

# Experimental Investigation of the Structure Functions of Bound Nucleons at Jlab

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for the

(The JUPITER Collaboration Jlab E02-109 E04-001 E06-009)

Presented by Arie Bodek at DIS 2015

WG1 – Structure Functions

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## Experimental Investigation of the Structure Functions of Bound Nucleons

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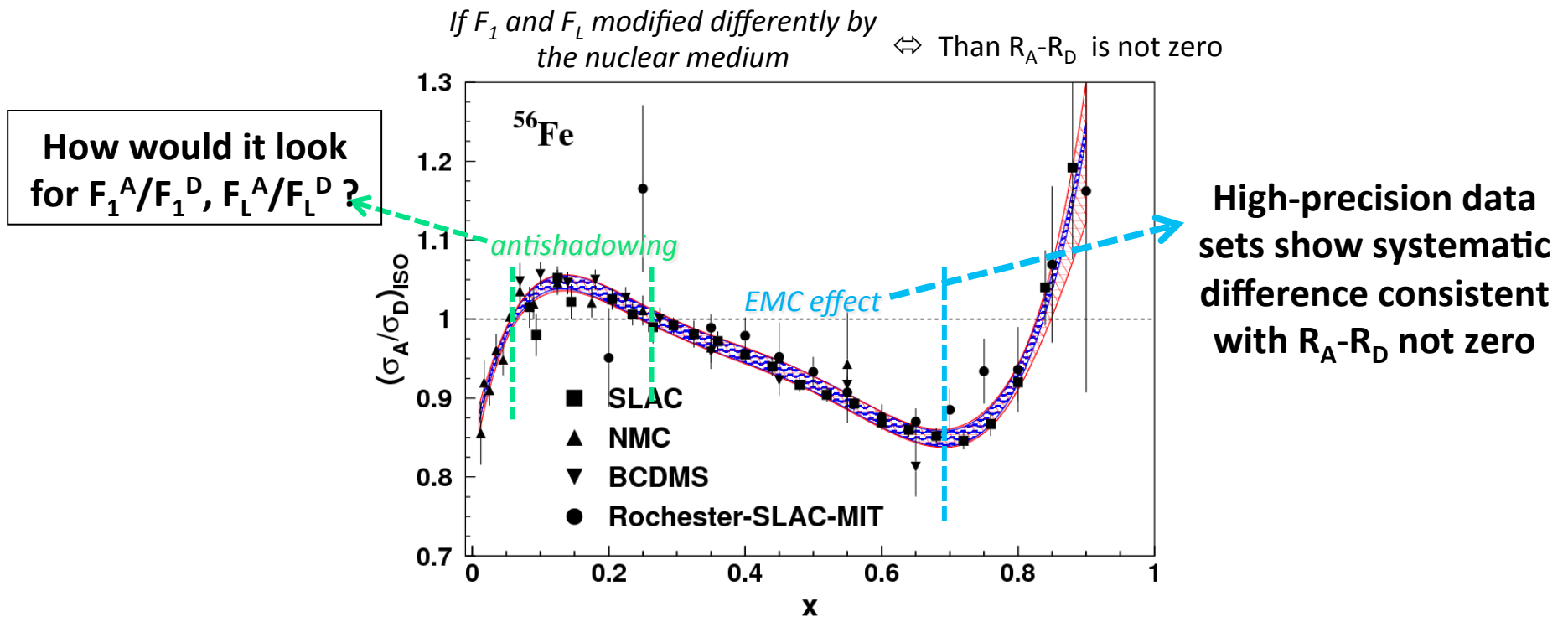
(The JUPITER Collaboration Jlab E02-109 E04-001 E06-009)

*Are  $F_2$ ,  $F_1$  and  $F_L$  (or  $R$ ) modified differently by the nuclear medium?*

*Many plots in this talk are thanks to Simona Malace, Jefferson Lab, and from Vahe Mamyan, Ph.D. thesis on E04-001, University of Virginia*

# Physics Motivation for Nuclear L/Ts

- Fundamental questions on the nuclear modifications of the nucleon structure functions



- What is the origin of the antishadowing?
- EMC effect
- Nuclear Parton Distribution Functions: Currently there no constraints from separated structure functions  $\rightarrow$  assumption is of  $\sigma_A/\sigma_D = F_2^A/F_2^D$
- Of interest to neutrino experiments (which are on nuclear targets and are in the Jlab energy range).

Only a few measurements on  $R_A - R_D$ ,  $F_L^{A,D}$ ,  $F_1^{A,D}$ ,  $F_2^{A,D}$ , and even on  $R_p$ ,  $F_1^p$ ,  $F_L^p$ ,  $F_2^p$

# Basics: Rosenbluth L/T Separations

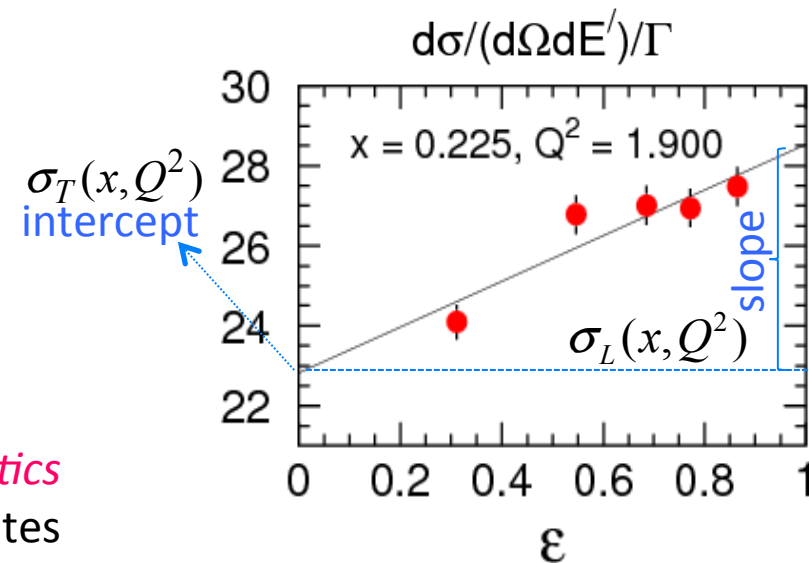
- **Separate L and T contributions** to the total cross section by performing a **fit of the reduced cross section dependence with  $\epsilon$**  at *fixed  $x$  and  $Q^2$*

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma(\sigma_T(x, Q^2) + \epsilon\sigma_L(x, Q^2)) = \Gamma\sigma_T(1 + \epsilon R) \quad \epsilon = 1/(1 + 2(1 + \nu^2/Q^2)\tan^2(\theta/2))$$

$$F_1(x, Q^2) = \frac{KM}{4\pi^2\alpha}\sigma_T(x, Q^2) \quad F_2(x, Q^2) = \frac{K}{4\pi^2\alpha}\frac{\nu}{(1+\nu^2/Q^2)}[\sigma_T + \sigma_L]$$

Requirements for precise L/Ts:

- As **many  $\epsilon$  points** as possible spanning a large interval from 0 to 1  
 → *as many  $(E, E', q)$  settings as possible*
- *Very good control of point-to-point systematics*  
 → 1-2 % on the reduced cross section translates into 10-15 % on  $F_L$



**Relations of structure functions to QCD and quark distributions:  
F2 is fundamental (not 2xF1)**

$$\mathcal{F}_{2,LO}^{e/\mu}(x, Q^2) = \sum_i e_i^2 [xq_i(x, Q^2) + x\bar{q}_i(x, Q^2)] .$$

**Only F2 (not F1) is related to the sum of quark and antiquark distributions.** At high Q2 we use the variable x. At lower Q2, we include the target mass scaling variables

$$\xi_{TM} = \frac{Q^2}{M\nu[1 + \sqrt{1 + Q^2/\nu^2}]},$$

For neutrino structure functions, Quark-Hadron duality ( when integrated over all  $\nu$ ) is EXACT for the Adler sum rule down to  $Q^2=0$  only for the Structure Function  $F_2$ .

**$F_2$  is the quark PDF distribution**

In quark language the Adler sum rule is number of u quarks minus the number of d quarks in the nucleon is 1. (2 up and 1 down). It uses  $F_2$ .

