photon exchange contributions that show up as non-linearities in Rosenbluth separations. We have used existing data in the elastic and deep-inelastic scattering region and recent data in the nucleon resonance region. We do not find any evidence for TPE effects. The 95% confidence level upper limit on the curvature parameter, $P_2$, was found to be 6.4% (10.6%) for the elastic (inelastic) data. This limits maximum deviations from a linear fit to $\lesssim$0.4% (0.7%) for typical elastic (inelastic) Rosenbluth separation data sets.

#### Acknowledgments

This work was supported in part by research grants 0099540 and 9633750 from the National Science Foundation and DOE grant W-31-109-ENG-38. The authors wish to thank Arie Bodek for useful discussions and comments.

Notes from Fred Olness



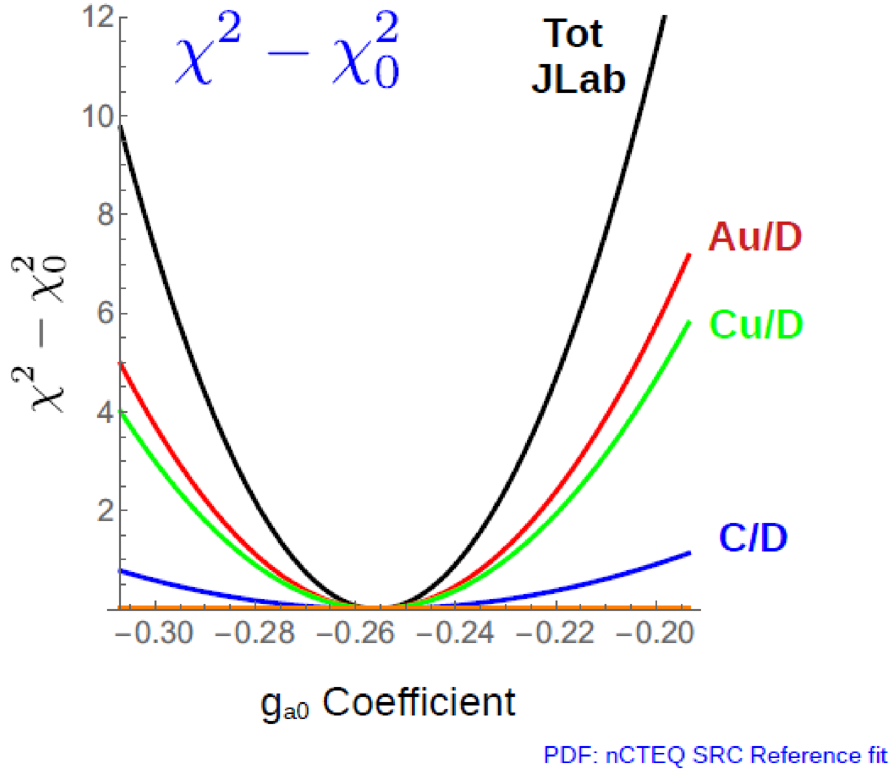

This shows the gluon uncertainty at Q=2 GeV vs. x for the EPPS and nCTEQ sets. The EPPS parameterization provides additional flexibility for the gluon nPDF. In contrast, the nCTEQ parametric $x^a(1-x)^b$… form is more restrictive in the high-x region. The EPPS values are probably more representative of the true uncertainties.

TAKEAWAY:

1) Additional information on the gluon, especially for large A can provide significant improvements.

2) These quick studies were performed in the nCTEQ framework. While we have tried to open the gluon parameters, these results are possibly conservative estimates.

