Jefferson Lab Measurements of Nuclear R and F_L

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Jefferson Lab

Outline

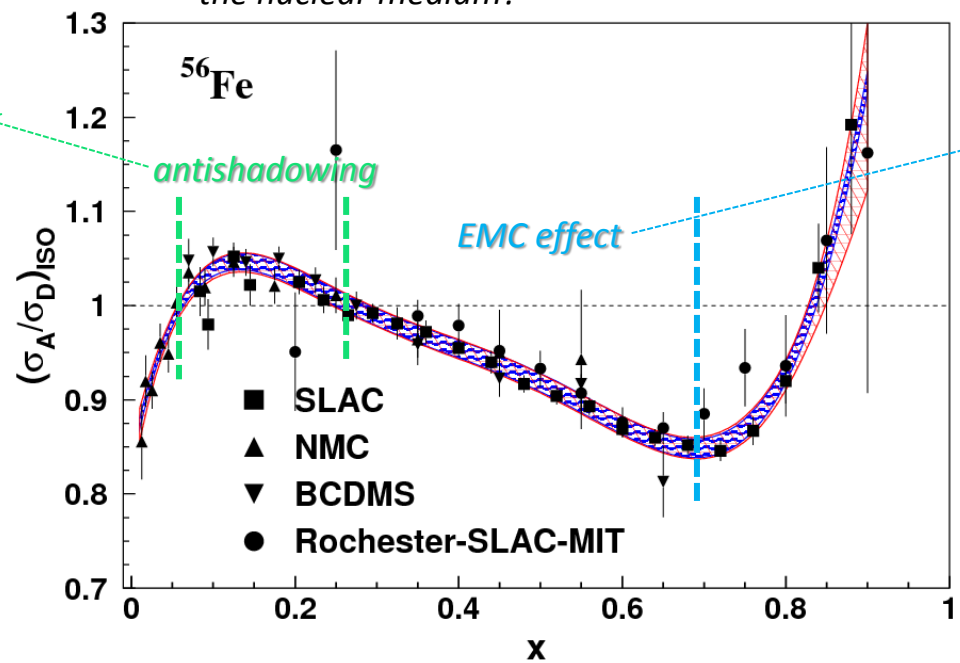
- Why are we interested in high-precision measurements of nuclear R and separated structure functions?
- Methodology of model-independent, true Rosenbluth L/T separations and why those are "hard" measurements to do! (*thus only few have been done*)
- Quantitatively, how small of a nuclear medium effect on R would be needed to re-assess the way we think about the antishadowing and the EMC effect regions?
- Brief summary of existing measurements of R_A-R_D from charged lepton scattering in the Deep Inelastic Scattering (DIS) region
- Preliminary, **exciting** results on R_A-R_D from **Jefferson Lab** in the Resonance (RES) region from the **6 GeV running**
- **Plans for future**: new experiment planned at **Jefferson Lab during the 12 GeV** running to measure nuclear modifications of R and of the separated structure functions via model-independent, true Rosenbluth L/T separations

Physics Motivation for Nuclear L/Ts

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

F_1 and F_L modified differently by the nuclear medium? ⇔ R_A-R_D not zero?

How would it look for F_1^A/F_1^D, F_L^A/F_L^D ?



High-precision data sets show systematic difference consistent with R_A-R_D not zero

- What is the origin of the antishadowing?
- EMC effect
- Nuclear Parton Distribution Functions: no constraints from separated structure functions → working in the limit of $\sigma_A/\sigma_D = F_2^A/F_2^D$

Too 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 ε** at *fixed x and Q^2*

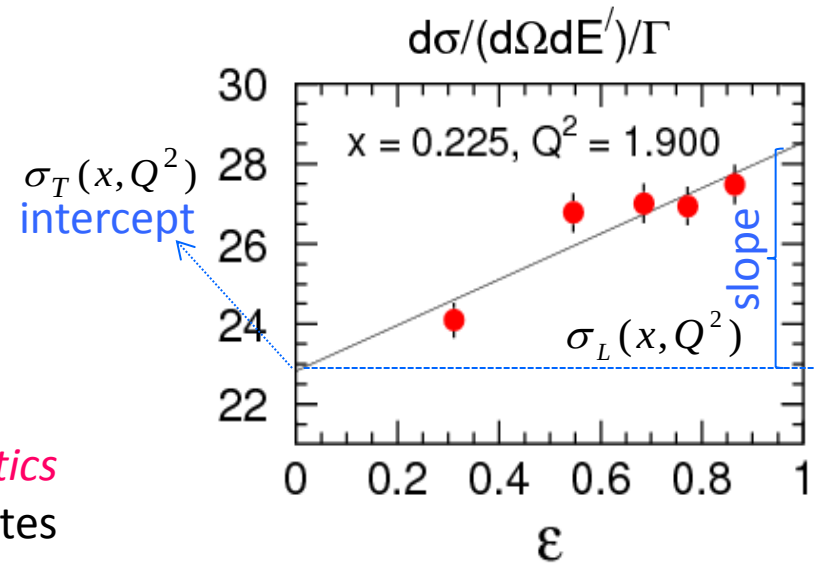
$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma(\sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)) = \Gamma\sigma_T(1+\varepsilon R) \qquad \varepsilon = 1/(1+2(1+{\nu^2}/{Q^2})tan^2({\theta}/{2}))$$

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

<u>Requirements for precise L/Ts</u>:

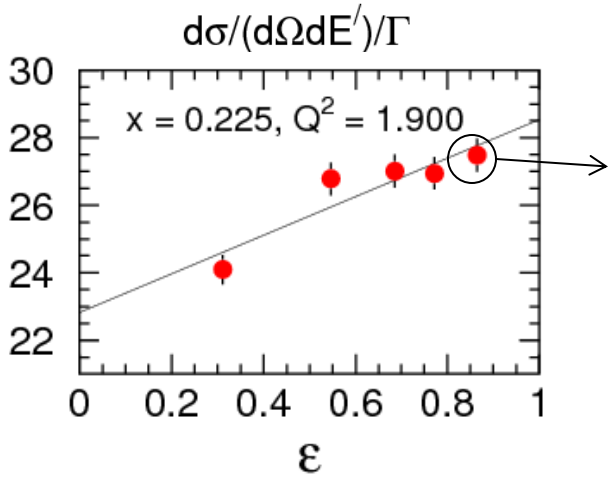
- As many ε points as possible spanning a large interval from 0 to 1
  → *as many (E, E', θ) settings as possible*

- *Very good control of point-to-point systematics*
  → 1-2 % on the reduced cross section translates into 10-15 % on F_L



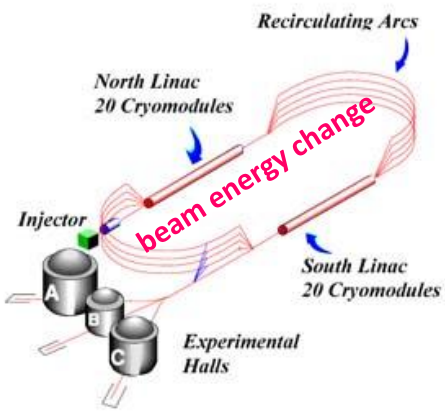
Example: L/Ts at Jefferson Lab

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



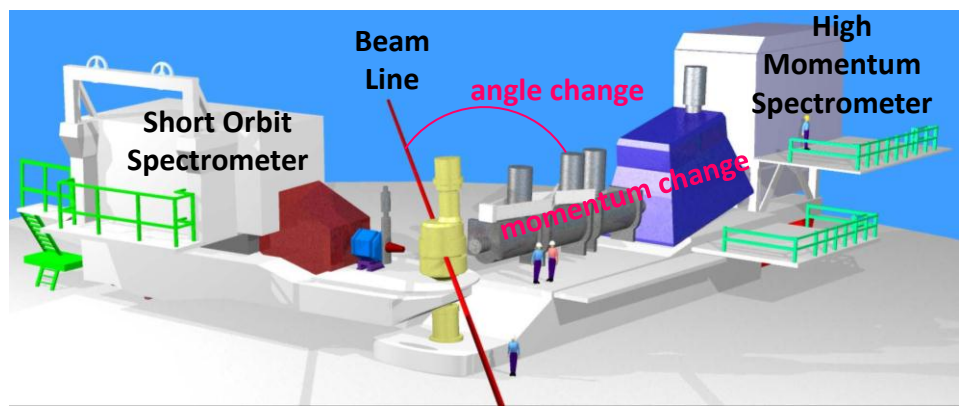
- Each ε point requires different values of: beam energy, momentum and angle
- Here 5 changes of beam energy, momentum and angle to obtain R and the separated structure functions at **one** given (x,Q^2) via model-independent true Rosenbluth L/T separations

CEBAF at Jefferson Lab



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

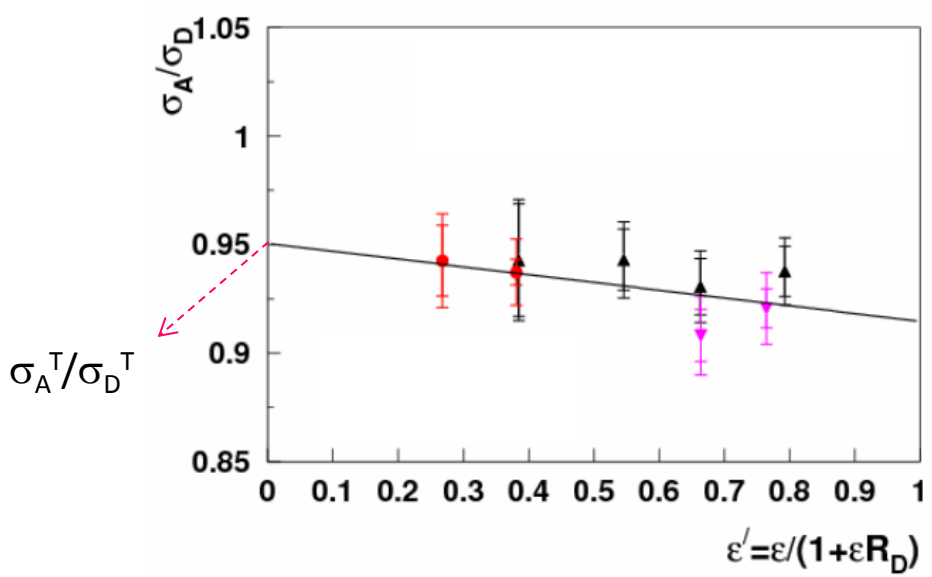
Hall C at Jefferson Lab



- 20 minutes per angle and momentum change

Basics: R_A-R_D from σ_A/σ_D

- $R_A - R_D$ and σ_A^T/σ_D^T are extracted by performing a fit of the cross section ratio dependence with ε' at fixed x and Q^2