The Adler sum rules are derived from current algebra and are therefore valid at all values of  $Q^2$ . The equations below are for *strangeness conserving*(sc) processes.

$$|F_V(Q^2)|^2 + \int_{\nu_0}^{\infty} \mathcal{W}_{2n-sc}^{\nu-vector}(\nu, Q^2) d\nu - \int_{\nu_0}^{\infty} \mathcal{W}_{2p-sc}^{\nu-vector}(\nu, Q^2) d\nu = 1$$

Where the limits of the integrals are from pion threshold  $\nu_0$  where  $W = M_\pi + M_P$  to  $\nu = \infty$ . At  $Q^2 = 0$ , the inelastic part of  $\mathcal{W}_2^{\nu-vector}$  goes to zero, and the sum rule is saturated by the quasielastic contribution  $|F_V(Q^2)|^2$ .

## FL includes:

- The effects of gluon radiation (QCD) which dominate at high  $Q^2$ .
- Target mass effects (+ quark transverse momentum) which dominate at high  $x$  and intermediate  $Q^2$  (Jlab energy range).
- Higher twist effects which dominate near  $Q^2=0$ .
- **In QCD  $2xF_1$  is derived from  $F_2$  by the subtraction of  $F_L$ .**

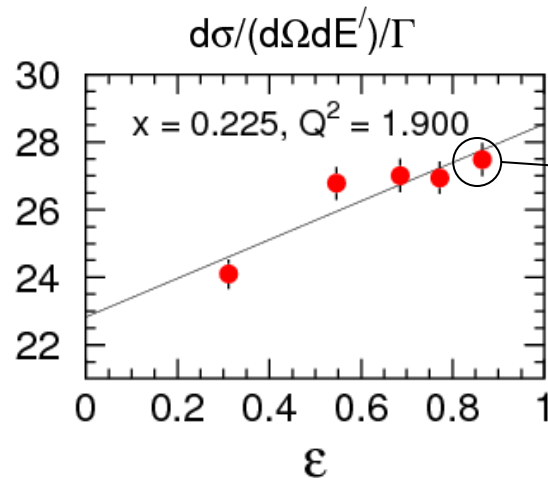
$$2xF_1 = F_2 \left( 1 + \frac{4M^2x^2}{Q^2} \right) - F_L(x, Q^2).$$

$$\mathcal{R}(x, Q^2) = \frac{\sigma_L}{\sigma_T} = \frac{F_2}{2xF_1} \left( 1 + \frac{4M^2x^2}{Q^2} \right) - 1 = \frac{F_L}{2xF_1}$$

For a complete understanding of the origin of the nuclear effects in electron scattering, we need to study nuclear effects in all three structure functions  $F_2$ ,  $\mathcal{R}$  and  $F_1$  (and also in  $F_3$  if we include neutrino scattering).

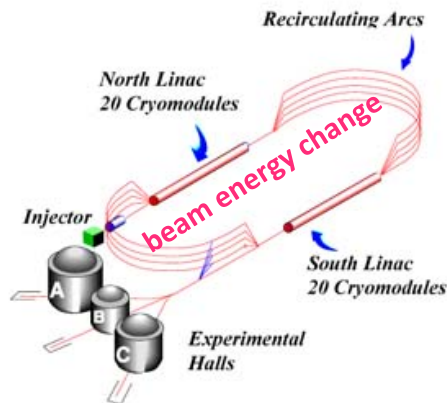
# Example: L/Ts at Jefferson Lab

- True, model-independent Rosenbluth L/Ts are time consuming



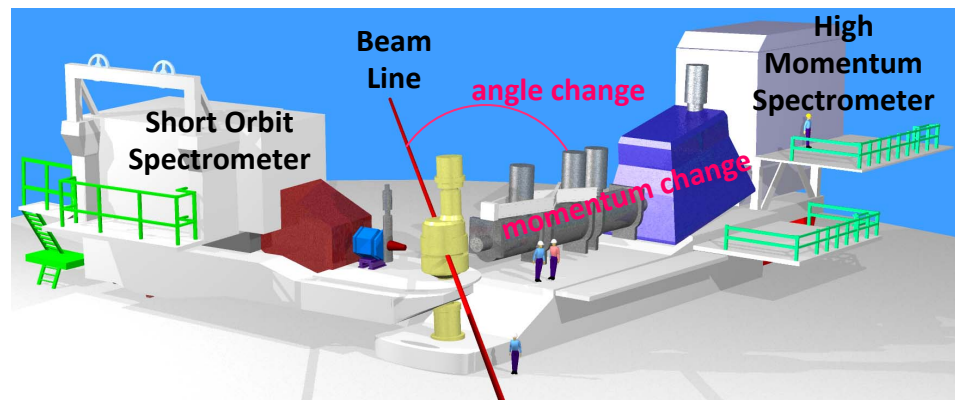
- Each e point requires different values of: beam energy, momentum and angle
- Here 5 changes of beam energy, momentum and angle to obtain R and the separated structure functions at **one** given  $(x, Q^2)$  via model-independent true Rosenbluth L/T separations

## CEBAF at Jefferson Lab



- 5 hours per beam pass change
- 12 hours per linac energy change

## Hall C at Jefferson Lab

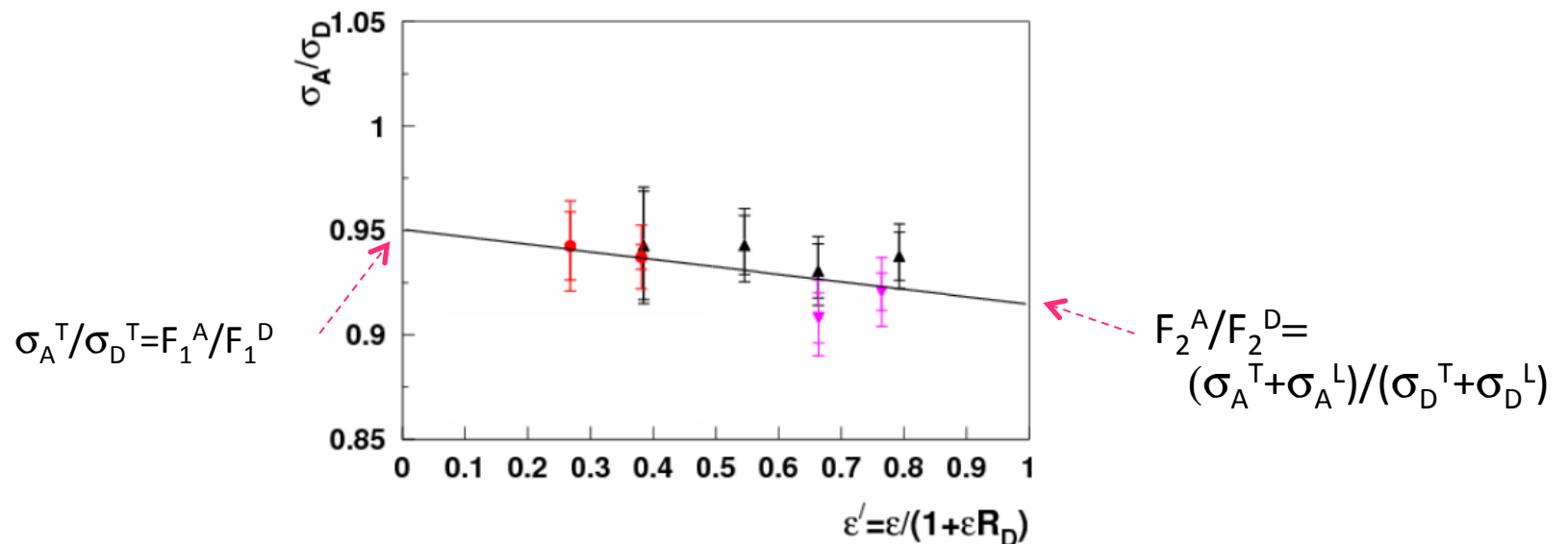


- 20 minutes per angle and momentum change



# Basics: $R_A - R_D$ from $\sigma_A/\sigma_D$

- $R_A - R_D$  and  $\sigma_A^T/\sigma_D^T$  are extracted by performing a fit of the cross section ratio dependence with  $\epsilon'$  at fixed  $x$  and  $Q^2$



$$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_A^T}{\sigma_D^T} \left(1 + \frac{\epsilon}{1 + \epsilon R_D} (R_A - R_D)\right) \quad \epsilon' = \frac{\epsilon}{1 + \epsilon R_D} \quad \frac{\sigma_A}{\sigma_D} \approx \frac{F_2^A}{F_2^D} \left[1 - \frac{(R_A - R_D)(1 - \epsilon)}{(1 + R_D)(1 + \epsilon R_D)}\right]$$

- The cross section ratio is equal to the  $F_2$  structure function ratio only if  $\epsilon = 1$  or  $R_A = R_D$

- Advantage of extraction method: many systematic uncertainties cancel in the cross section ratio (detector performance, kinematics, acceptance, beam...)

