Measurements of the Nuclear Dependence of $R = \sigma_L/\sigma_T$

Thia Keppel
Thomas Jefferson National Accelerator Facility

2nd Workshop on Quantitative Challenges in SRC and EMC Research
Massachusetts Institute of Technology
March 20-23, 2019

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

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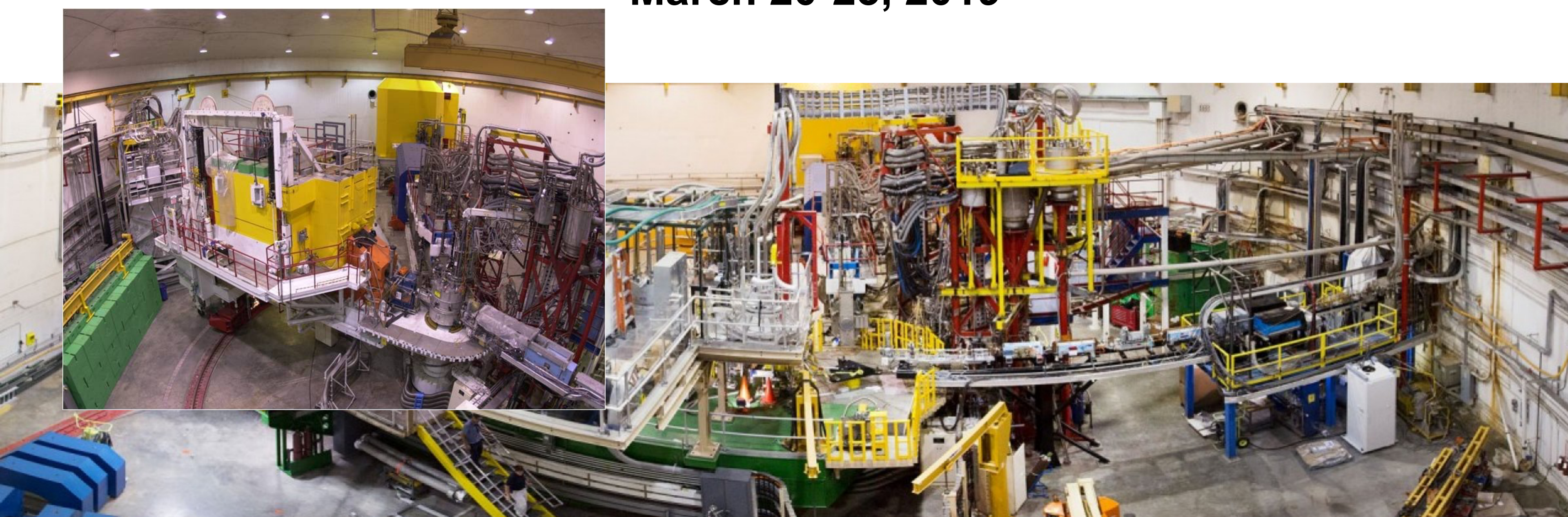

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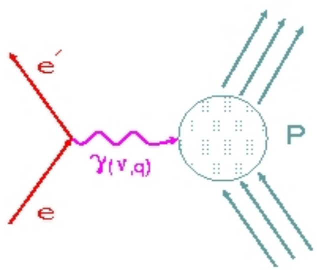
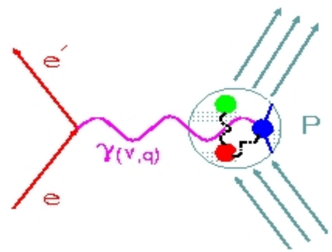
Inclusive $e + p \to e + X$ scattering

Single Photon Exchange

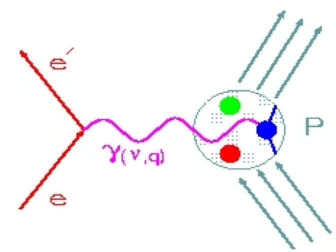
Elastic



Resonance



DIS



F

$$\frac{d\sigma}{d\Omega dE'} = \Gamma(\sigma_T + \varepsilon\sigma_L)$$

Where Γ : flux of transversely polarized virtual photons

ε : relative longitudinal polarization

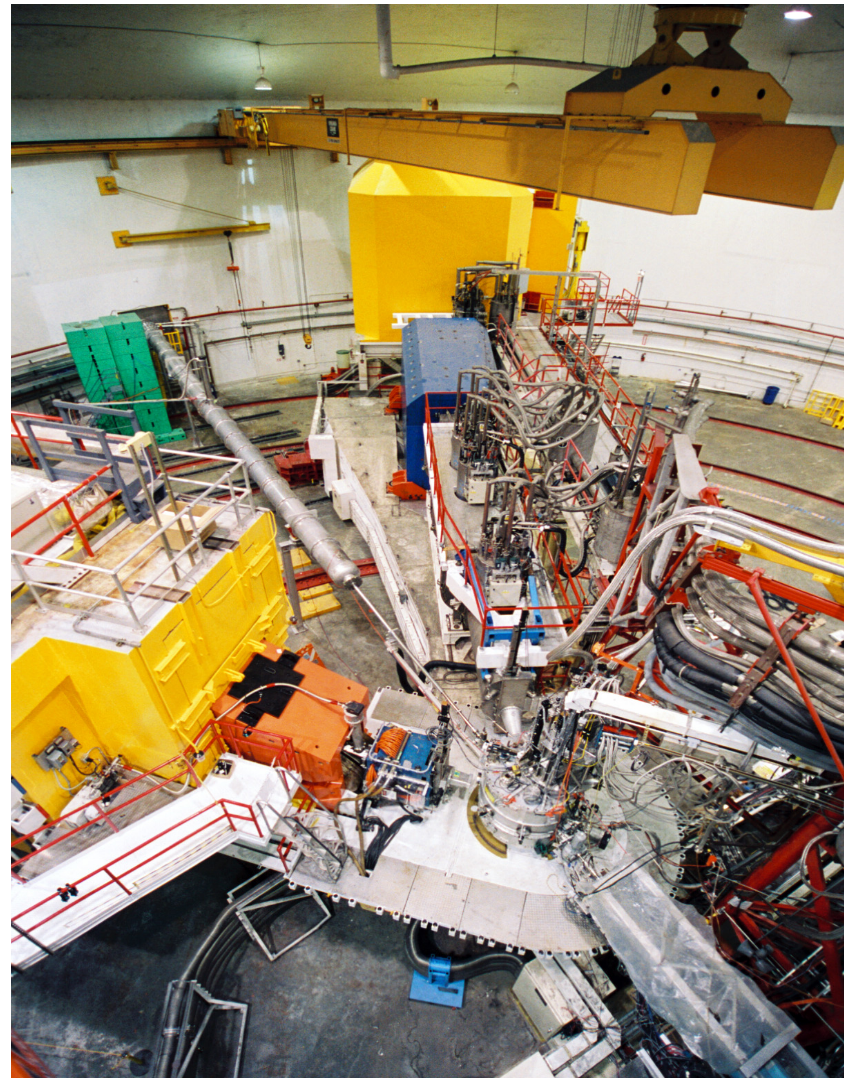
Alternatively:

$$\frac{d\sigma}{d\Omega dE'} = \sigma_{mott}(F_2/\nu + 2F_1 \tan^2(\theta/2)/M)$$

$$\sigma_{mott} = \frac{\alpha^2 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} \qquad R = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{2xF_1} \qquad F_L = (1 + \frac{4M^2x^2}{Q^2})F_2 - 2xF_1$$

6 GeV Era Program of Inclusive Structure Function Measurements in Hall C – *high precision cross sections and* ***L/T separations***

- E88-008: x>1
- E94-110: L/T Hydrogen Resonance Region
- E99-118: L/T Low x, Q^2 A-Dependence
- E00-002: L/T Low Q^2 Deep Inelastic H, D
- E00-116: High Q^2 H,D
- E04-001: L/T Nuclear Dependence, Neutrino Modeling
- E02-109: L/T Deuterium Resonance Region
- E02-109: x>1, A-Dependence
- E03-103: EMC Effect