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

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

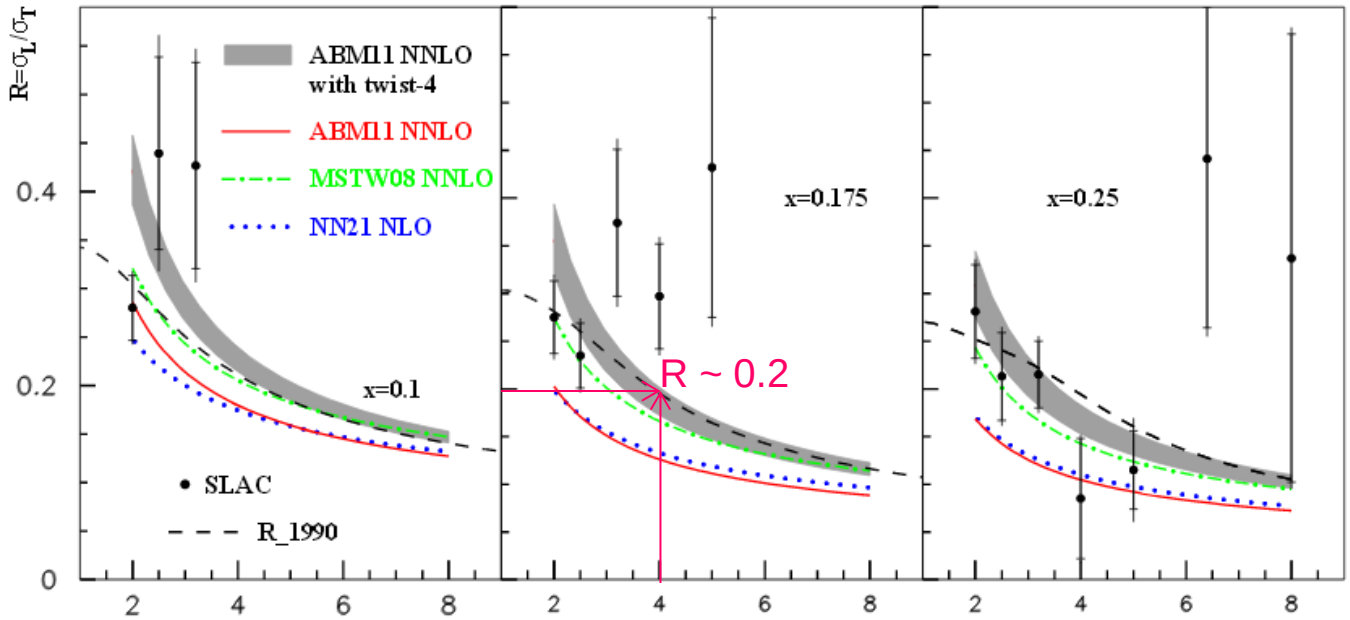
- Advantage of extraction method: many systematic uncertainties cancel in the cross section ratio (detector performance, kinematics, acceptance, beam…)

Basics: R_A-R_D from σ_A/σ_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 GeV^2 R ~ 0.2: if ΔR = 0.04 → ~20% effect from nuclear medium

x = 0.175, Q^2 = 20 GeV^2 R ~ 0.08: if ~20% effect from nuclear medium → ΔR = 0.016



Phys. Rev. D 86 054009 (2012)

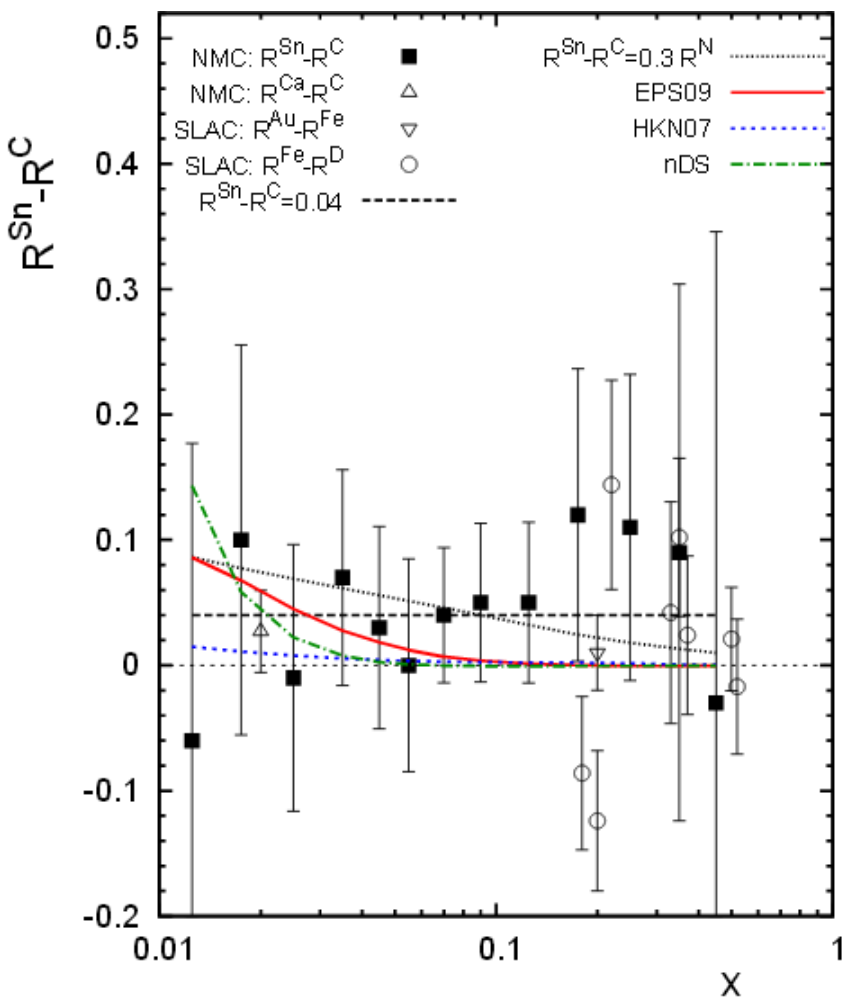
- Very good control of experimental systematics needed, all possible corrections to the cross section ratio must be accounted for (i.e. Coulomb corrections, if non-negligible)
- Search for medium effects most efficient at low to moderate Q^2 in a dedicated L/T experiment

Implications of $\Delta R \neq 0$

How small of a ΔR becomes significant?

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 $R_{Sn} - R_C$

<u>Two data sets have been analyzed</u>:

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

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

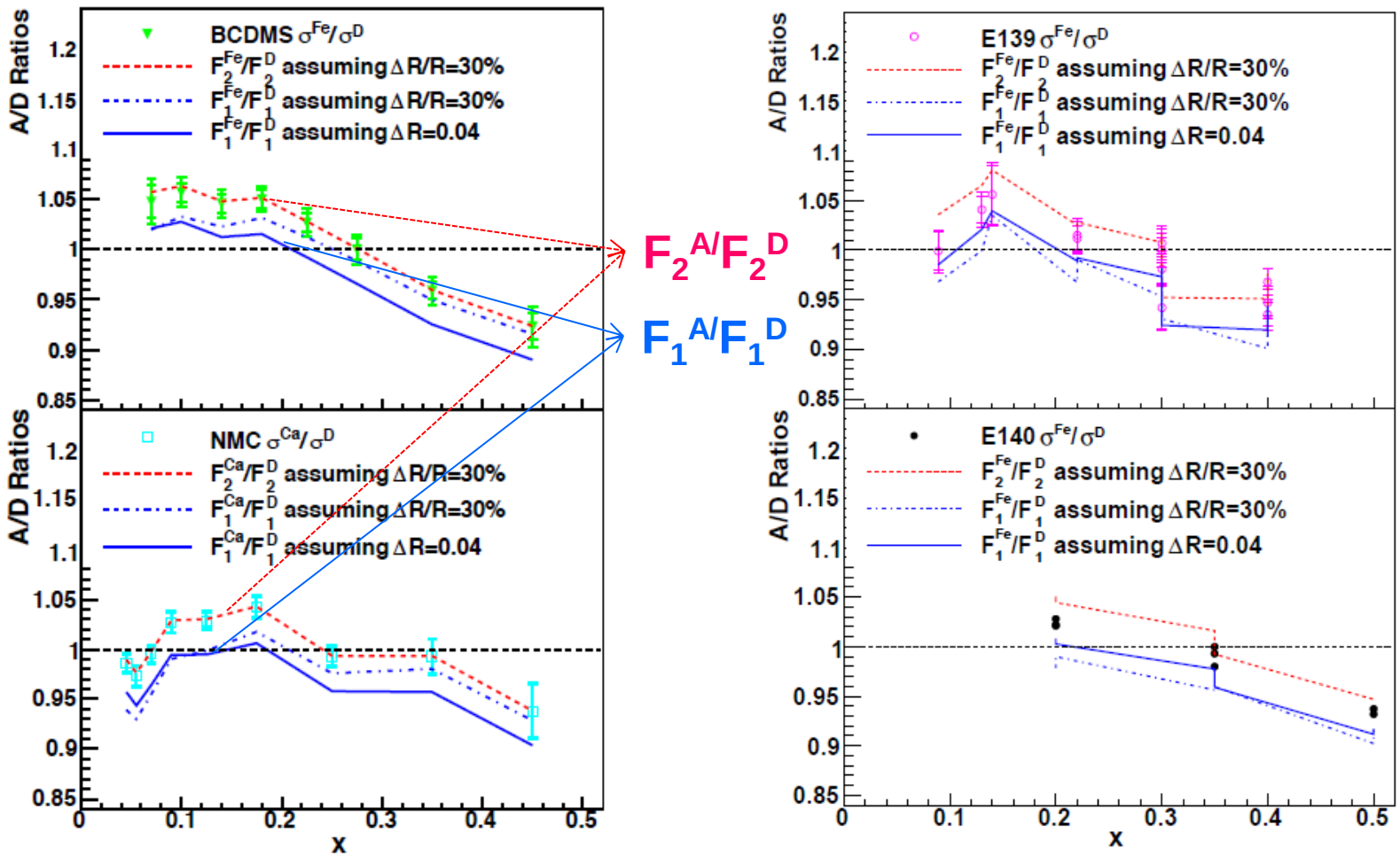
- SLAC: $\varepsilon < 1$

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

Implications of $\Delta R \neq 0$

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

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



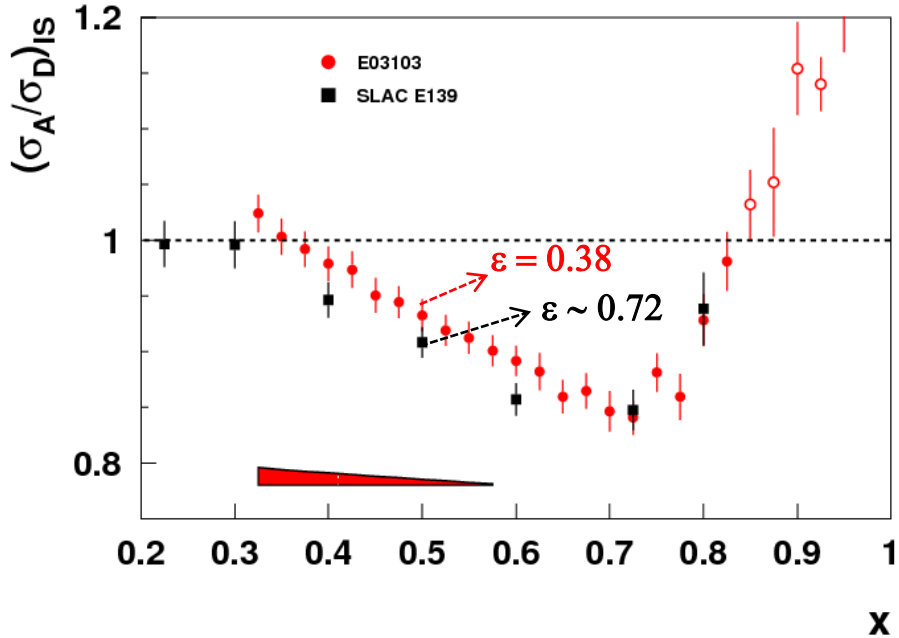
→ Antishadowing disappears for F_1 ratio, remains for F_2

→ Antishadowing from longitudinal photons?

Implications of $\Delta R \neq 0$

EMC effect

- A very well measured behaviour like the EMC effect still offers surprises – the tension between *low ε Jefferson Lab and high ε 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?
- Often the cross section ratio is identified with the F_2 structure function ratio and therefore with nuclear modifications of **quark** distributions

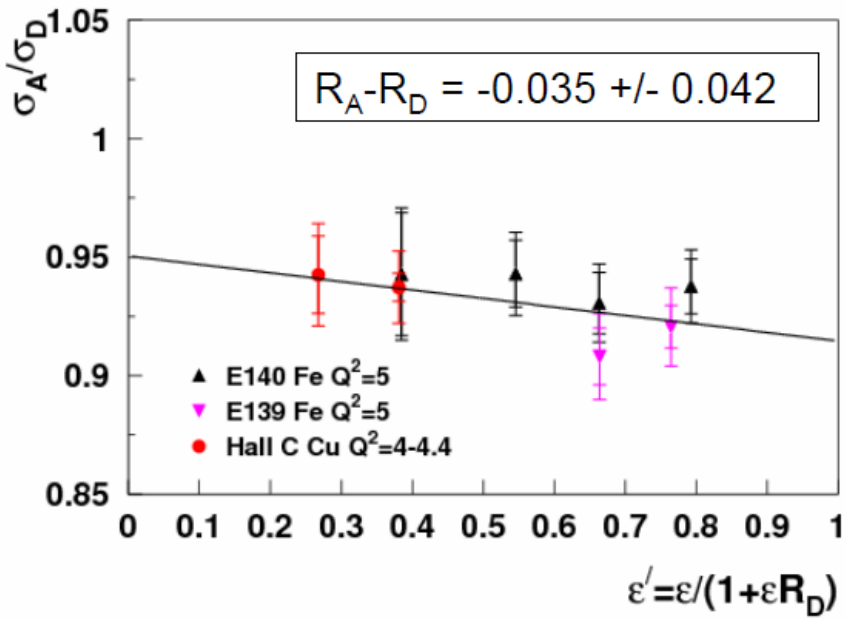
Is σ_A/σ_D ε dependent?

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

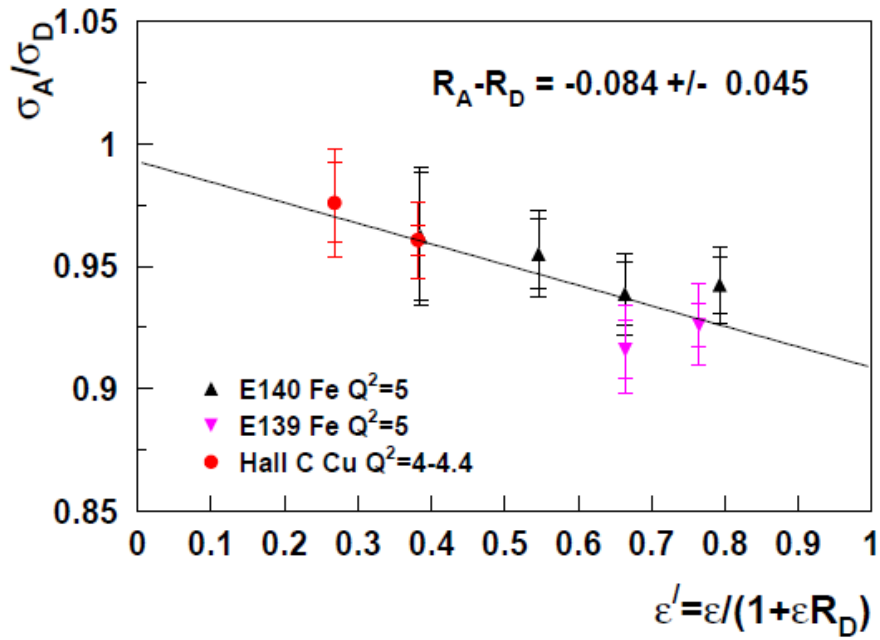
- **Coulomb effects** have not been accounted for in the SLAC E140 analysis (**non-negligible** at SLAC and Jefferson Lab kinematics)

→ 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 GeV^2 *arXiv:0906:0512*

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



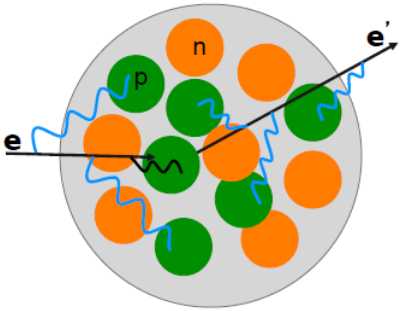
No Coulomb corrections



With Coulomb corrections: *ΔR 2σ from zero*

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 and NOT plane wave Born approximation (DWBA vs PWBA) is the appropriate framework to calculate the scattering cross section



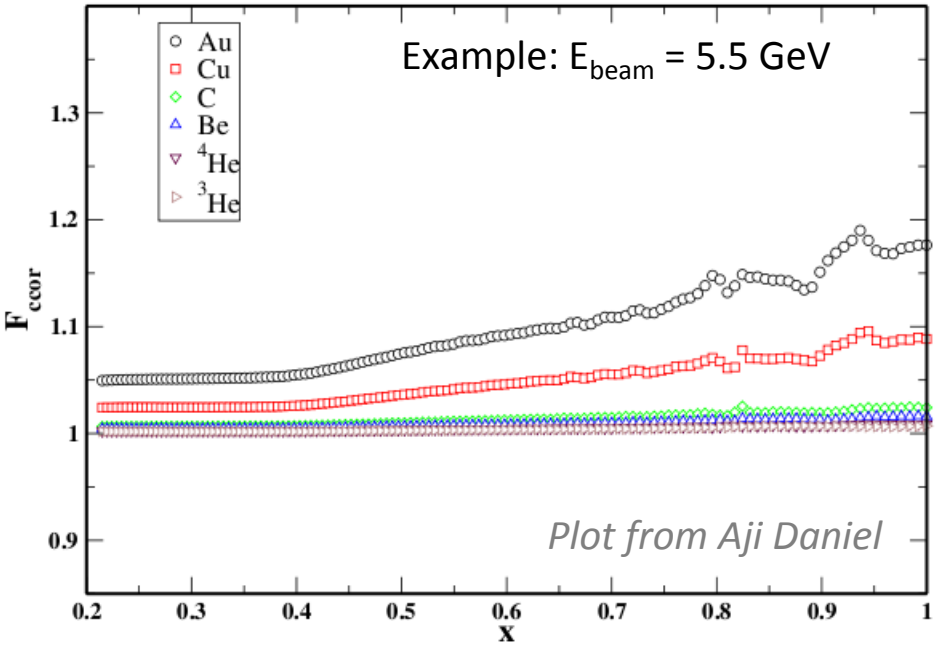
A more practical calculation, the Effective Momentum Approximation (EMA) has been verified/tuned to agree with DWBA calculations in the quasielastic region (no such study done for DIS)

Correction factor for cross sections in EMA:

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

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

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



Coulomb corrections calculated with EMA

Existing Measurements of R_A-R_D from Charged-Lepton Scattering

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

E140, SLAC – before 1988	DIS	Fixed target: D, Fe, Au 5 beam energies	Q^2 : 1 – 5	R_d, R_{Fe}, R_{Au} $R_{Fe,Au}$ - R_d
E140x, SLAC - 1991	DIS	Fixed target: H, D, Be 5 beam energies	Q^2 : 0.5 – 7	R_p, R_d, R_{Be} $R_{d,Be}$ - R_p
E02-109/E04-001, JLab – 2005	QE+RES	Fixed target: H, D, C, Al, Fe 4 beam energies	Q^2 : 0.2 – 2.5	$R_{d,C,Al,Fe}$ $R_{C,Al,Fe}$ - R_d
E06-009/E04-001, JLAB – 2007	QE+RES	Fixed target: D, C, Al, Fe, Cu 6 beam energies	Q^2 : 0.5 – 4	$R_{d,C,Al,Fe,Cu}$ $R_{C,Al,Fe,Cu}$ - R_d