## Global Fits to $R_p$ , $R_d$ that have been used by electron and neutrino experiments

R\_1990 = R-world

20. L. W. Whitlow *et al.* (SLAC-MIT), Phys. Lett. B**282**, 433 (1995)

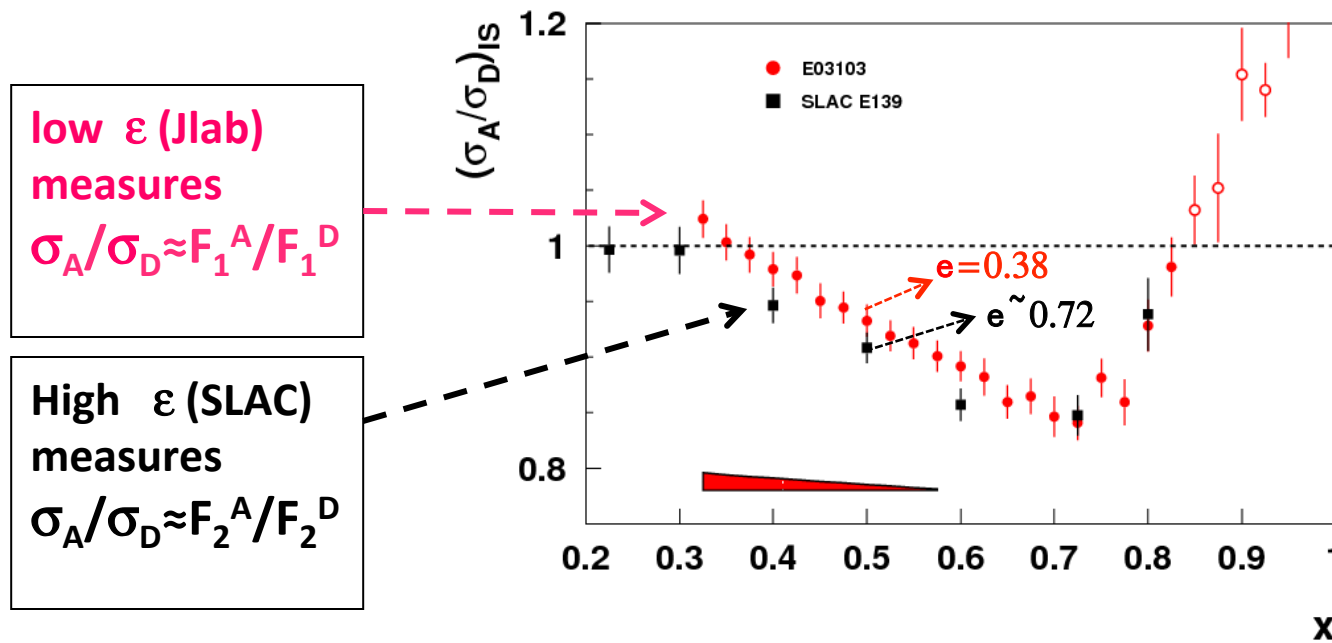
R\_1998

37. K. Abe *et al.*, Phys. Lett. B**452**, 194 (1999)

# Implications of $\Delta R \neq 0$

## EMC effect

- A very well measured behaviour like the **EMC effect** still offers surprises – the tension between *low  $e$  Jefferson Lab* and *high  $e$  SLAC* data on heavy targets



Plot from Dave Gaskell

- How would the ratio look for the separated structure functions  $F_2$ ,  $F_1$ ,  $F_L$ ? Is  $F_1$  modified differently than  $F_2$  by the nuclear medium because of nuclear dependence of  $R$ ?
- Often the cross section ratio is identified with the  $F_2$  structure function ratio and therefore as nuclear modifications of **quark** distributions

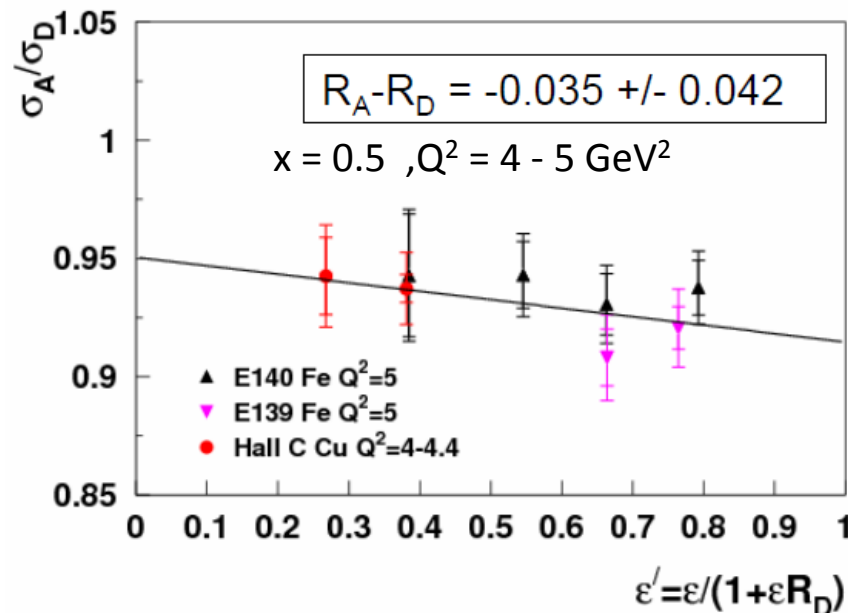
**Simplest way is to investigate if  $\sigma_A/\sigma_D$  is  $\epsilon$  dependent?**

# Hints of $\Delta R \neq 0$ in DIS

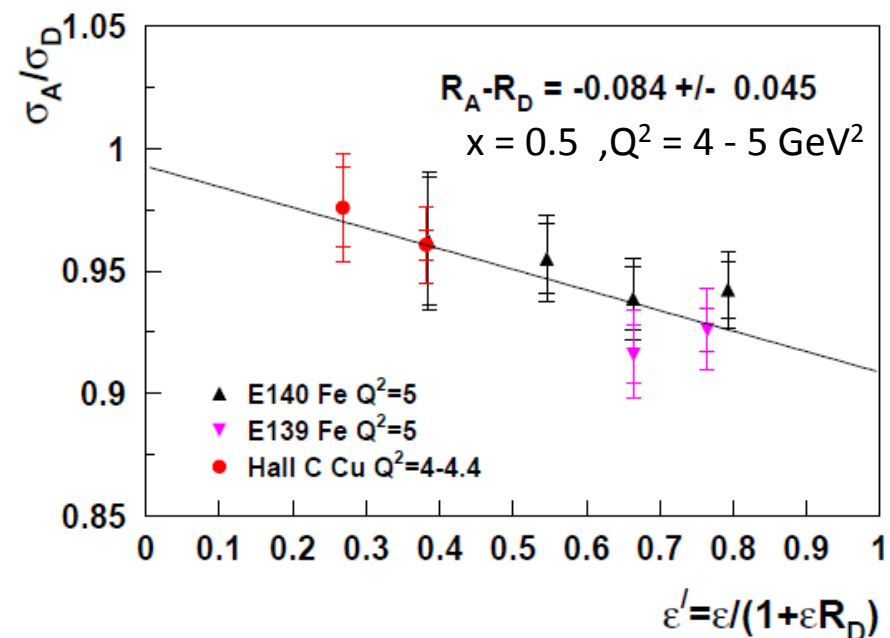
➤ **Coulomb effects** have not been accounted for in the SLAC E140 analysis (**non-negligible** at SLAC and Jefferson Lab kinematics)

→ **Re-analysis** of **combined data sets** from SLAC and Hall C: E140 (Fe), E139 (Fe) and Hall C (Cu) at  $x = 0.5$  and  $Q^2 = 4 - 5 \text{ GeV}^2$  *arXiv:0906:0512*

- **Coulomb corrections** calculated within the Effective Momentum Approximation and the  $e'$  dependence of the cross section ratios  $\sigma_A/\sigma_D$  fitted to re-extract  $R_A - R_D$