Example: Rosenbluth Separations on p from E94-110

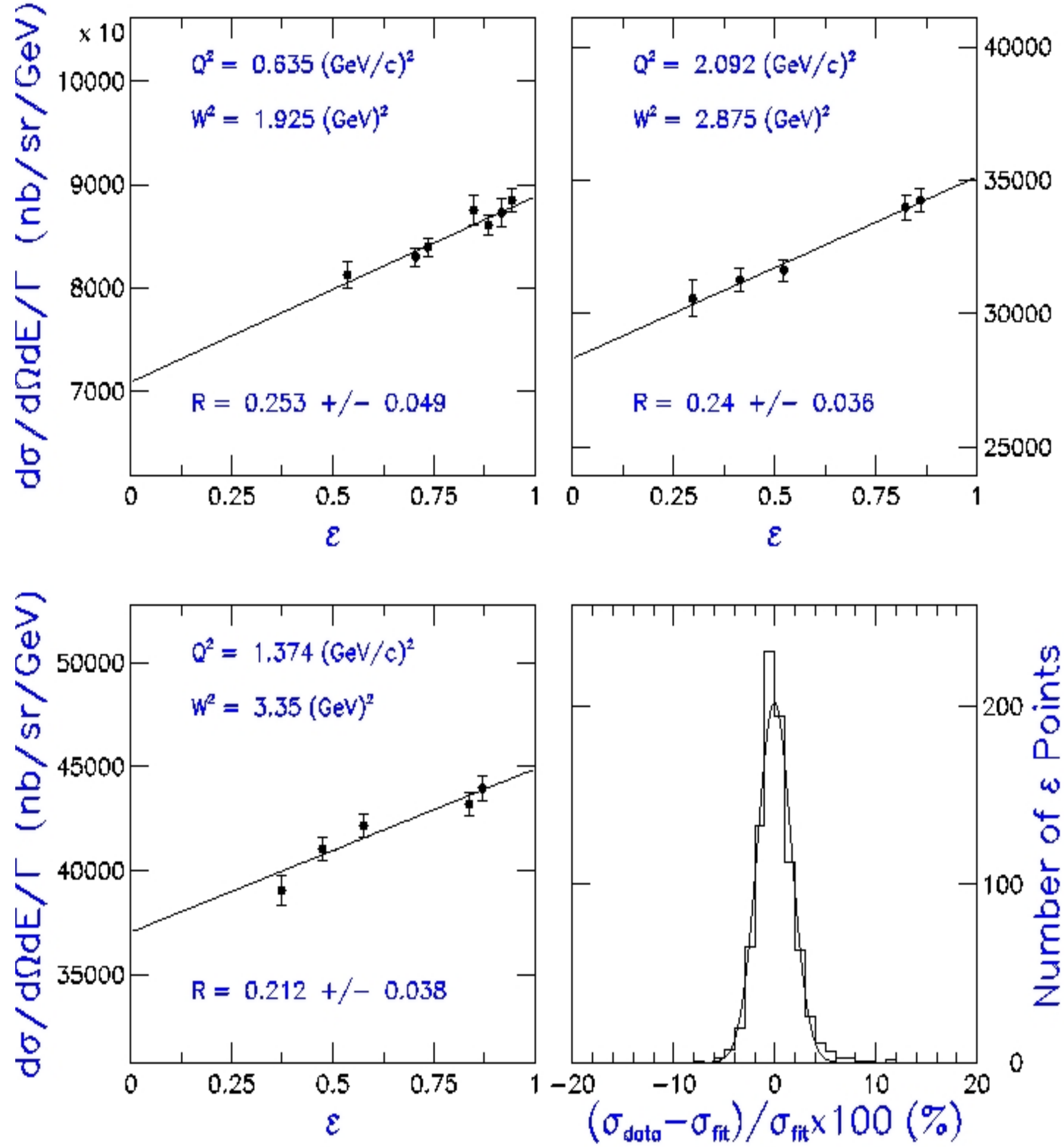
R is small and difficult to measure

- point-to-point systematic uncertainties must be small and well understood!

180 L/T separations total (most with 4-5 ε points)

Spread of points about the linear fits is Gaussian with $\sigma \sim 1.6$ % - *consistent with the estimated pt-pt experimental uncertainty*

A systematic "tour de force"



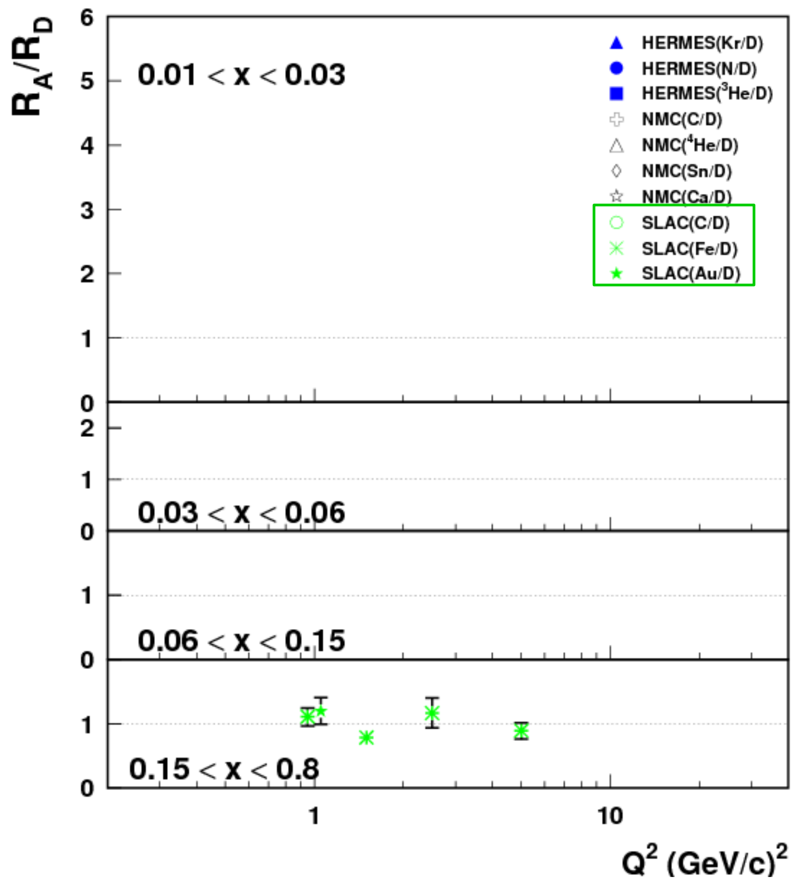
V. Tvaskis, et al., Phys.Rev. C73 (2006) 025206

M.E. Christy et al., Phys.Rev. C70 (2004) 015206

Y. Liang et al., nucl-ex/0410027

Y. Liang, et al., Phys.Rev. C73 (2006) 065201

Nuclear Dependence of R: Experimental Status



→ ***Model-independent*** extractions:

- **SLAC (E140):** *Phys. Lett. D 49 (1993)*

$$x = 0.2 - 0.5 \quad Q^2 = 1 - 5\ GeV^2$$
$$R_{Fe} - R_D \qquad R_{Au} - R_D$$

ΔR consistent with zero?

→ ***Model-dependent*** extractions:

- **NMC**: *Phys. Lett. B 294, 120 (1992)*

$$x = 0.01 - 0.25 \quad \langle Q^2 \rangle = 9\ GeV^2$$
$$R_D - R_P = 0.031 \pm 0.016\,(stat) \pm 0.011\,(syst)$$

$$x = 0.01 - 0.20 \quad \langle Q^2 \rangle = 4\ GeV^2$$
$$R_{Ca} - R_C = 0.027 \pm 0.026\,(stat) \pm 0.020\,(syst)$$

*Conclusion: **ΔR consistent with zero***

- **NMC**: *Nucl. Phys. B 481, 23 (1996)*

$$x = 0.01 - 0.5 \quad \langle Q^2 \rangle = 10\ GeV^2$$
$$R_{Sn} - R_C = 0.040 \pm 0.021\,(stat) \pm 0.026\,(syst)$$

ΔR: positive shift?

- **HERMES:** *Phys. Lett. B 567, 339 (2003)*

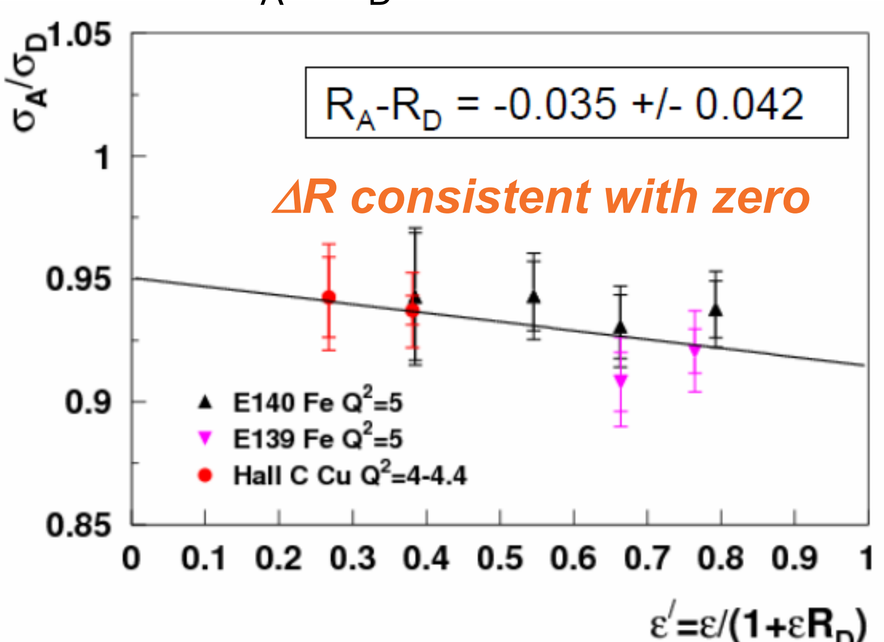
$$x = 0.01 - 0.65 \quad Q^2 = 0.5 - 15\ GeV^2$$
$$R_{^3He} / R_D \qquad R_{^{14}N} / R_D$$