Notes from Fred Olness

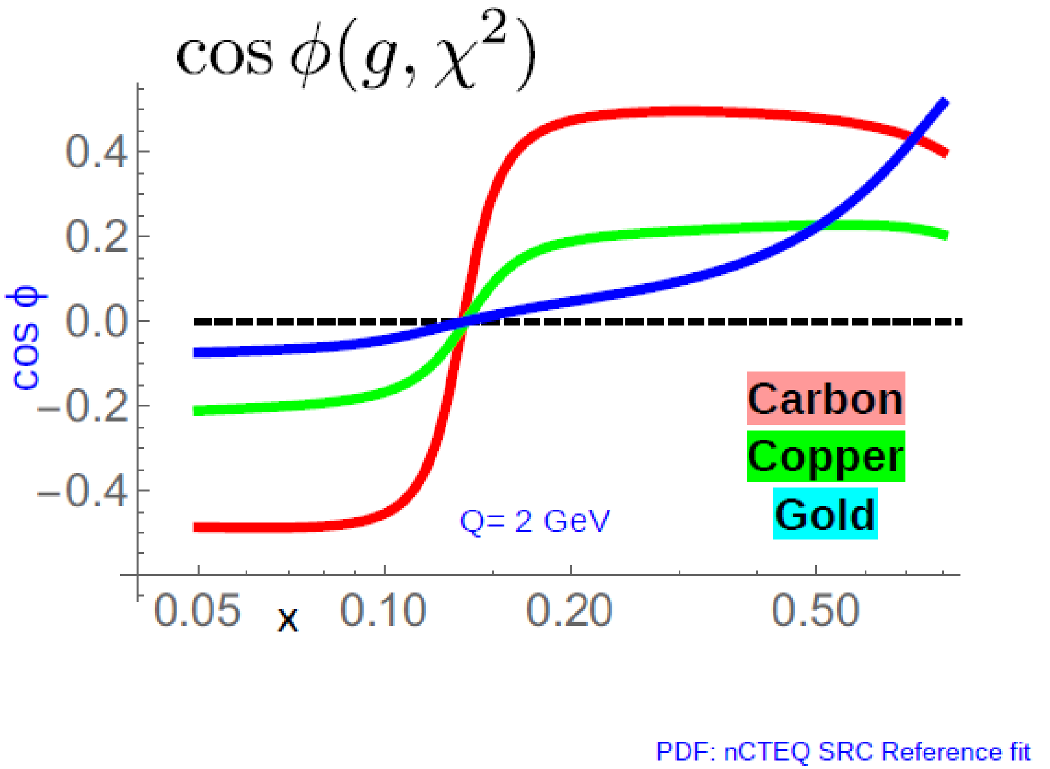



This shows the chi2 scans of the ga0 coefficient which, in part, controls the momentum fraction of the nuclear gluon component. The total of the JLab experiments yields between 10 and 15 units of chi2. For comparison, recall the nCTEQ15 tolerance was delta-chi2 of 35, and these scans run over approximately 50 units of chi2. Thus these experiments can help constrain the gluon across different nuclear A values.

*Not shown, but the results for the gb0 coefficient is similar.*

The PDF is the nCTEQ-SRC reference fit; it is closely related to the nCTEQ-HIX PDF with additional gluon parameters opened.

Notes from Fred Olness




This shows the cosine correlation between the gluon and the JLab data as a function of x for Q=2 GeV. This shows the differing influence of the data across the kinematic range, and for the different nuclear A values.

In a sense, this matched the gluon sensitivity observed in the parameter scans of ga0 and gb0.