**No Coulomb corrections**



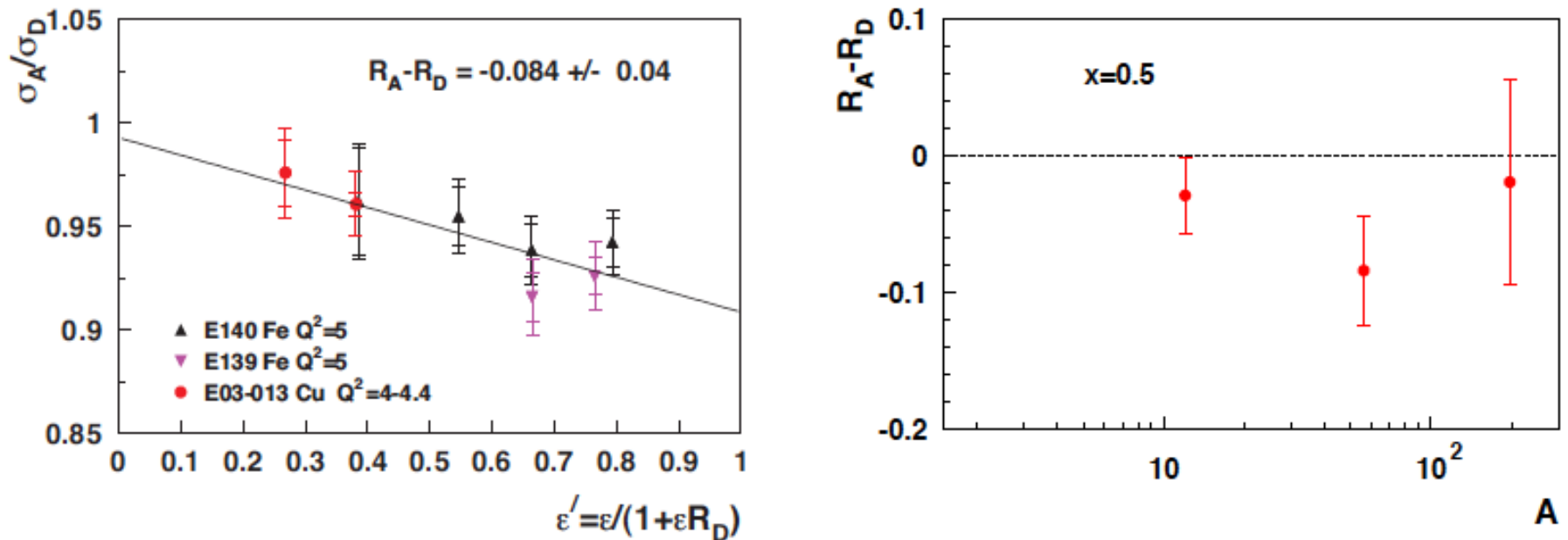
**With Coulomb corrections:  $\Delta R$   $2\sigma$  from zero**

# Hints of $\Delta R \neq 0$ in DIS

→ **Re-analysis** of **combined data sets** from SLAC and Hall C: E140 (Fe), E139 (Fe) and Hall C (Cu) at  $x = 0.5$  and  $Q^2 = 4 - 5 \text{ GeV}^2$  *arXiv:0906:0512 (now include Coulomb corrections)*

- **Coulomb corrections** calculated within the Effective Momentum Approximation and the  $e'$  dependence of the cross section ratios  $\sigma_A/\sigma_D$  fitted to re-extract  $R_A - R_D$

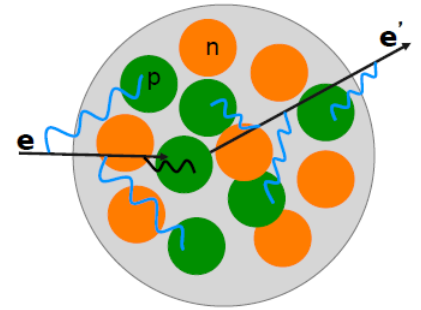
$$x = 0.5, Q^2 = 4 - 5 \text{ GeV}^2$$



**FIGURE 3.** Extraction of the nuclear dependence of  $R$  for  $^{56}\text{Fe}$ - $^{63}\text{Cu}$  at  $x = 0.5$  (left plot). Results from the same extraction method for  $^{12}\text{C}$ ,  $^{56}\text{Fe}$ - $^{63}\text{Cu}$  and  $^{197}\text{Au}$  (right plot). The JLab E03-103 data are preliminary.

# Basics: Coulomb Effects

- Acceleration of incoming and deceleration of outgoing electrons in the Coulomb field of the target nucleus
- Effect can be neglected at high energies but not at Jefferson Lab and SLAC kinematics
- Distorted (NOT plane wave) Born approximation (DWBA vs PWBA) is the appropriate framework to calculate the scattering cross section



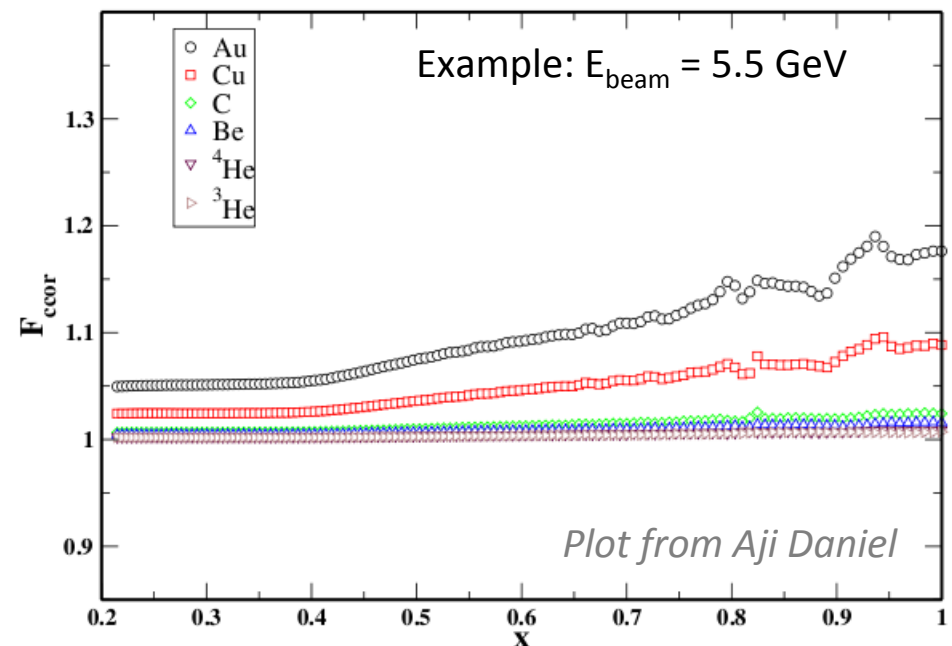
A more practical calculation, the **Effective Momentum Approximation (EMA)** has been verified/tuned to agree with DWBA calculations in the quasielastic region (no such study done for DIS)

**Correction factor for cross sections in EMA:**

$$F_{\text{ccor}} = \frac{\sigma(E, E')}{\sigma(E+V, E'+V)} \times \frac{1}{F_{\text{foc}}^2} \quad F_{\text{foc}} = \frac{E+V}{E}$$

$$V = \frac{4}{5} V_0 \quad V_0 = \frac{3\alpha(Z-1)}{2R}$$

Aste et al., Eur.Phys.J.A26 167-178, 2005



**Coulomb corrections calculated with EMA**

# Measurements of $R_A - R_D$ from Charged-Lepton Scattering JUPITER Collaboration

➤ **Model-independent** extractions from **dedicated L/T experiments**

(The JUPITER Collaboration Jlab E02-109 E04-001 E06-009)

E02-109/E04-001, <b>JLab</b> – 2005	<b>QE +RES</b>	Fixed target: H, D, C, Al, Fe 4 beam energies <b>Low Q2 results to be published 2016</b>	$Q^2 : 0.2 - 2.5$ <b>Currently in analysis- to be published 2016</b>	$R_{d',C,Al,Fe}$ $R_{C,Al,Fe} - R_d$
E06-009/E04-001, <b>JLAB</b> – 2007	<b>QE +RES</b>	Fixed target: D, C, Al, Fe, Cu 6 beam energies <b><i>This Talk – Final Results to be published 2015</i></b>	$Q^2 : 0.5 - 4$ <b><i>Preliminary results Reported here</i></b>	$R_{d',C,Al,Fe,Cu}$ $R_{C,Al,Fe,Cu} - R_d$