RES → W < 2, DIS → W > 2, QE → quasielastic scattering on nuclei

- Other extractions: NMC, HERMES

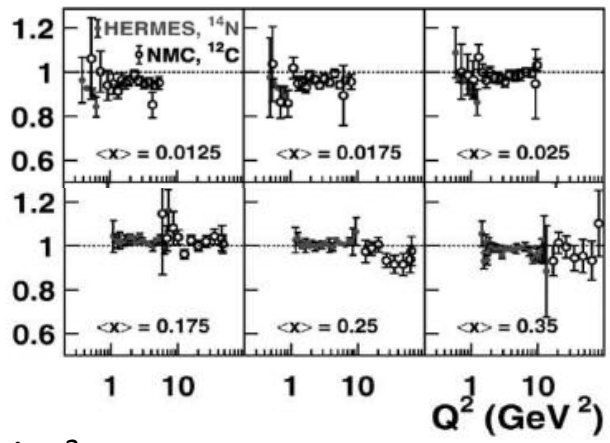
NMC, CERN – before	DIS	Fixed target: C, Ca, Sn several beam energies	Q^2 : 3 – 35	R_{Sn}-R_C, R_{Ca} - R_C
HERMES, DESY – before 2000	DIS	Fixed target: H, D, He, N 1 beam energy	Q^2 : 0.5 – 15	R_N/R_D, R_{He}/R_D

Existing Measurements of R_A-R_D in DIS: HERMES

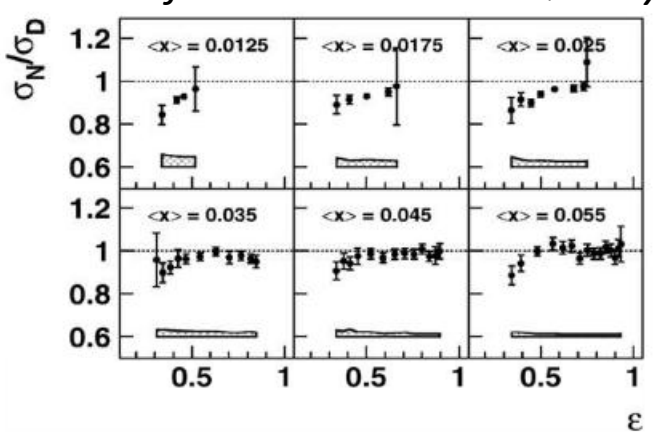
- Other extractions, HERMES: single beam energy (**no ε arm at fixed x and Q^2**)

→ Q^2 range for HERMES data per fixed x bins

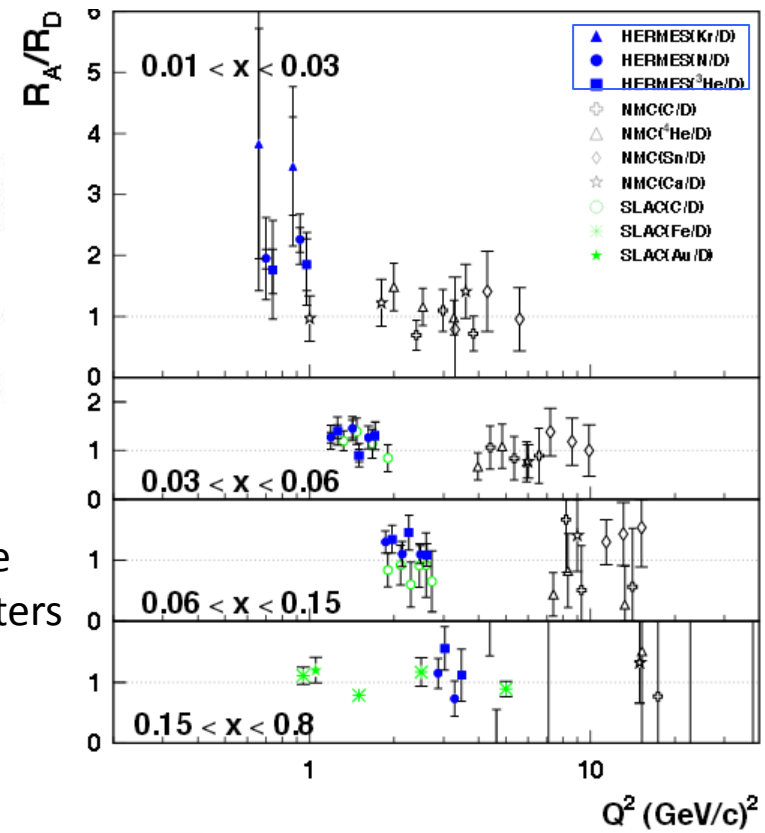
→ R_A/R_D and F_2^A/F_2^D are assumed Q^2 independent per fixed x bins



At fixed x both ε and Q^2 vary



→ R_A/R_D and F_2^A/F_2^D are extracted as fit parameters from fits of the cross section ratios with ε



- No clear pattern from HERMES: at lower Q^2 R_A/R_D appears to be systematically larger than 1

Existing Measurements of R_A-R_D in DIS: NMC

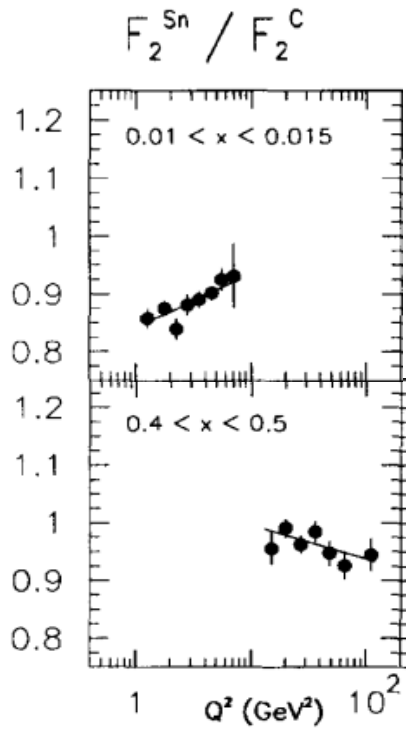
- Other extractions, NMC: several beam energies Arneodo *et al.*, Nucl. Phys. B 481 23-39, 1996

The cross section ratio in each x bin is fitted simultaneously to the data at all muon energies for all values of Q^2 using a parametrization with 4 free parameters: ΔR and 3 other to describe the Q^2 dependence of the F_2 structure function ratio

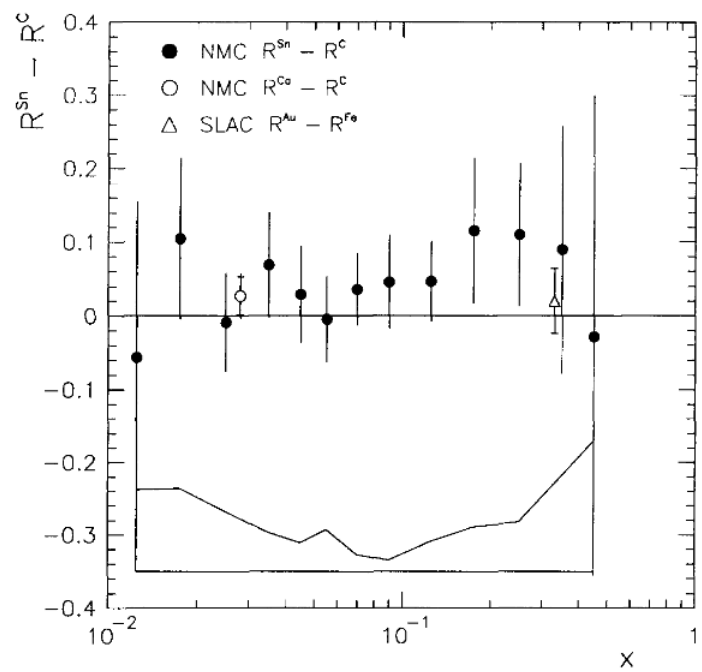
$$\frac{\sigma^A}{\sigma^C} \approx \frac{F_2^A}{F_2^C}\left[1-\frac{1-z_i}{(1+\bar{R})(1+z_i\bar{R})}\Delta R\right] \quad z_i = f(y, Q^2, E) \quad \bar{R}=\frac{1}{2}(R^A + R^C) \quad \frac{F_2^A}{F_2^C}=(a_1+a_2 ln Q^2)(1+a_3/Q^2)$$

Fit results for each x bin;
Q^2 shown is an average

x	Q^2	ΔR
0.0125	3.3	$-0.06 \pm 0.21 \pm 0.11$
0.0175	4.3	$0.10 \pm 0.11 \pm 0.11$
0.025	5.6	$-0.01 \pm 0.07 \pm 0.08$
0.035	7.2	$0.07 \pm 0.07 \pm 0.05$
0.045	8.6	$0.03 \pm 0.07 \pm 0.04$
0.055	9.9	$0.00 \pm 0.06 \pm 0.06$
0.070	11.4	$0.04 \pm 0.05 \pm 0.02$
0.090	13.1	$0.05 \pm 0.06 \pm 0.02$
0.125	15.2	$0.05 \pm 0.05 \pm 0.04$
0.175	17.9	$0.12 \pm 0.10 \pm 0.06$
0.25	20.8	$0.11 \pm 0.10 \pm 0.07$
0.35	26.6	$0.09 \pm 0.17 \pm 0.13$
0.45	35.1	$-0.03 \pm 0.33 \pm 0.18$



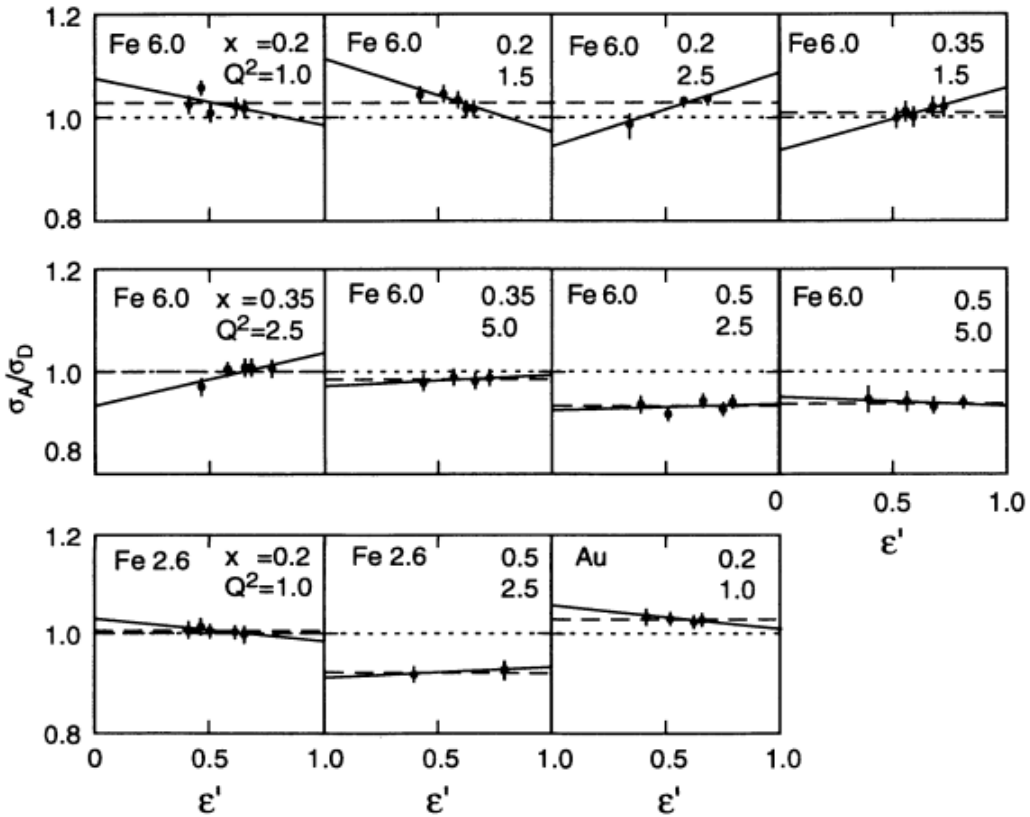
$\Delta R = R^{Sn} - R^C = 0.040 \pm 0.021$ (stat.) ± 0.026 (syst.).