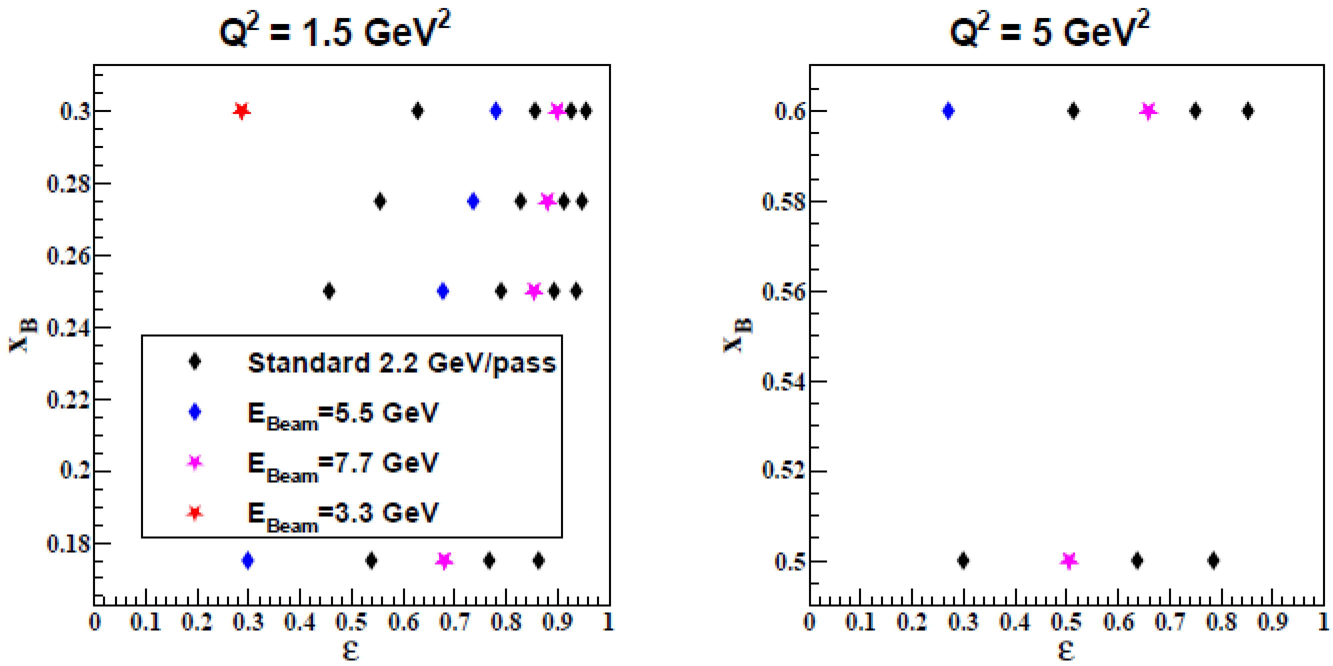
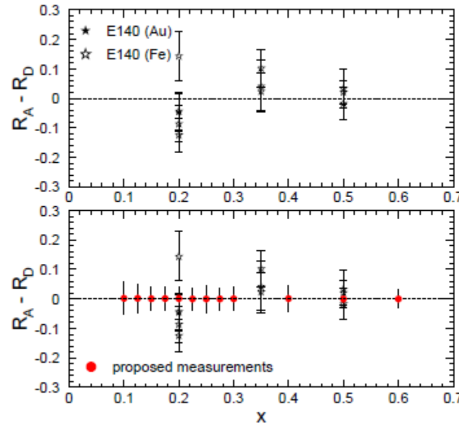
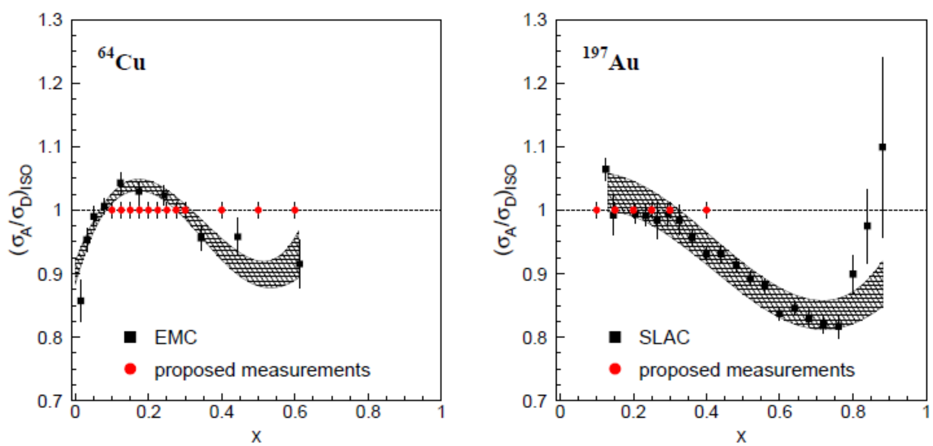



Figure 6: The $\epsilon$ range for a subset of the fixed $Q^2$ and $x_B$ settings. The diamonds represent beam energies using the standard 2.2 GeV/pass linac gradient. If a 1.1 GeV/pass gradient would be available, this experiment would be able to use it for the 4.4 and 5.5 GeV running. In the event that a beam energy of 7.7 GeV (magenta stars) is not available, an additional low $\epsilon$ could be obtained using a 3.3 GeV beam (red stars).




IG. 28: Projected systematic uncertainties on the $R_{Cu} - R_D$ extraction as a function of $x$ at all proposed central kinematics. :milar extractions at select kinematics (see Table VIII) will be performed for $R_C - R_D$ and $R_{Au} - R_D$. Measurements on iron ıd gold from SLAC E140 are also shown in black symbols.