$RES \rightarrow W < 2$ ,  $DIS \rightarrow W > 2$ ,  $QE \rightarrow$  quasielastic scattering on nuclei

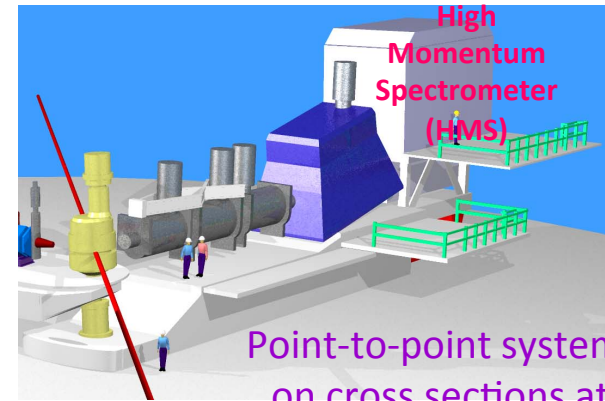
# Measurements of $\Delta R$ in the Res. Region: JLab

- Jefferson Lab @ 6 GeV: **E04-001/E06-109**, true Rosenbluth L/T separations on **D** and **Al, C, Fe, Cu** in the **resonance region**

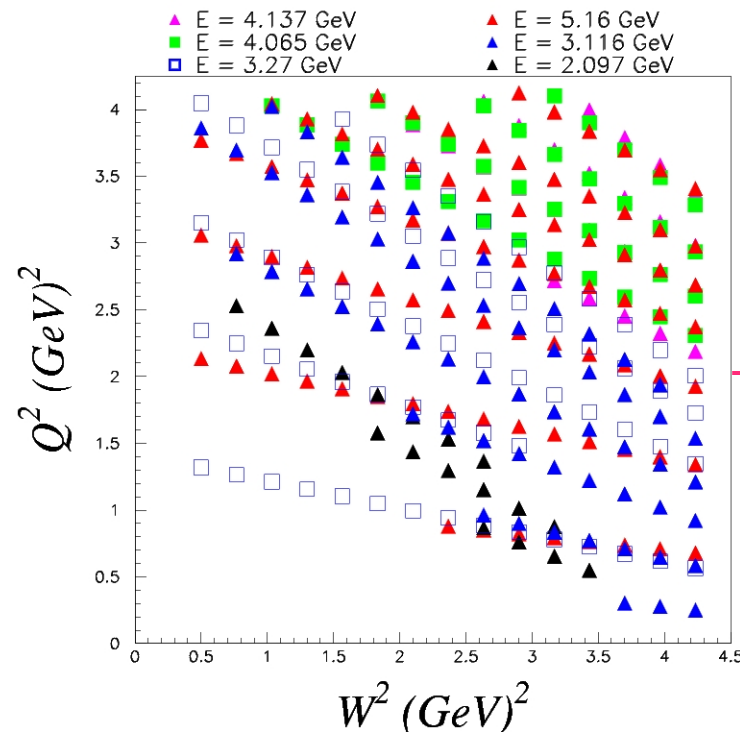
Primary physics goals:

- ➔ Study the nuclear dependence of R and of the separated structure functions
- ➔ Study quark-hadron duality in nuclei