Nuclear Dependence of R: Experimental Status

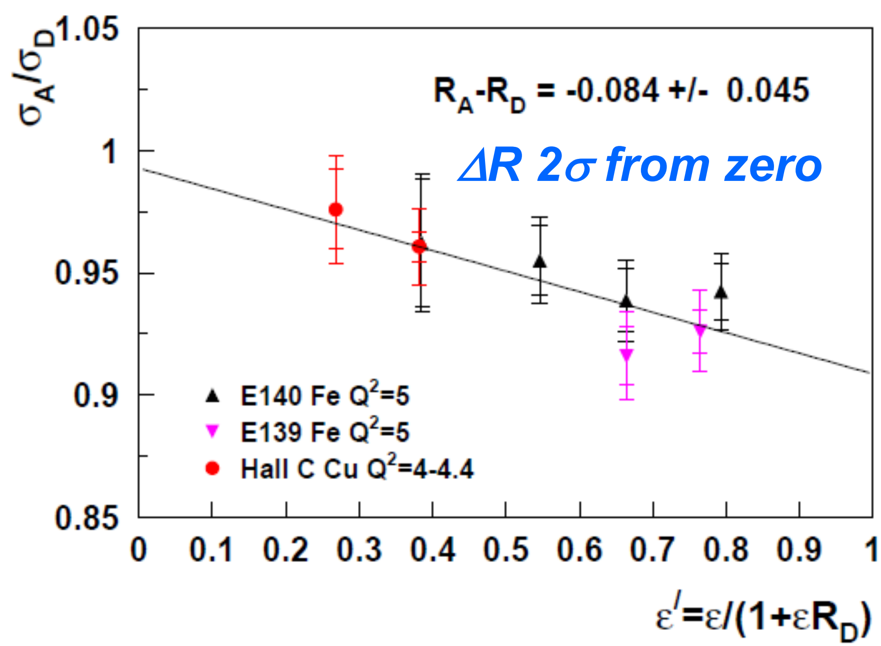
→ **Coulomb effects** have not been accounted for in the SLAC E140 analysis (***correction is non-negligible at SLAC and JLab kinematics***)

→ Re-analysis of combined data sets from E140 (Fe), E139 (Fe) and Hall C (Cu) at x = 0.5 and Q^2 = 4 - 5 GeV^2 P. Solvignon et al., AIP Conf.Proc. 1160 (2009) no.1, 155

- Coulomb corrections calculated within the Effective Momentum Approximation framework
- the ε' dependence of the cross section ratios σ_A/σ_D has been fitted to extract R_A - R_D



No Coulomb Corrections



With Coulomb Corrections

Nuclear Dependence of R: Experimental Status

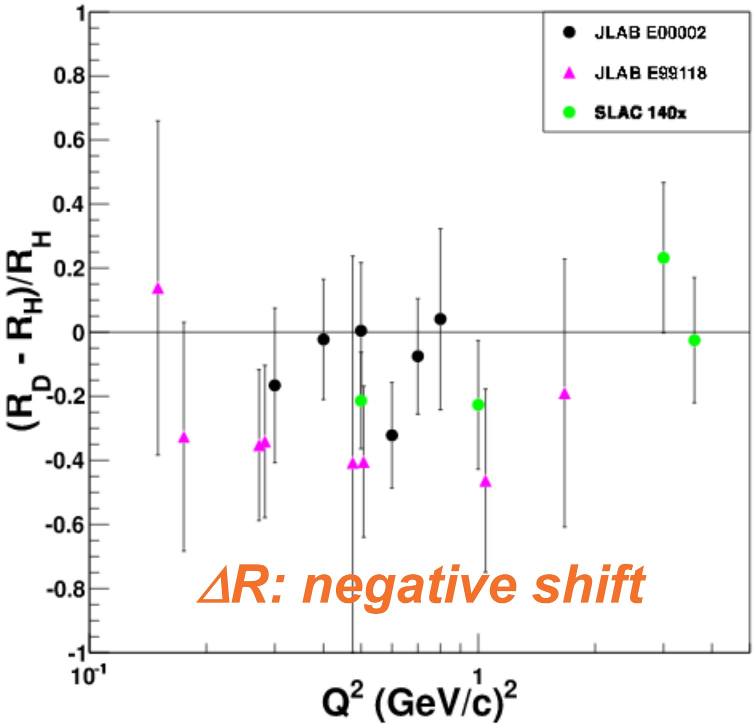
Published d-p (dedicated, model-independent) extractions from JLab

→ L/T separations on proton and deuteron at low Q^2

E99-118 (Hall C): *PRL 98 142301 (2007)*

$$R_D - R_H = -0.054 \pm 0.029$$

A first hint?



Nuclear Dependence of R: Experimental Status

Published d-p (dedicated, model-independent) extractions from JLab

→ L/T separations on proton and deuteron at low Q^2

E99-118 (Hall C): *PRL 98 142301 (2007)*

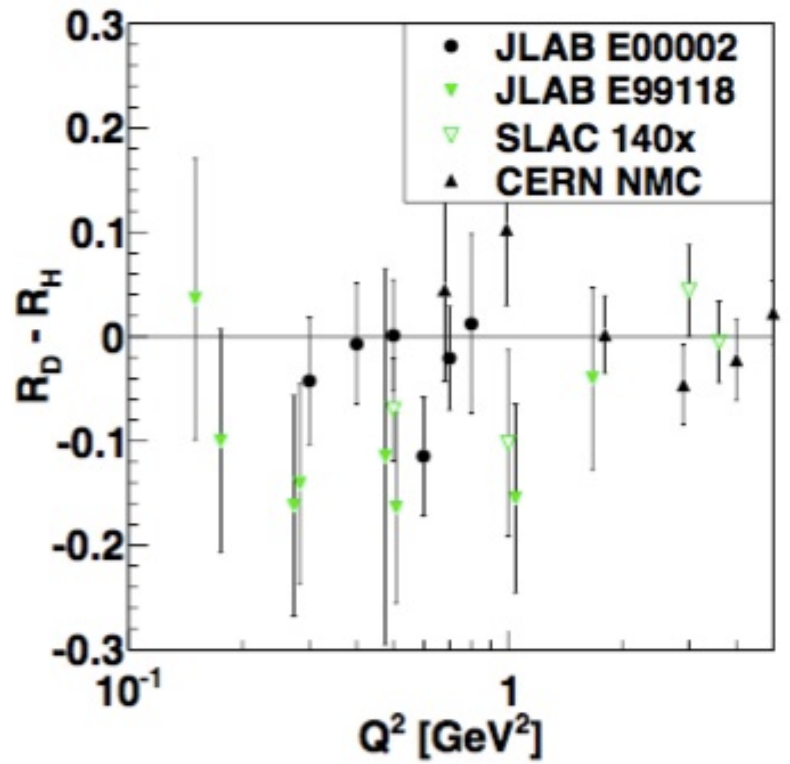
$$R_D - R_H = -0.054 \pm 0.029$$

A first hint?

E99-002 (Hall C): *PRC 97 4, 045204 (2018)*

$$R_D - R_H = -0.042 \pm 0.018$$

Conclusion: **~30% effect in deuterium**

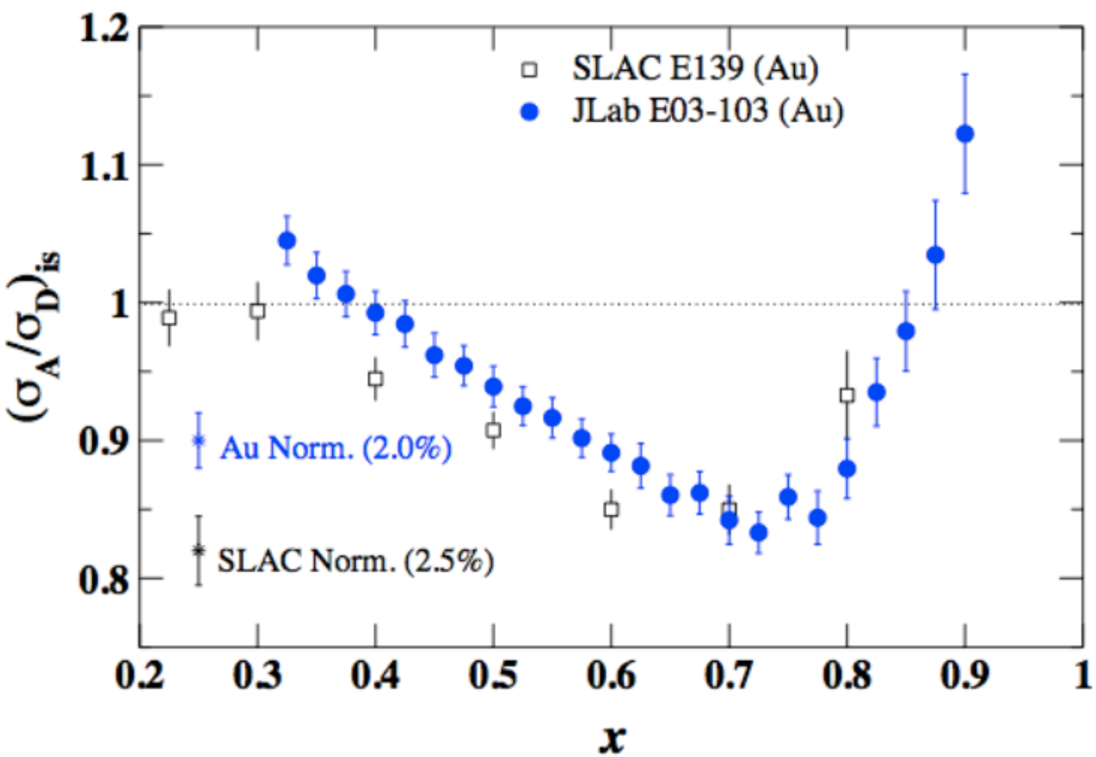


What if there's a nuclear dependence not just at low Q^2 and not just for deuterium?....