IG. 29: $\sigma_A/\sigma_D$ for copper (left panel) and gold (right pnael). Existing data from EMC and SLAC (black squares) and :ojections for our proposed measurements (red circles) are shown. We pnly show the coveraged provided by our proposed :ntral kinematics but due to the Hall C spectrometers acceptance we will cover both the lower and larger $x$ regions.

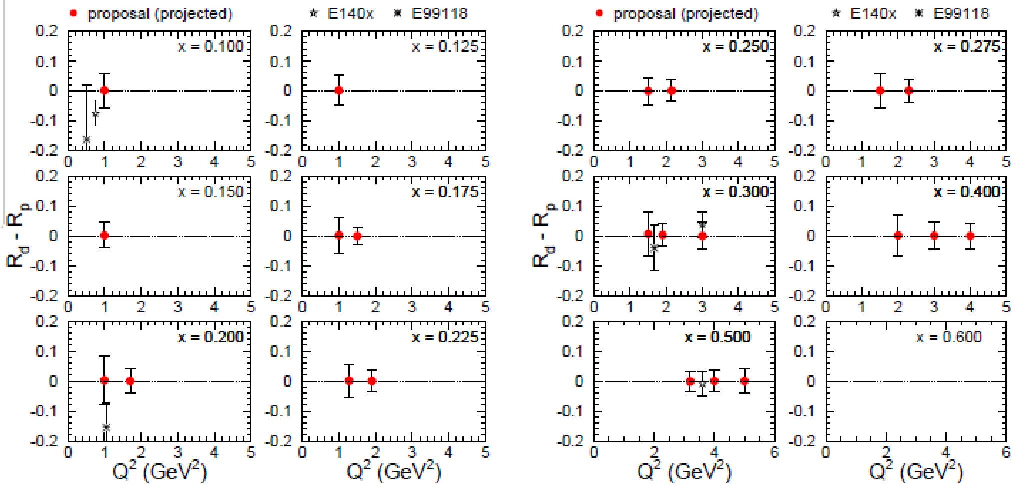



FIG. 24: Projected systematic uncertainties (red circles) for $R_d - R_p$ extractions at all the proposed central kinematics. Existin true Rosenbluth L/T separations in DIS from SLAC and JLab are displayed in black symbols.

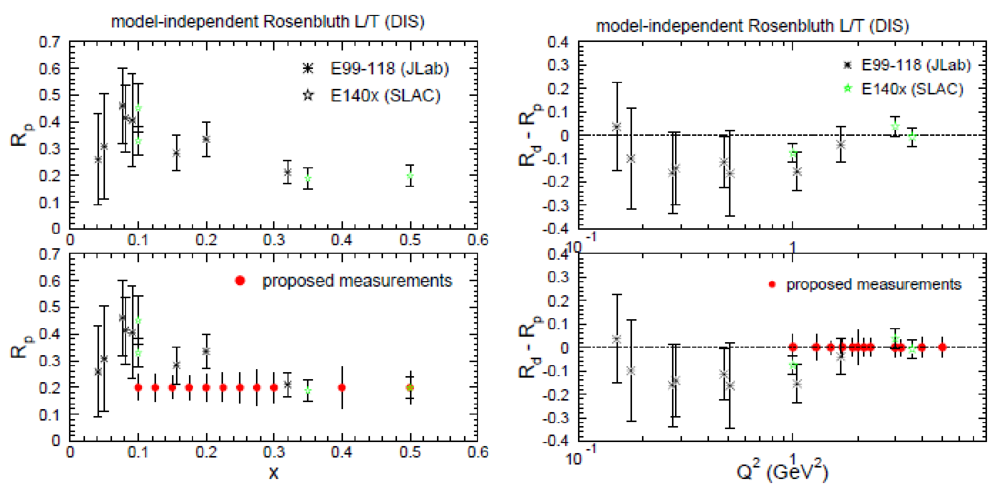



FIG. 25: **Left:** Projected systematic uncertainties on the $R_p$ extraction as a function of $x$ at all proposed central kinematic **Right:** $R_d - R_p$ versus $Q^2$: our proposed measurements are shown as red circles while existing data from SLAC and JLab a stars and snowflakes.