## Hall C at Jefferson Lab

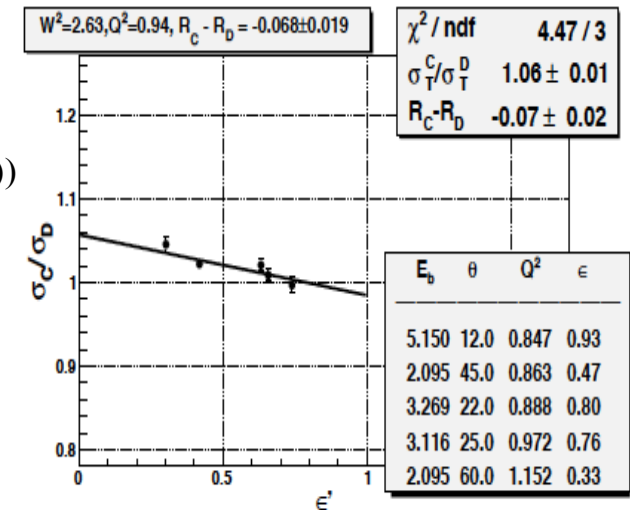


Point-to-point systematics on cross sections at the level of 1.7%



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

True Rosenbluth L/T



Vahe Mamyán, Ph.D. thesis, University of Virginia



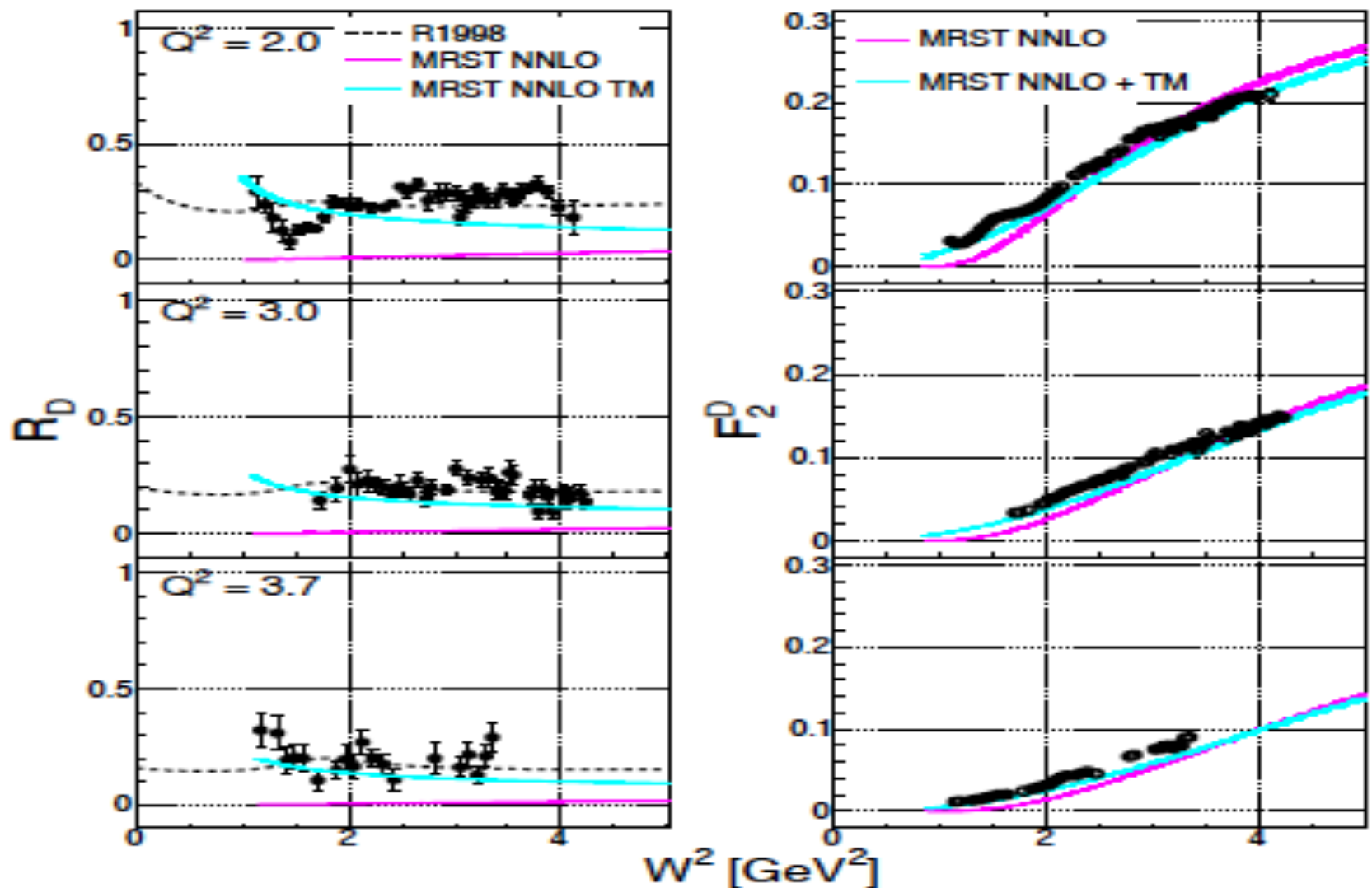
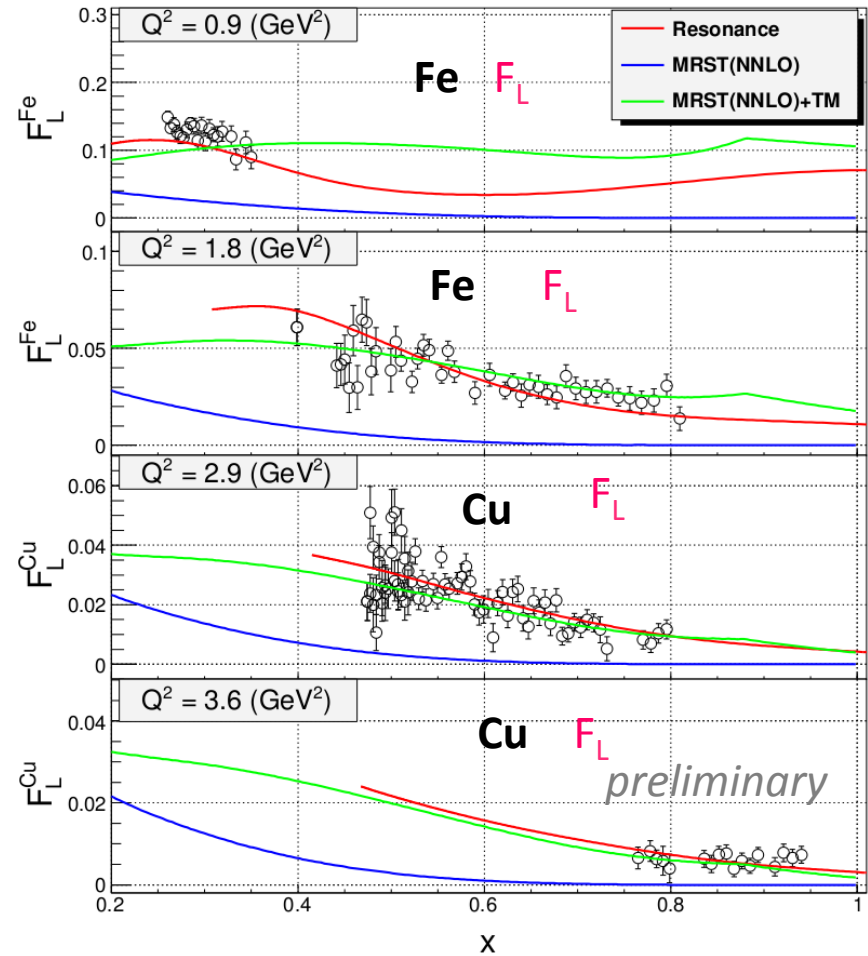
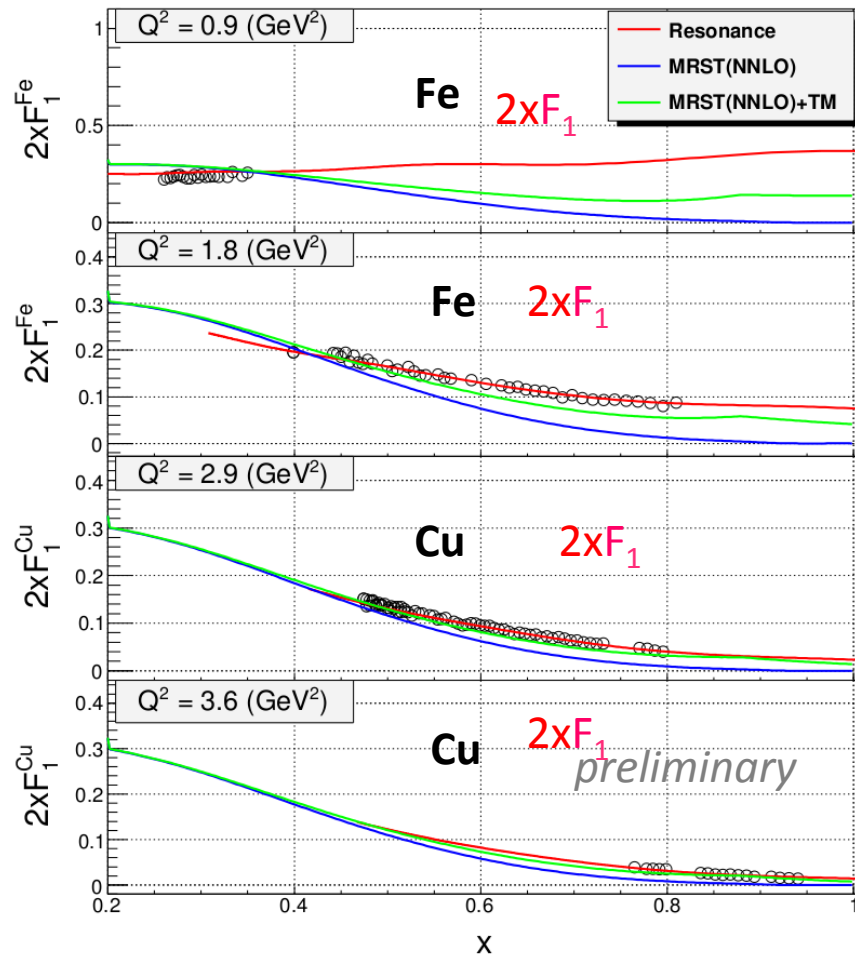


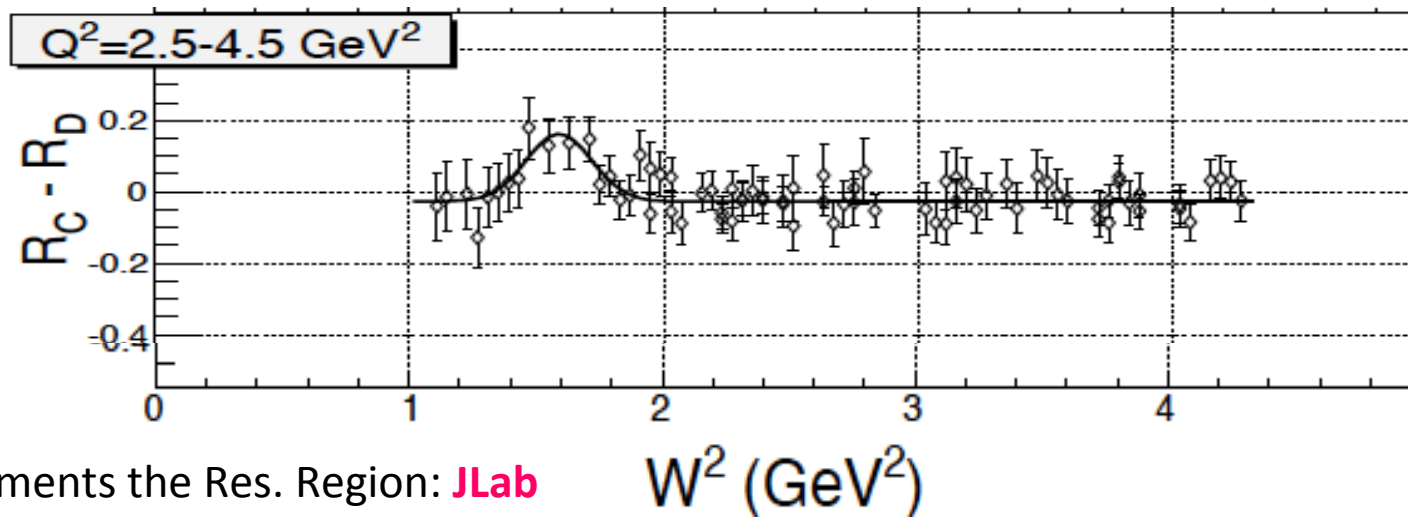
FIG. 1: Fig.1 Extracted values of  $R_D$  and  $F_{2D}$  in fine bins of  $W$  for three values of  $Q^2$  compared to the theoretical expectation for  $R_D$  from NNLO QCD, from NNLO QCD including target mass corrections, and from a fit to the world's previous measurements of  $R$  for free protons ( $R_{1998}$ ).