Implications of a Possible Nuclear Dependence of R

→ Not enough experimental evidence to support the often made assumption of $\Delta R = 0$ when transitioning from cross section ratio to structure function ratio

$$\frac{\sigma_A}{\sigma_D} \approx \frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)}\left[1 - \frac{\Delta R(1-\varepsilon)}{(1+R_D)(1+\varepsilon R_D)}\right] \qquad \frac{\sigma_A}{\sigma_D} = \frac{F_1^A(x,Q^2)}{F_1^D(x,Q^2)}\left[1 + \frac{\varepsilon \Delta R}{(1+\varepsilon R_D)}\right]$$



→ Why we see antishadowing in DIS but not in Drell-Yan?

→ A very well measured behaviour like the EMC effect still offers surprises – *the tension between low* ε *JLab and high* ε *SLAC data on heavy targets*

→ Is there gluonic (spin-0) contribution to the antishadowing and/or to the EMC effect?

Shadowing Region Not Well Understood
– Could Longitudinal Dependence Explain This?

Nuclear PDFs

$$F_L(x,Q^2) = \langle e^2 \rangle \int_x^1 \mathrm{d}w C_{L,g}(w,Q^2) G\left(\frac{x}{w}, Q^2\right)$$

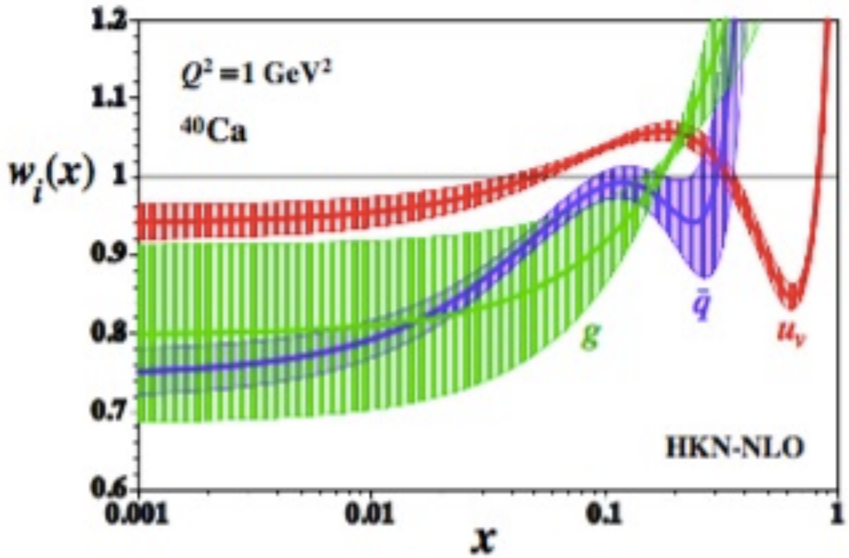
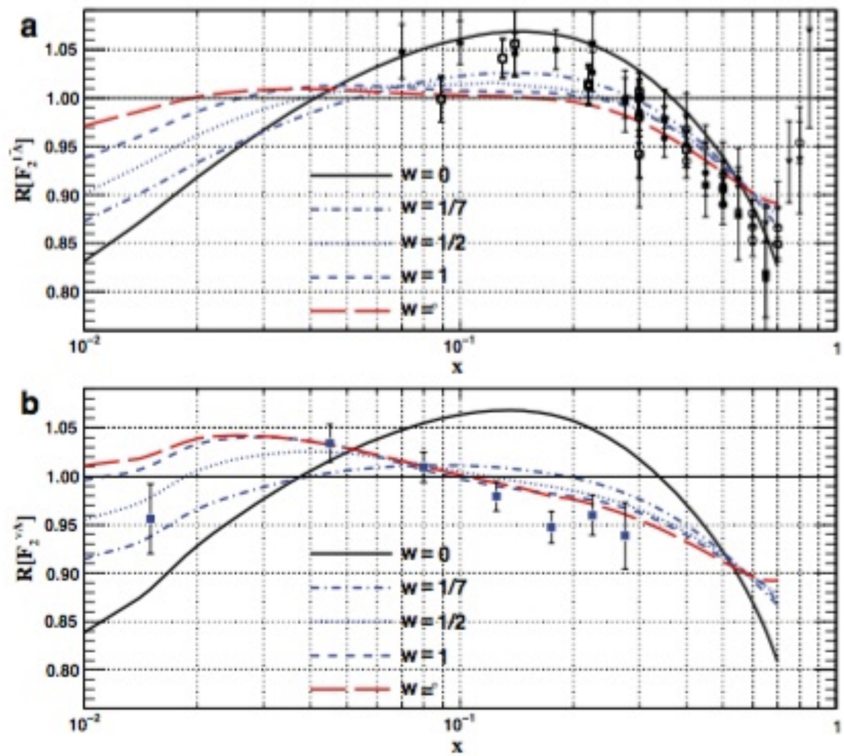


Fig. 4. Typical nuclear modifications of PDFs for ^{40}Ca at $Q^2 = 1$ GeV^2.

S. Kumano, JPS Conf.Proc. 12 (2016) 010004

Comparison of electron and neutrino DIS

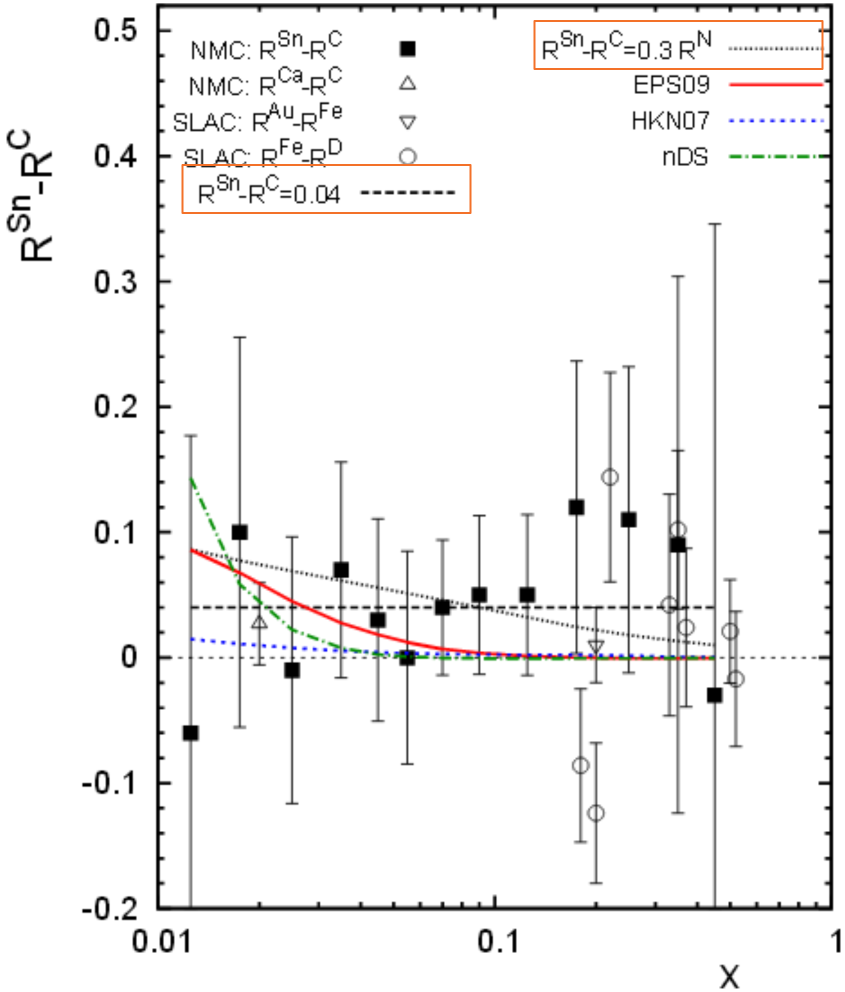


K. Kovarik et al., nCTEQ Collaboration,
Phys. Rev. Lett. 106 (2011) 122301

Implications of a Possible Nuclear Dependence of R

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

→ The impact of a non-zero ΔR for *the antishadowing region* has been analyzed



"Since the nuclear dependence of R has not as yet been systematically measured, we shall test two assumptions for ΔR…"

1) (Absolute) $R_A - R_D = 0.04$

2) (Relative) $(R_A - R_D)/R_N = 30\%$

Both assumptions based on NMC $R_{Sn} - R_C$

→ Two data sets have been analyzed:

- EMC, BCDMS, NMC: $\varepsilon \sim 1$

$$\frac{\sigma_A}{\sigma_D} \approx \frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)} \qquad \frac{\sigma_A}{\sigma_D} > \frac{F_1^A(x,Q^2)}{F_1^D(x,Q^2)}$$

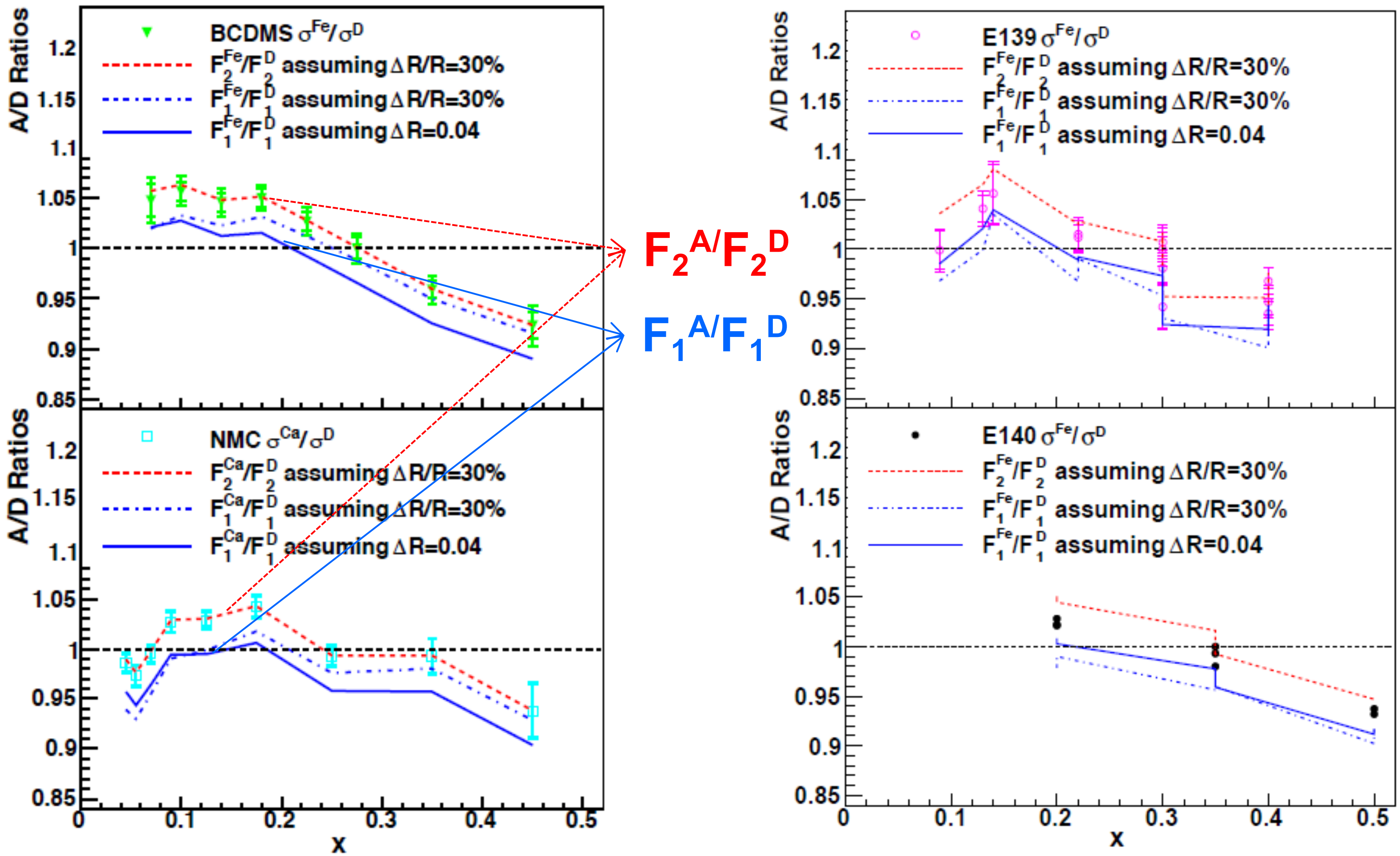
- SLAC: $\varepsilon < 1$

$$\frac{F_1^A(x,Q^2)}{F_1^D(x,Q^2)} < \frac{\sigma_A}{\sigma_D} < \frac{F_2^A(x,Q^2)}{F_2^D(x,Q^2)}$$

Implications of a Possible Nuclear Dependence of R

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

→ The impact of a non-zero ΔR for *the antishadowing region*



→ Antishadowing disappears for F_1 ratio, remains for F_2

Antishadowing predominantly resides in the longitudinal structure function F_L^A

Implications of a Possible Nuclear Dependence of R

→ Comparison between the size of the EMC effect, $-dR_{EMC}/dx$, and the relative number of short-range correlations, SRC scale factor *Phys. Rev. Lett. 106 052301 (2010)*

Possible Conclusions:

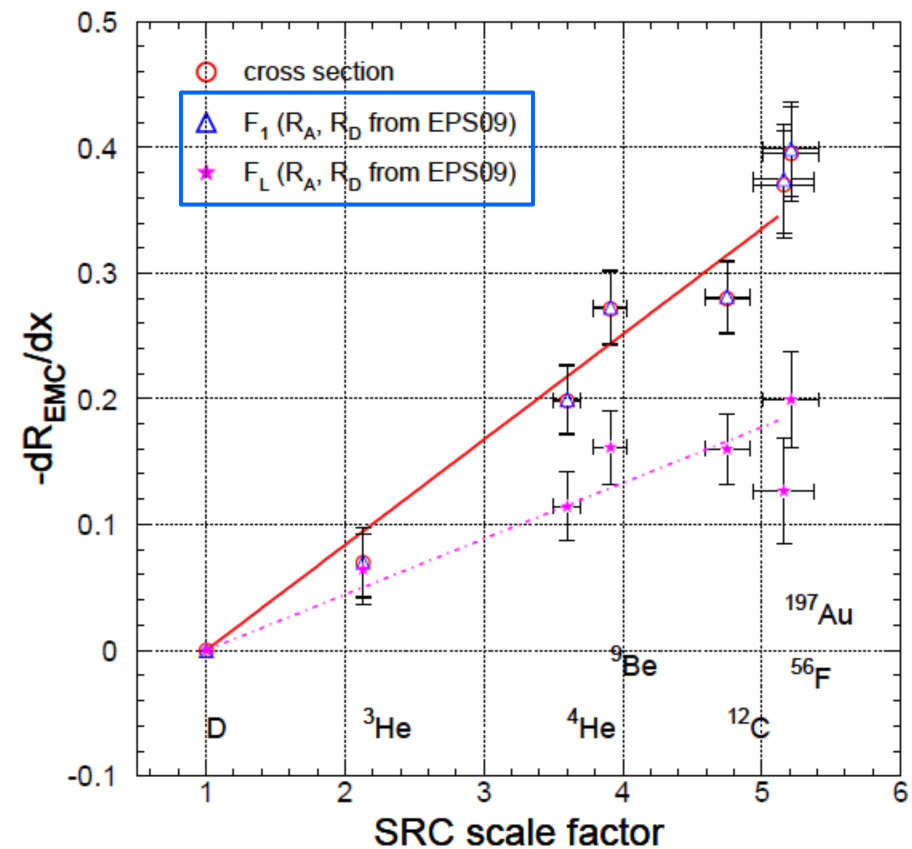
- The SRC and EMC effect: a common (as yet unknown) origin

- SRC: measure of some quantity like local density experienced by a nucleon in a correlated pair which gives rise to the EMC effect

However:

→ *If R is A-dependent this interpretation may need revision*

→ *Does the correlation between $-dR_{EMC}/dx$ and SRC apply the same to F_2, F_1, F_L?*



Implications of a Possible Nuclear Dependence of R

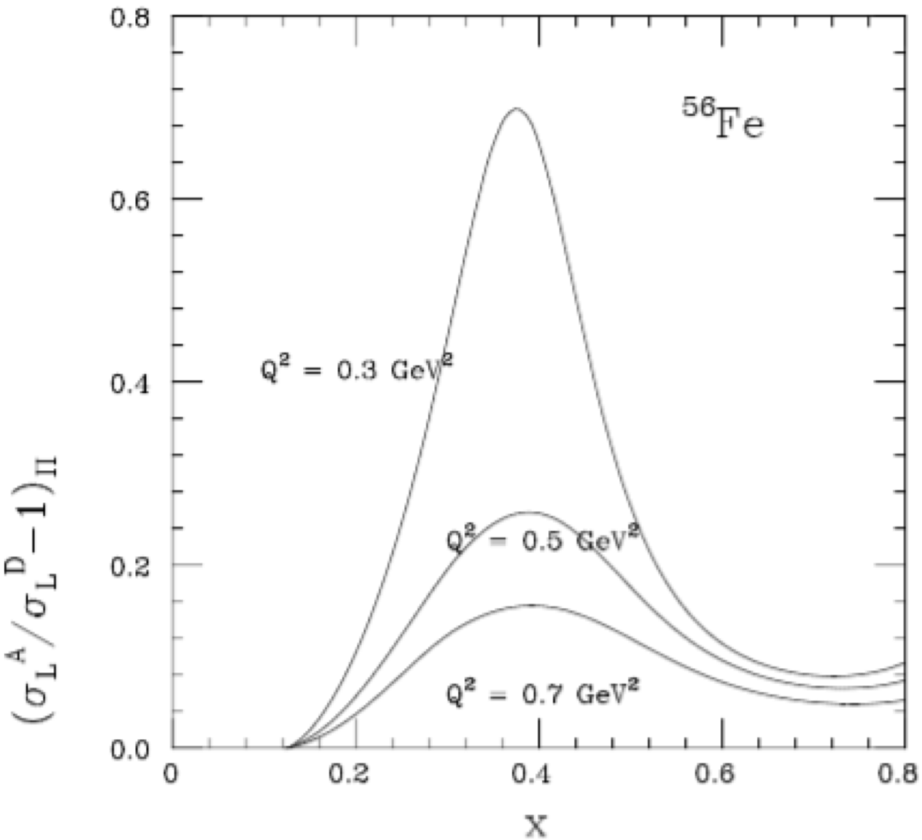


FIG. 4. Enhancement of longitudinal cross sections, as a function of Q^2 and x.