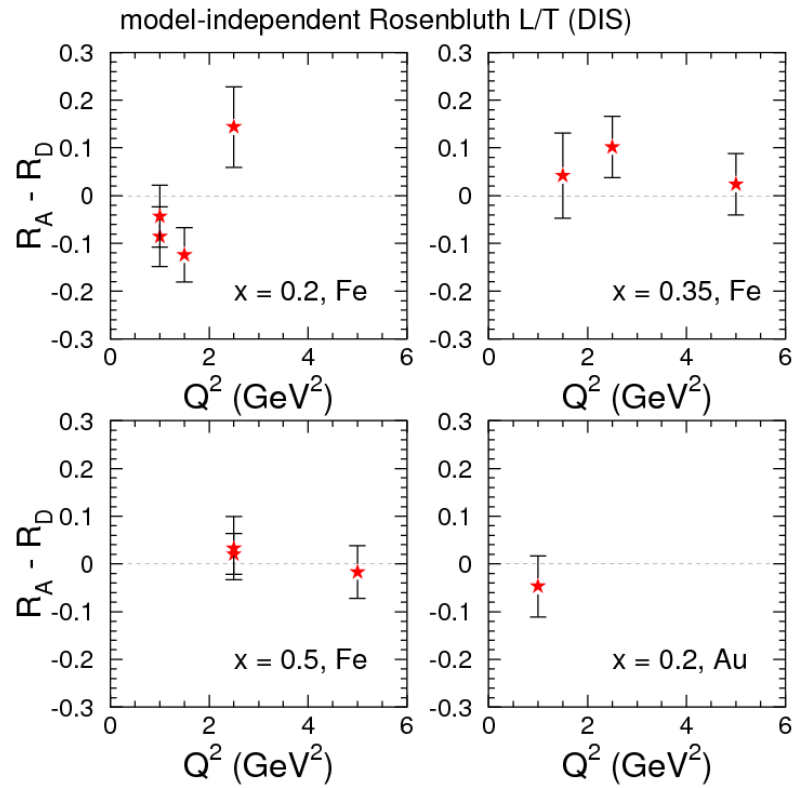


Existing Measurements of R_A-R_D in DIS: SLAC

- Model-independent extractions, SLAC: 5 beam energies, extractions of $R_A - R_D$ at fixed x and Q^2

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





Published average over x, Q^2 and targets:
R_A-R_D = 0.001+/- 0.018 +/- 0.016

- Coulomb corrections **have not been applied**; corrections are not negligible: for example, for Fe at x = 0.5 and Q^2 = 5 it can range from 0.5% at large ε to 2% at low ε

Measurements of ΔR in the Res. Region: JLab

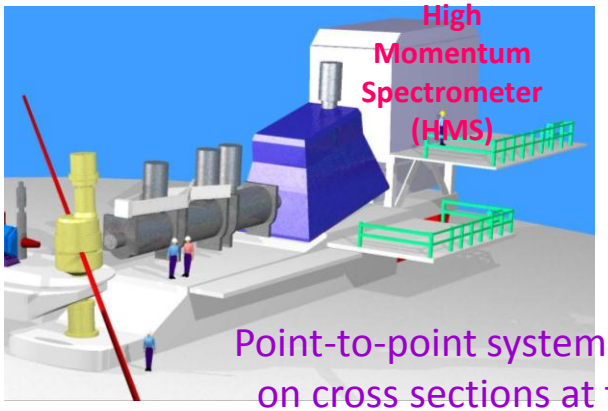
- Jefferson Lab @ 6 GeV: **E04-001/E06-109**, true Rosenbluth L/T separations on D and Al, C, Fe, Cu in the resonance region

Primary physics goals:

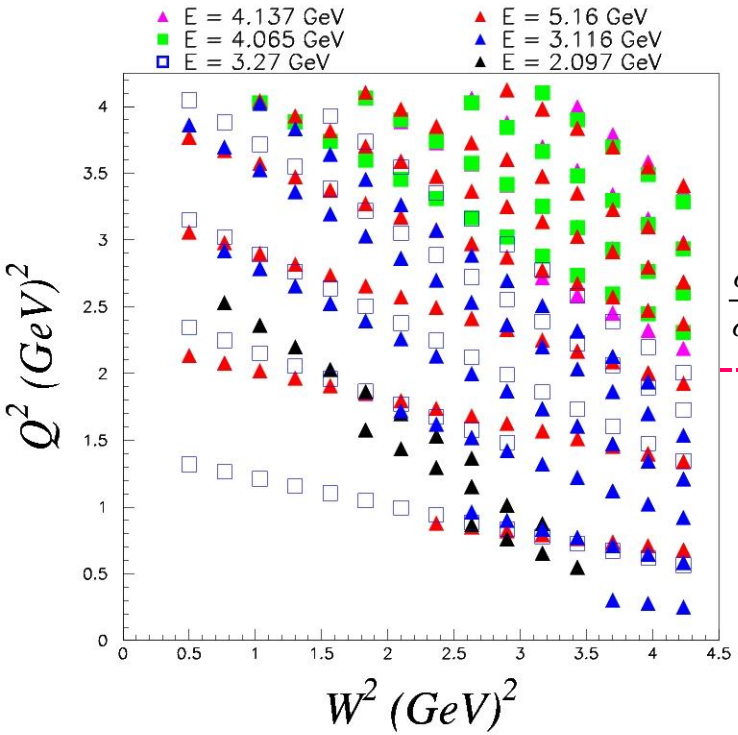
→ Study the nuclear dependence of R and of the separated structure functions

→ Study quark-hadron duality in nuclei

Hall C at Jefferson Lab

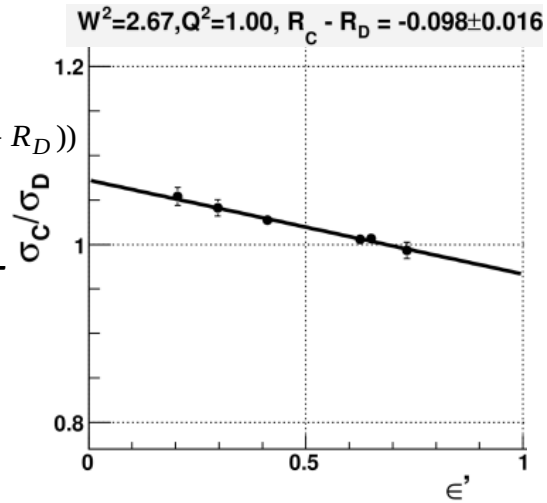


Point-to-point systematics on cross sections at the level of 1.7%



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

True Rosenbluth L/T



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

Measurements of $\Delta R \neq 0$ in the Res. Region: JLab

- 6 GeV JLab **E04-001/E06-109**: very careful analysis to yield a high-precision measurements of ΔR
  - → all relevant corrections applied (Coulomb corrections included)
  - → 2 methods for cross sections extraction employed
  - → exhaustive study of systematics underway

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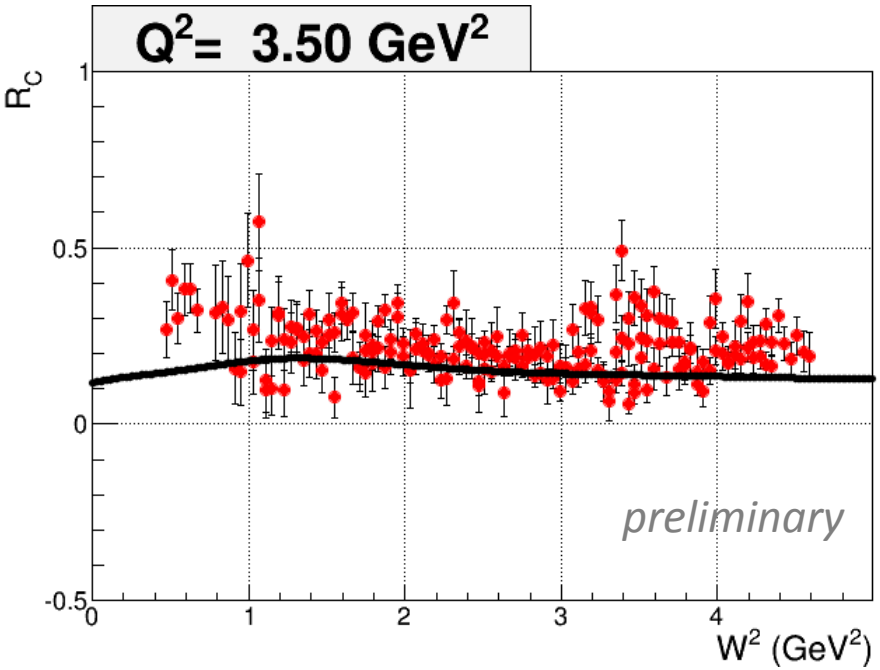
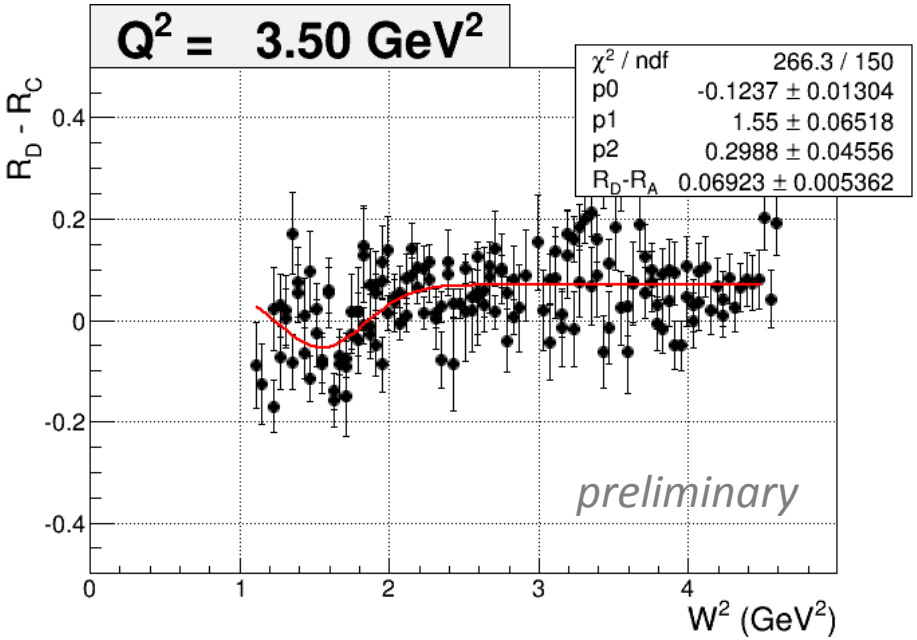