The experiment also measures  $2xF_1$ ,  $F_2$ ,  $F_L$  in the Res. Region for several nuclear targets **C, Al, Fe, Cu** as well as RA-RD

- 6 GeV JLab **E04-001/E06-109**: access the separated structure functions on nuclei and study quark-hadron duality

*To the MRST pQCD fit EMC effect corrections and isoscaler corrections are also added*





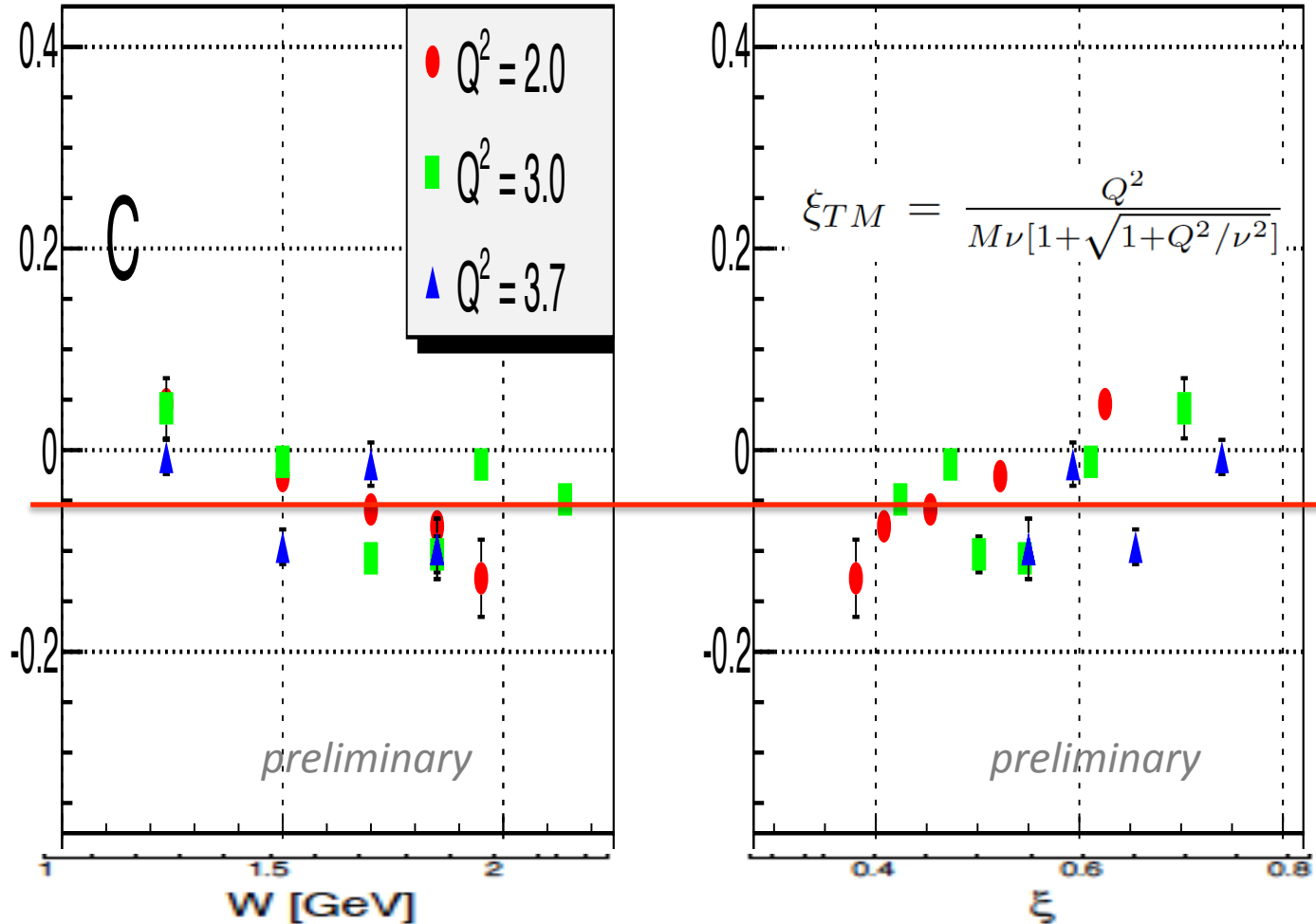
- 6 GeV JLab E04-001/E06-109: very careful analysis for high-precision measurements of  $\Delta R$ 
  - all relevant corrections applied (Coulomb corrections included)
  - 2 methods for cross sections extraction employed
  - exhaustive study of systematics underway
- Preliminary results point to nuclear medium modifications of  $R$  in the resonance region.
- **Surprisingly  $R_A - R_d$  is NEGATIVE. (Fine bins in  $W$  are averaged for this plot)**

Peak at  $W = 1238$  is Delta resonances which is mostly transverse and Deuterium is not smeared by Fermi motion.

Better to average over larger  $W$  bins.

Delta resonance is mostly transverse, so R is small to begin with

RC-RD



➤ Fine bins in W are averaged for this plot

Rc-Rd is negative and about -0.05

FIG. 2: Extracted values of  $R_A - R_D$  for C, Al, Fe and Cu versus W (left panel) and versus  $\xi_{TM}$  (right panel). The three values of  $Q^2$  are shown as different symbols.

**The Overall Estimated Experimental Systematic Error is +- 0.028**

Overall normalization errors cancel in the extraction of  $R_D$ . The overall 1.4% systematic error[7] in the  $\epsilon$  dependence of the cross that originates from  $E_0$  (0.25%), beam charge (0.3%), efficiencies (0.35%), CS background (0.1-0.4%), acceptance (0.7%) and radiative corrections (<1%), yields a systematic uncertainty in  $R_D$  of  $\pm 0.028$ .

**Theoretical Expectations – The result is unexpected.  
None of the models predict  $R_A < R_D$ )**

Our result that  $R_A < R_D$  is contrary to several theoretical expectations. Calculations [15] of the effect of the Fermi motion on nucleons in nuclei predict a small difference in the opposite direction to what we observe.

[15] M. Erickson, S. Kumano, Phys. Rev. C, 022201 (2003).

A decrease of the gluon distributions in nuclei yields  $R_A < R_D$  in the  $x < 0.1$  shadowing region. However, the contribution of the gluon distributions to  $R$  for  $x > 0.3$  is small and these models[16] predict  $R_A = R_D$  for the  $x$  region of our measurements (i.e. the EMC effect region).

[16] N. Armesto et. al. Phys. Lett. B694, 38 (2010).

Models[14] which attribute the EMC effect to the presence of pions in nuclei also predict an effect in the opposite direction to what we observe (these models also predict enhancement of antiquarks in the nucleus which has been ruled out by Drell-Yan experiments on nuclear targets[3]).

[3] G. A. Miller, Eur.Phys. J. A 31, 578 (2007).

[14] G. A. Miller, Phys. Rev. C 64, 022201 (2001).



## Can we explain the results within current models of the EMC effect

In the naive quark parton model[17],  $R = 4\langle K_T^2 \rangle / Q^2$ , where  $K_T$  is the momentum of quarks in a nucleon perpendicular to the direction of the momentum transfer vector. Therefore, a possible interpretation of the data is that  $\langle K_T^2 \rangle$  is smaller for bound nucleons, and that the distributions for both the parallel and perpendicular momentum components of quarks in a nucleon are softened in a nuclear medium. This is consistent with the hypotheses that the EMC effect may be due to partial deconfinement[18] of quarks caused by short range nucleon-nucleon correlations (SRC) in nuclei[19].

- [17] R. P. Feynman, Photon-Hadron Interactions (Benjamin, Reading, MA,1972), pp. 138-139.
- [18] Partial deconfinement of quarks in low momentum nucleons in nuclei has been ruled out by measurements of the form factors of bound nucleons, but not for high momentum nucleons with high virtuality from SRC.
- [19] L. B. Weinstein et al. Phys. Rev. Lett. 106, 052301 (2011)

However, the effect is probably too large for this interpretation

## Other Possibilities

**Two-photon exchange with partons in the same nucleon is probably the same for free and bound nucleons.**

At present, there is no reliable calculation of two-photon exchange contributions to the radiative corrections. The two photon exchange contribution to the cross section for a point like proton has been estimated[11] to be +0.3% at  $\epsilon = 1$  and +2.3% at  $\epsilon = 0$ . If we assume that the contributions for inelastic scattering from point like quarks is similar to a point like proton, the two-photon contribution changes  $F_{2D}$  by +0.3% and  $R_D$  by +0.04.

[11] J. Arrington, P.G. Blunden, and W. Melnitchouk. Prog.Part.Nucl.Phys. 66, 782 (2011).