May also indicate nuclear pions:

G. Miller, Phys.Rev. C64 (2001) 022201

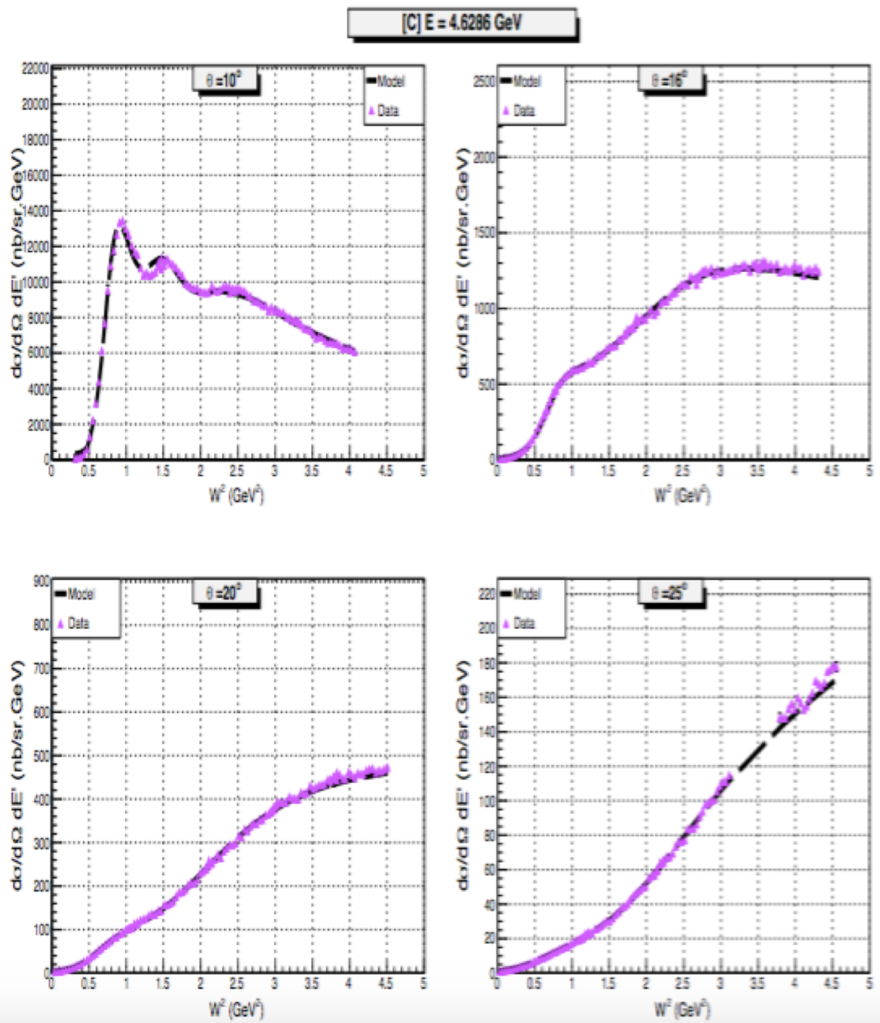
$$\frac{\sigma_L(A)}{\sigma_L(D)} = 1 + x\frac{2}{3}f_\pi(\xi)\frac{\nu^2}{(Q^2+\nu^2)}\frac{F_\pi^2(Q^2)}{F_2^D R_D}(1+R_D),$$

Look for rapid drop-off in Q^2 of longitudinal A/D cross section ratio

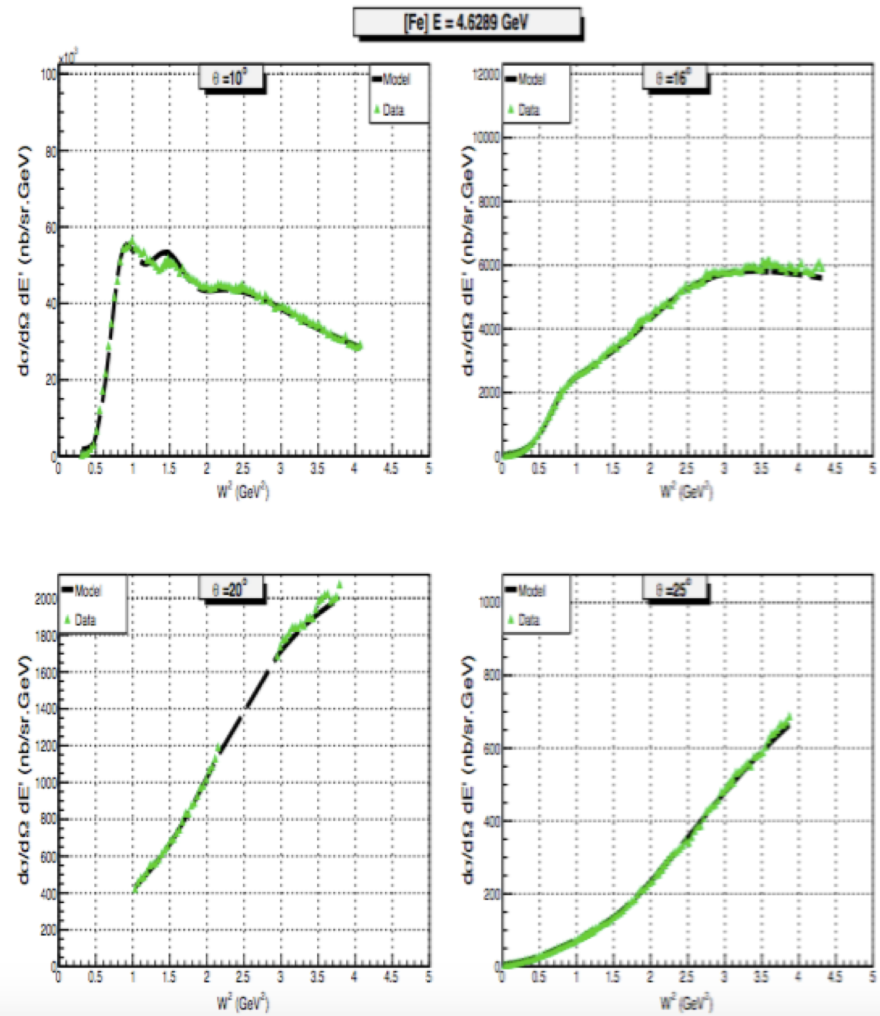
Nice to have a prediction!