$R_C - R_D$ (Q^2 = 3.5) = 0.07 +/- 0.005 (uncorr.) +/- 0.016 (corr.) *preliminary*

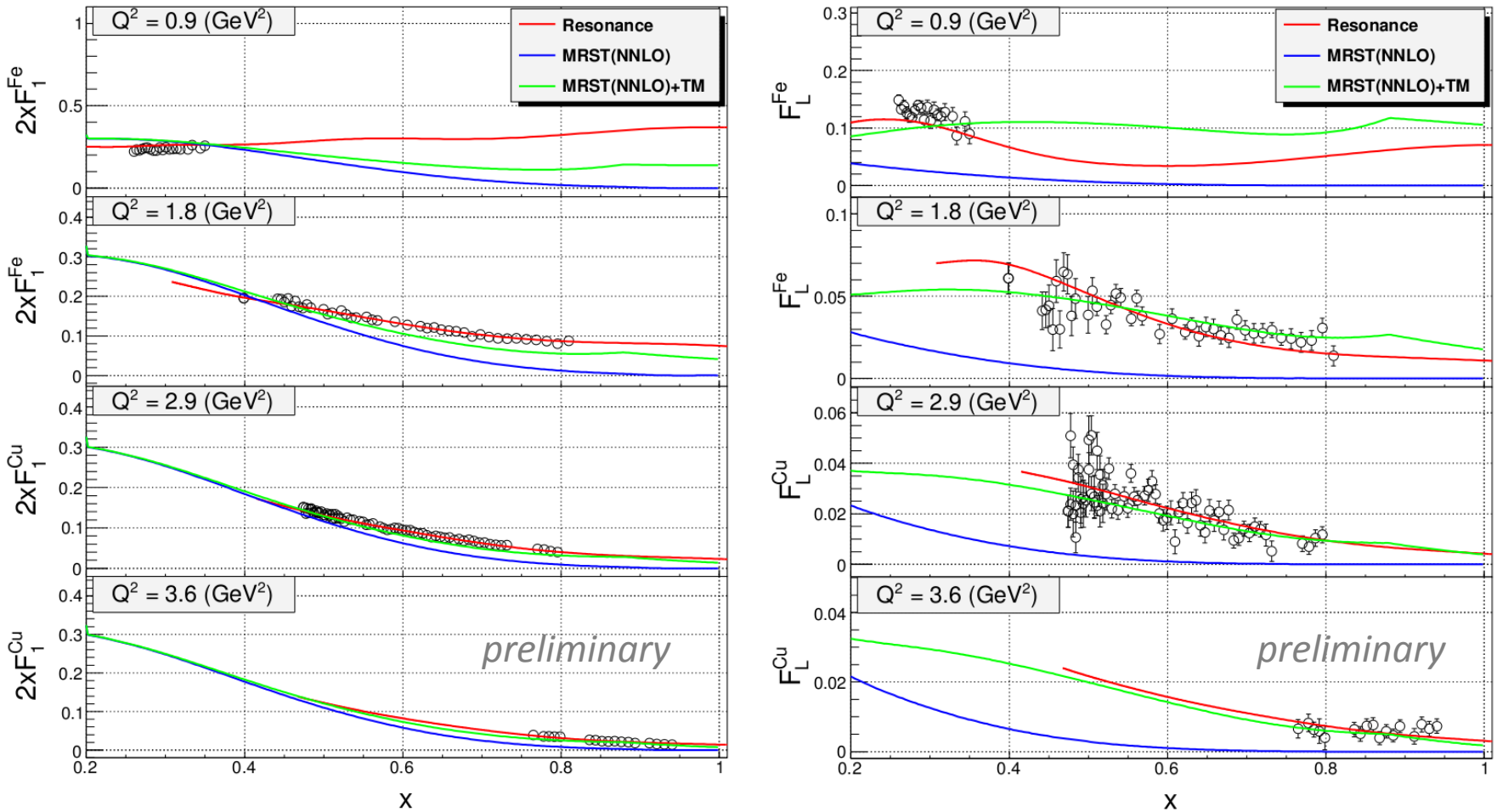
- Preliminary results point to detectable nuclear medium modifications of R in the resonance region

paper to be submitted for publication by the end of 2014

Measurements of F_1, F_L in the Res. Region: JLab

- 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



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

Plans for Future: E12-14-002 at JLab

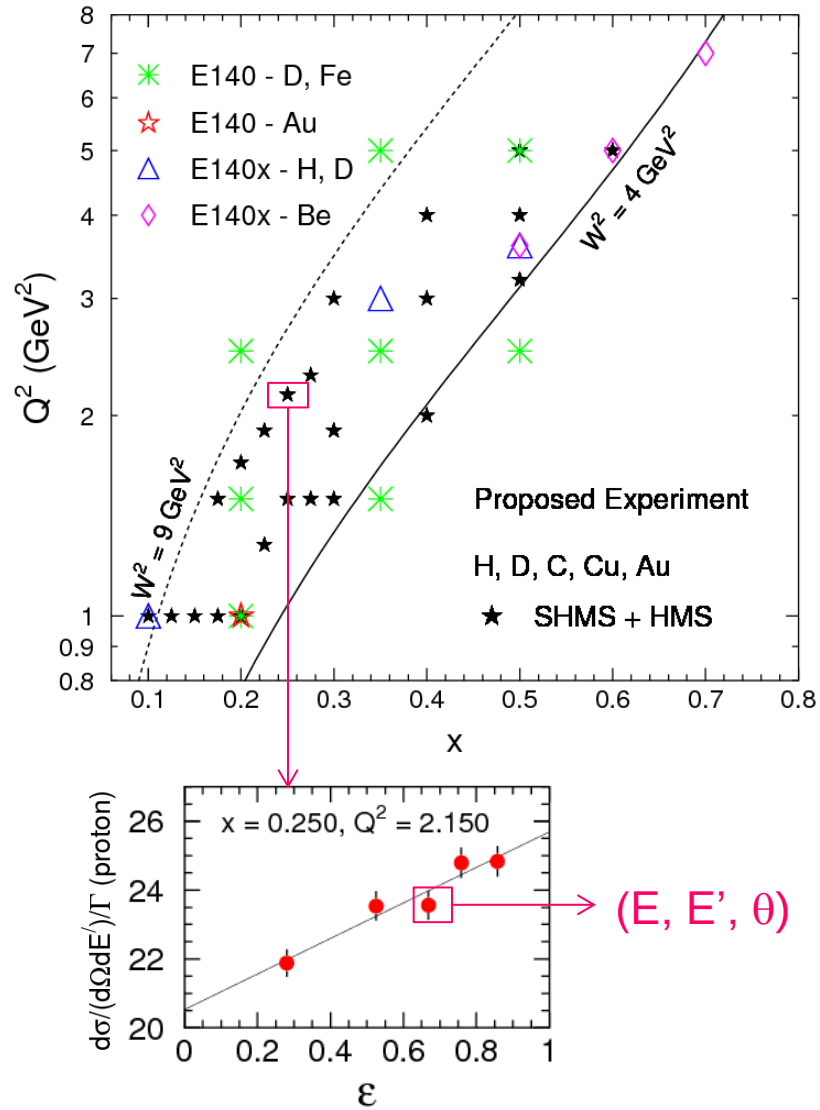
- We plan to extract *in a **model independent** fashion via the Rosenbluth technique*:

  → R_p, $R_D - R_p$
  → $R_A - R_D$ for C, Cu, Au
  → F_1, F_L, F_2 for H, D, C, Cu, Au
  x: 0.1 - 0.6 ; Q^2:1 - 5 GeV^2

- Each central L/T extraction (black stars) :

  → Hall C spectrometers, SHMS and HMS
  → up to 6 beam energies
  → D, Cu at all kinematics shown; H, C, Au at select kinematics