**There is a two-photon double/parton process  
which is different for free vs bound nucleons-**

is two-photon exchange where the two photons scatter from quarks in different nucleons in the nucleus. The contribution from interactions involving one hard photon absorbed by one nucleon and multiple soft photons absorbed by other nucleons in the nucleus is already included in the Coulomb correction. However, exchange of one hard photon with a quark in one nucleon, and another hard photon with a quark in another nucleon is not included. Theoretical estimates of the contribution of this process are not presently available.

*In QE scattering we observe scattering from two nucleons in nuclear targets e.g. Transverse enhancement/ meson exchange currents (MEC).*

*We may be seeing a similar effect originating from two-photon exchange or double-parton scattering from partons in two different nucleons in the nucleus*

*This has a lot of implications for all measurements on nuclear targets..*

## **Next Step**

Neutrino experiments are mostly interested in low  $Q^2$ .

Our results at lower  $Q^2$  results will be available in early 2016 (Simona Malace).

The lower  $Q^2$  data will provide more information on the  $Q^2$  dependence of RA-RD for several nuclei.

If the unexpected results are from double parton scattering from partons in two different nucleons (e.g. via two-photon/boson processes), then the effect is likely to be different in electron vs neutrino scattering on nuclear targets. This has implications for all experiments on nuclear targets (e.g. the NuTeV anomaly, nuclear parton distributions etc).

Stay tuned.

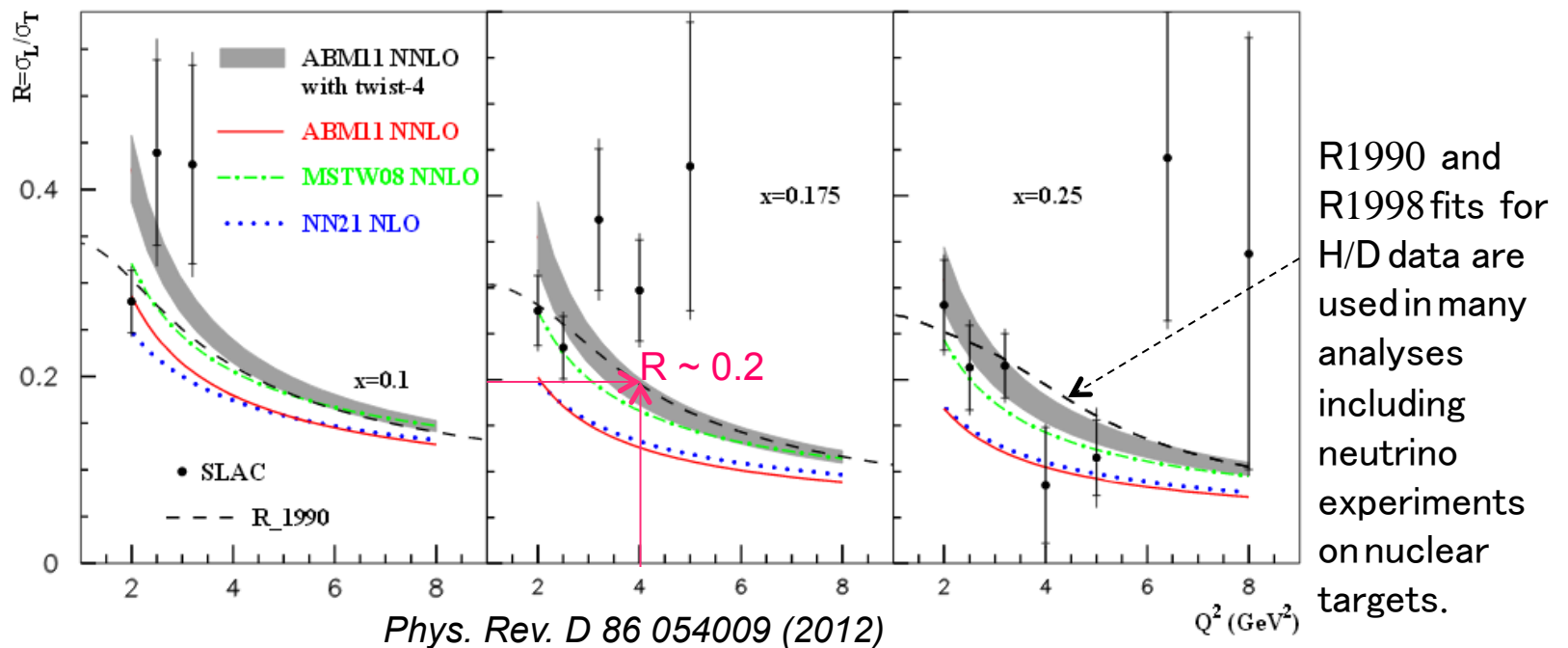
Additional Slides

# Basics: $R_A - R_D$ from $\sigma_A/\sigma_D$

- $R$  typically a small quantity ( $< 1$ ): even a *small non-zero*  $R_A - R_D$  in absolute value could imply *non-negligible nuclear medium modifications of  $R$*

**Example:**  $x = 0.175$ ,  $Q^2 = 4 \text{ GeV}^2$   $R \sim 0.2$ : if  $DR = 0.04 \rightarrow \sim 20\%$  effect from nuclear medium

$x = 0.175$ ,  $Q^2 = 20 \text{ GeV}^2$   $R \sim 0.08$ : if  $\sim 20\%$  effect from nuclear medium  $\rightarrow DR = 0.016$



- Very good control of experimental systematics needed, all possible corrections to the cross section ratio must be accounted for (i.e. Coulomb corrections, if non-negligible)
- **Search** for medium effects most efficient at **low to moderate  $Q^2$  in a dedicated L/T experiment**

Neutrino experiments are mostly interested in low Q<sup>2</sup>.

Low Q<sup>2</sup> results will be available in 2015/16.

## Using the results in neutrino experiments on nuclear targets

Models of neutrino cross sections use R<sub>D</sub>=R<sub>1990</sub>, or R<sub>D</sub>=R<sub>1998</sub>.

The expression below is a correction factor that can be applied using a fit to our R<sub>A</sub>-R<sub>D</sub> measurement.

$$\frac{\sigma_A}{\sigma_D} \approx \frac{F_2^A}{F_2^D} \left[ 1 - \frac{(R_A - R_D)(1 - \varepsilon)}{(1 + R_D)(1 + \varepsilon R_D)} \right]$$

However, the unexpected results are from double parton scattering from partons in two different nucleons via two-photon/boson processes, which may be different in electron vs. neutrino experiments on nuclear targets.

Our data at lower Q<sup>2</sup> (to be finalized next year) would provide new information on the Q<sup>2</sup> dependence of these unexpected results.

$$\mathcal{F}_2^\nu(x, Q^2) = 2\Sigma_i [\xi_w q_i(\xi_w, Q^2) + \xi_w \bar{q}_i(\xi_w, Q^2)] .$$

and

$$x\mathcal{F}_3^\nu(x, Q^2) = 2\Sigma_i [\xi_w q_i(\xi_w, Q^2) - \xi_w \bar{q}_i(\xi_w, Q^2)]$$

where

$$q^{\nu p} = d + s; \quad \bar{q}^{\nu p} = \bar{u} + \bar{c}$$

$$q^{\nu n} = u + s; \quad \bar{q}^{\nu p} = \bar{d} + \bar{c}$$

$$q^{\bar{\nu} p} = u + c; \quad \bar{q}^{\nu p} = \bar{d} + \bar{s}$$

$$q^{\bar{\nu} n} = d + c; \quad \bar{q}^{\nu p} = \bar{u} + \bar{s}$$

$$\mathcal{F}_1 = \frac{MK}{4\pi^2\alpha}\sigma_T,$$

$$\mathcal{F}_2 = \frac{\nu K(\sigma_L + \sigma_T)}{4\pi^2\alpha(1 + \frac{Q^2}{4M^2x^2})}$$

$$\mathcal{F}_L(x, Q^2) = \mathcal{F}_2 \left(1 + \frac{4M^2x^2}{Q^2}\right) - 2x\mathcal{F}_1$$

$$2x\mathcal{F}_1(x, Q^2) = \mathcal{F}_2(x, Q^2) \frac{1 + 4M^2x^2/Q^2}{1 + \mathcal{R}(x, Q^2)}.$$

$$2x\mathcal{F}_1 = \mathcal{F}_2 \left(1 + \frac{4M^2x^2}{Q^2}\right) - \mathcal{F}_L(x, Q^2).$$