Results from Hall C 04-001 (C, Fe only)
– thanks to Sheren Alsalmi

C Cross Sections



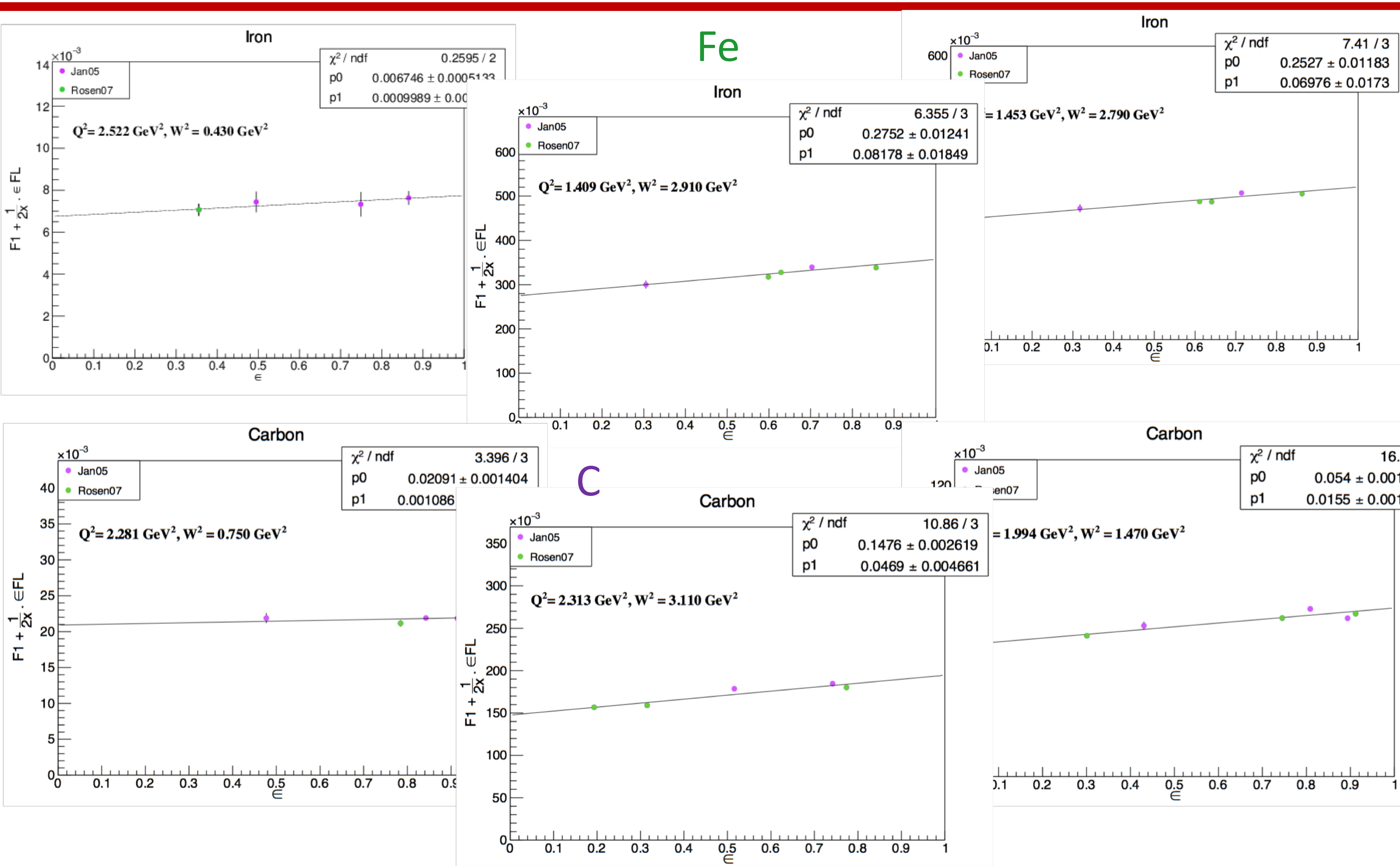
Fe Cross Sections



Statistical Uncertainties are Shown. Curve is Christy-Bosted Fit

Results from Hall C 04-001 (C, Fe only)

– thanks to Sheren Alsalmi



Over 250 individual L/T separations – *no repeated cross sections!!*

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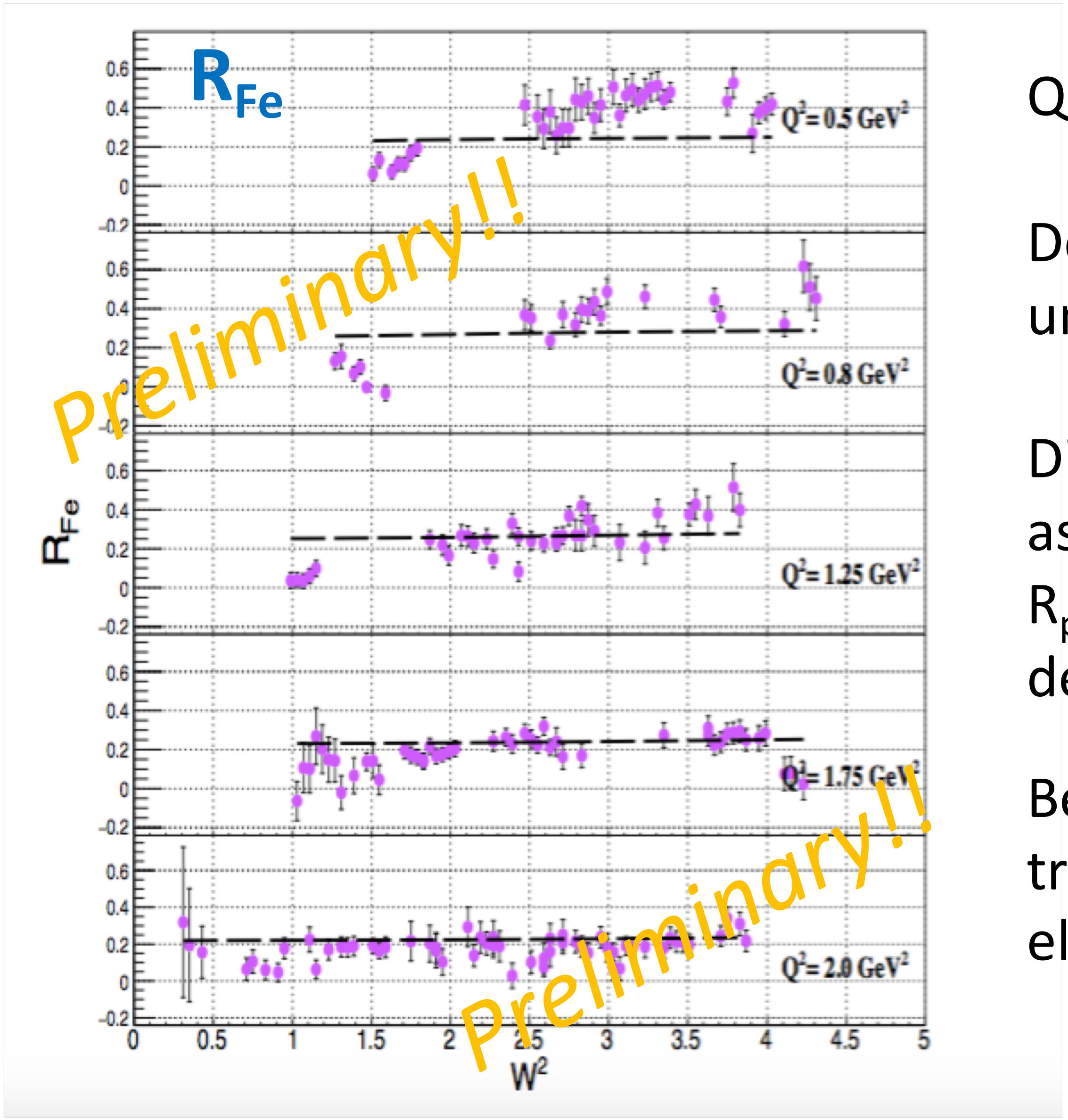
Results from Hall C 04-001 (C, Fe only)
– thanks to Sheren Alsalmi