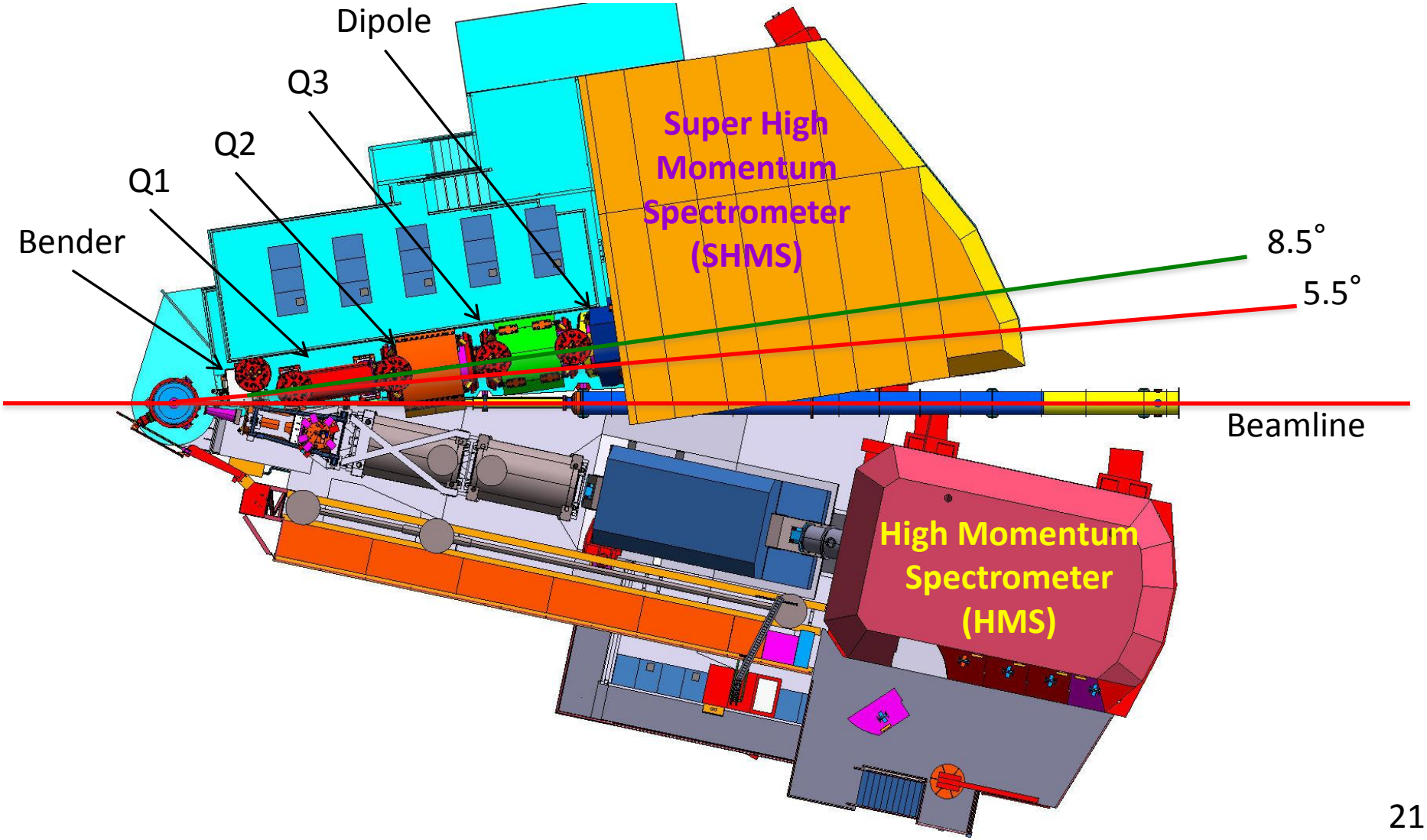
- Statistical goal: 0.2 – 0.5% (depending on the target) in a W^2 bin of 0.1 GeV^2



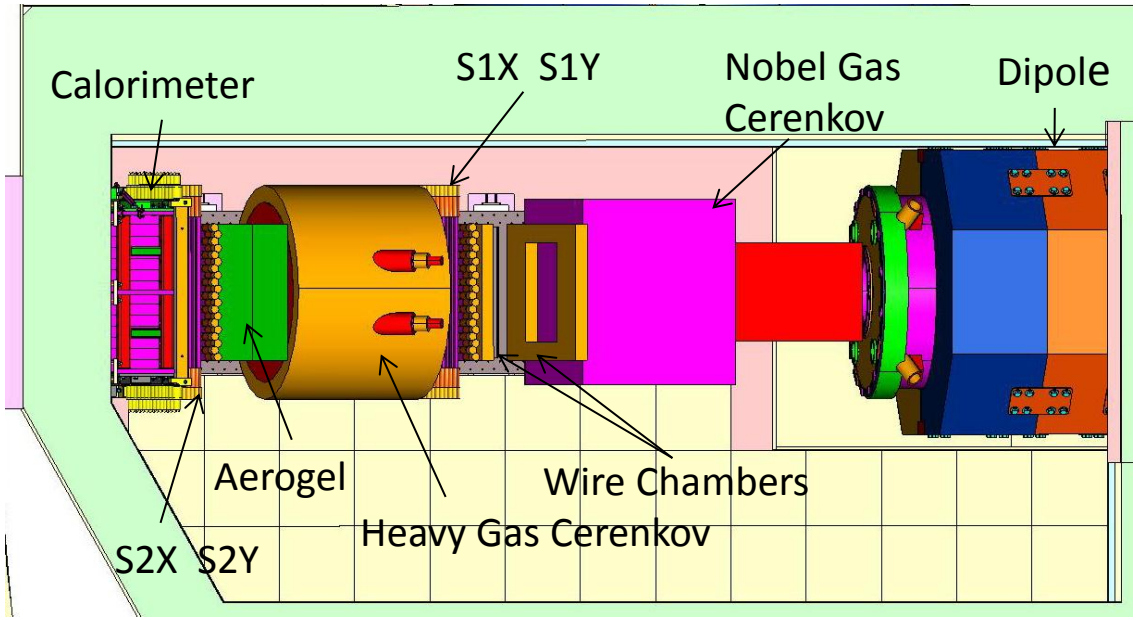
S.P. Malace - Spokesperson and contact
E. Christy, D. Gaskell, C. Keppel, P. Solvignon spokespeople

Hall C at JLab after the 12 GeV Upgrade

- A new spectrometer (SHMS) built and installed in Hall C for the 12 GeV run
- E12-14-002 will use both spectrometers for L/Ts



SHMS in Hall C at JLab



Parameter	SHMS Design
Range of Central Momentum	2 to 11 GeV/c
Momentum Acceptance δ	-10% to +22%
Momentum Resolution	0.03-0.08%
Scattering Angle Range	5.5 to 40 deg
Solid Angle Acceptance	> 4.5 msr
Horizontal Angle Resolution	0.5 - 1.2 mrad
Vertical Angle Resolution	0.3 - 1.1 mrad
Vertex Length Resolution	0.1 - 0.3 cm
Tracking Rate Capability	5 MHz
Beam Capability	Up to 90 μA, 11 GeV beam

→ Trigger: 2 pairs of scintillators segmented in the x and y directions (quartz bars)

→ Tracking: 2 drift chambers, 6 planes each

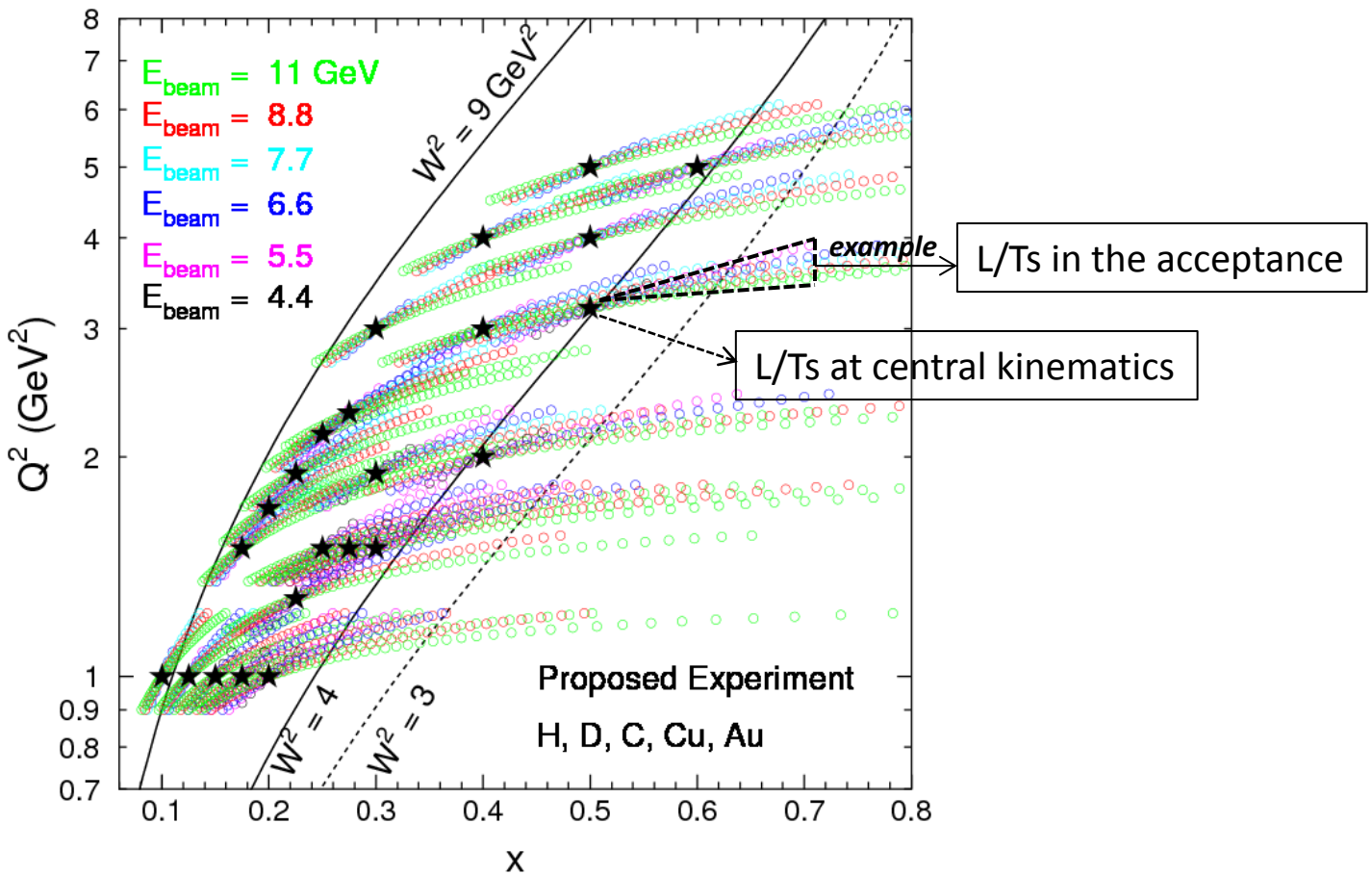
→ Particle identification: Nobel Gas Cherenkov (Ar/Ne) for electron – pion separation

→ Particle identification: Heavy Gas Cherenkov (C_4F_8O) for kaon – pion separation

→ Particle identification: electromagnetic shower calorimeter (Pb glass)

E12-14-002: Experimental Setup

- SHMS has a large momentum bite: we will collect a wealth of data within the spectrometers acceptance



- Besides the model-independent L/T separations at the central kinematics, we will perform L/Ts everywhere in the spectrometers acceptance where (E, E', θ) scans overlap

S.P. Malace - Spokesperson and contact

E. Christy, D. Gaskell, C. Keppel, P. Solvignon spokespeople

E12-14-002: Projections

→ Models/fits to generate the σ_{red} (to extract R, σ_T) and σ_A/σ_D (for ΔR and σ_A^T/σ_D^T extraction)

→ Best assumptions for (ε) point-to-point systematic uncertainties (inspired by 6 GeV JLab run): 1.8 % on σ_{red} and 1.1 % on σ_A/σ_D and use a Monte Carlo method to propagate the uncertainties into the extraction of σ_T, R, σ_A^T/σ_D^T, R_A-R_D