Q^2 dependent effect

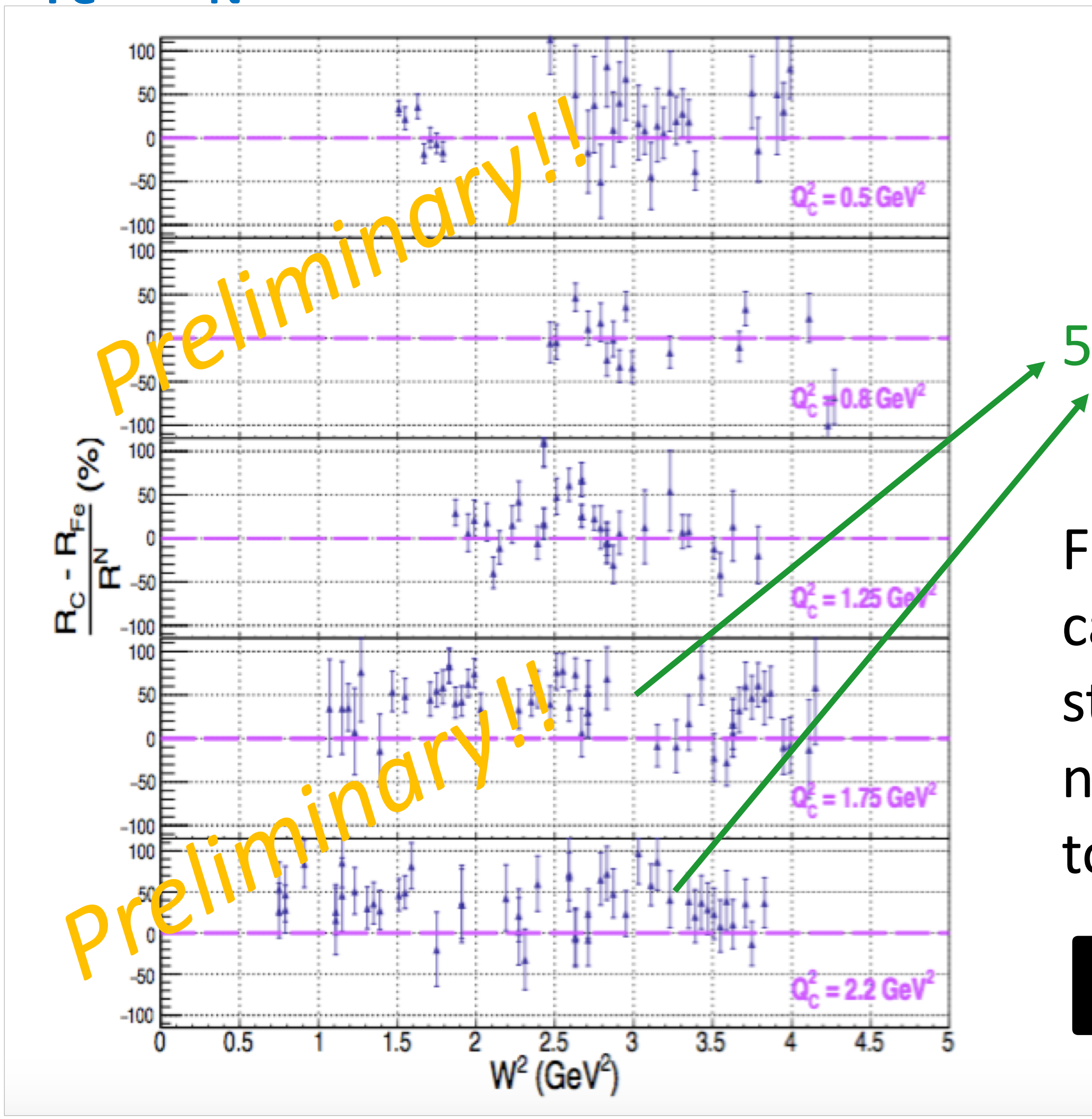
Decreases with Q^2, not unexpected

Differs from fit with assumption $R_A = R_D = R_p$, nuclear dependence….

Be careful of low W – triple checking quasi-elastic regime

Results from Hall C 04-001 (C, Fe only)
– thanks to Sheren Alsalmi

$(R_C - R_{Fe})/R_N$

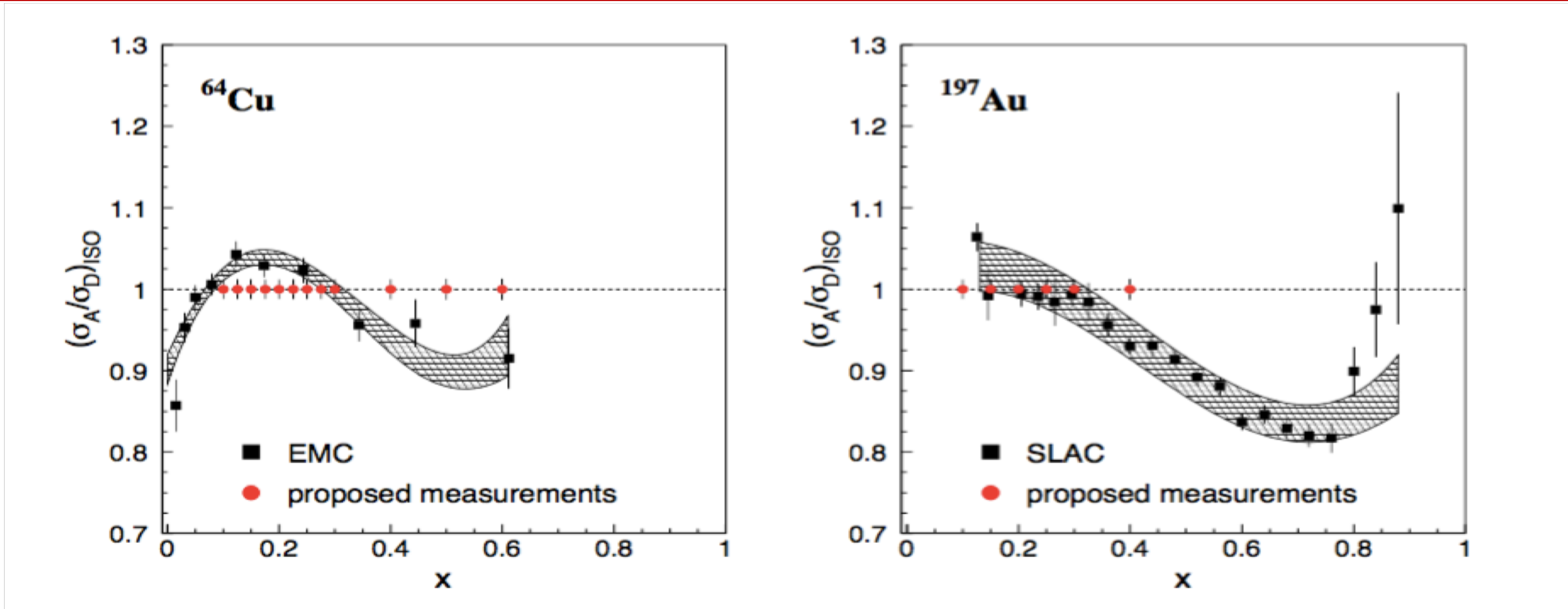


50%!

For the first time, we can unequivocally state that there **IS** a nuclear dependence to R (F_L)… and it's

BIG

Continue into 12 GeV Era: Hall C Experiment E12-14-002



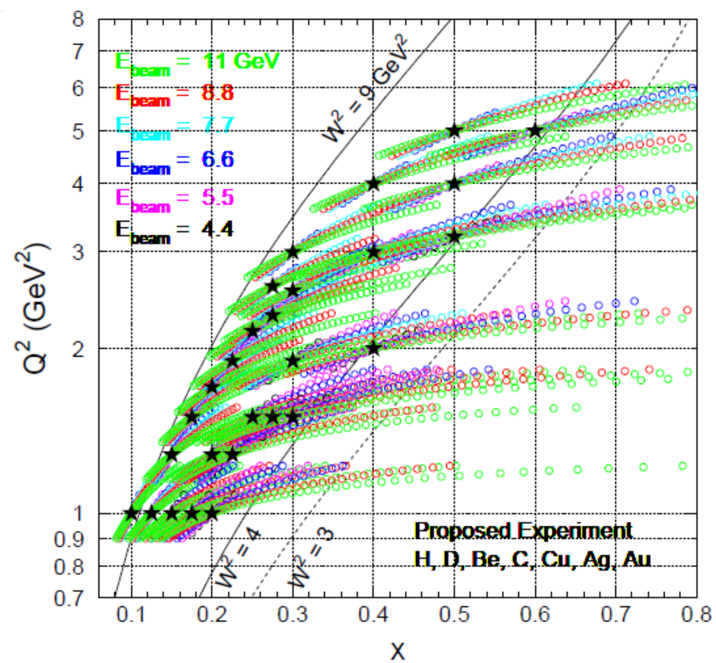
~1.6% point-to-point systematic uncertainty cross sections

H,D,Be,C,Cu,Ag,Au targets

0.1 < x < 0.8

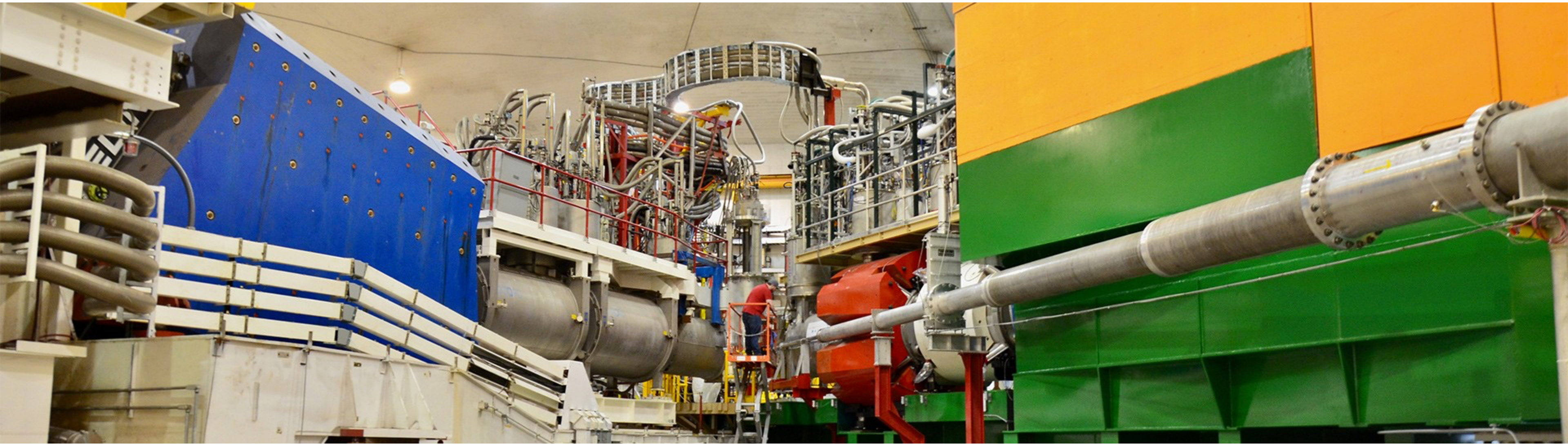
$0.9 < Q^2 < 6\ \mathrm{GeV}^2$

300+ L/Ts



Study both anti-shadowing and EMC regimes

Thank You!



Hall C Downstream Today….