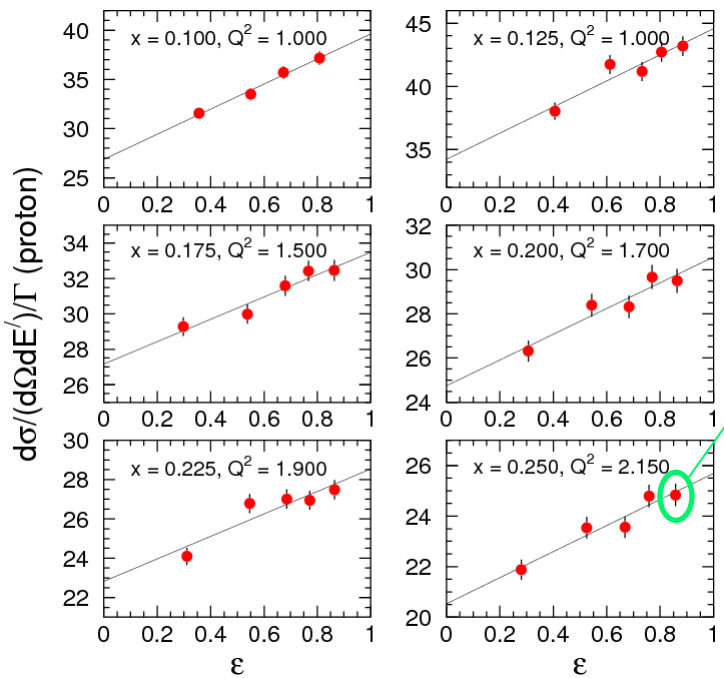
Method:

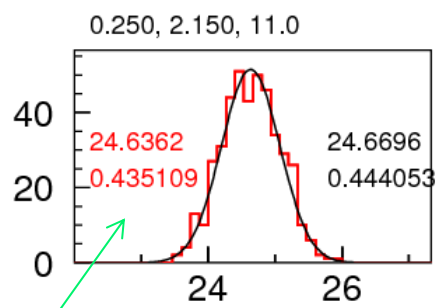
→ large sets of random numbers are generated and used as weights for σ_{red} or σ_A/σ_D at each individual ε

→ fits are performed with ε to pseudo-data sets of randomized quantities and the average and the standard deviation of each collective are obtained

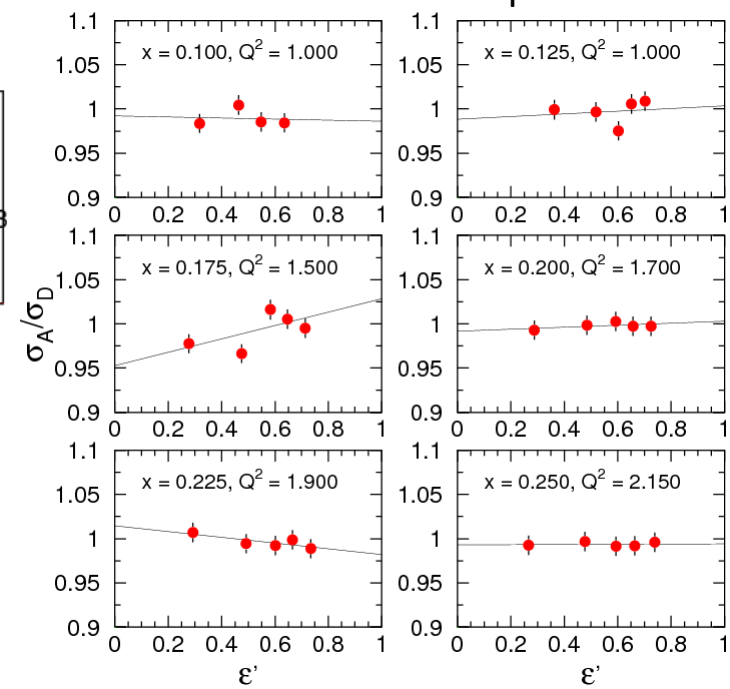
$\sigma_{red} = \sigma_T(1+\varepsilon R)$ → R and σ_T are fit parameters

$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_A^T}{\sigma_D^T}(1+\varepsilon'(R_A - R_D))$ → ΔR and σ_A^T/σ_D^T are fit parameters





Randomization at a given (x,Q²,ε)

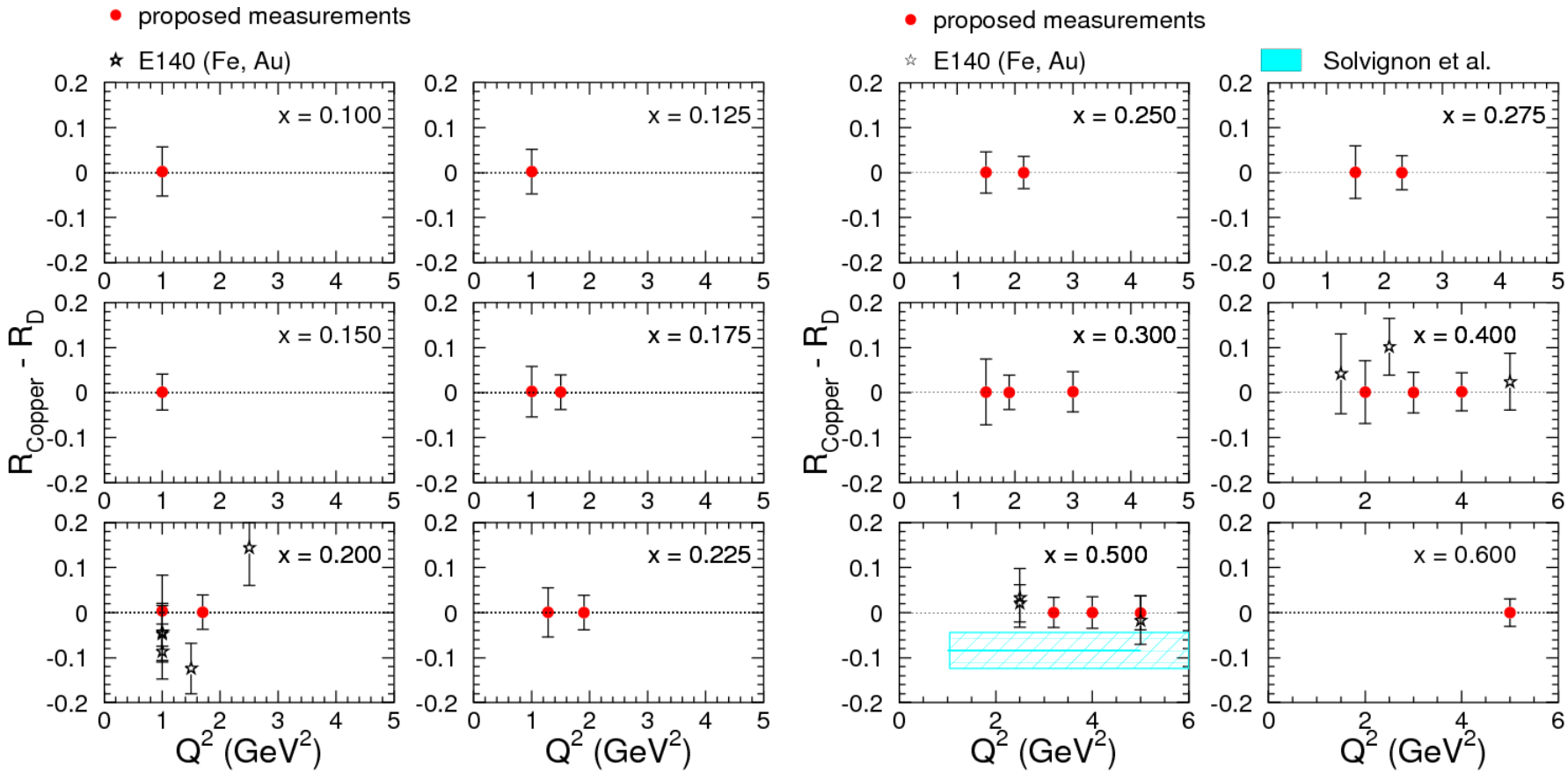


S.P. Malace - Spokesperson and contact

E. Christy, D. Gaskell, C. Keppel, P. Solvignon spokespeople

E12-14-002: Impact for R_A-R_D

- Map the x and Q^2 dependence of **R_A-R_D** independently by measuring on **Copper**



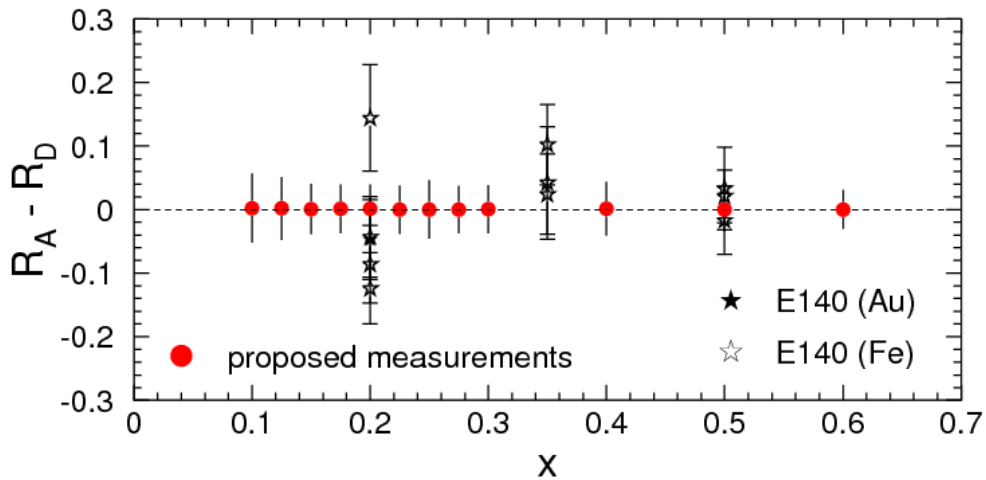
- We will use **C** and **Au** to measure **R_A-R_D** at select kinematics to map the **A-dependence** of medium modifications of R

S.P. Malace - Spokesperson and contact

E. Christy, D. Gaskell, C. Keppel, P. Solvignon spokespeople

E12-14-002: Impact for R_A-R_D

- Recent analyses have shown that a relatively small but non-zero value of R_A-R_D changes the way we interpret the observations of medium modifications in the antishadowing or in the EMC effect regions



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

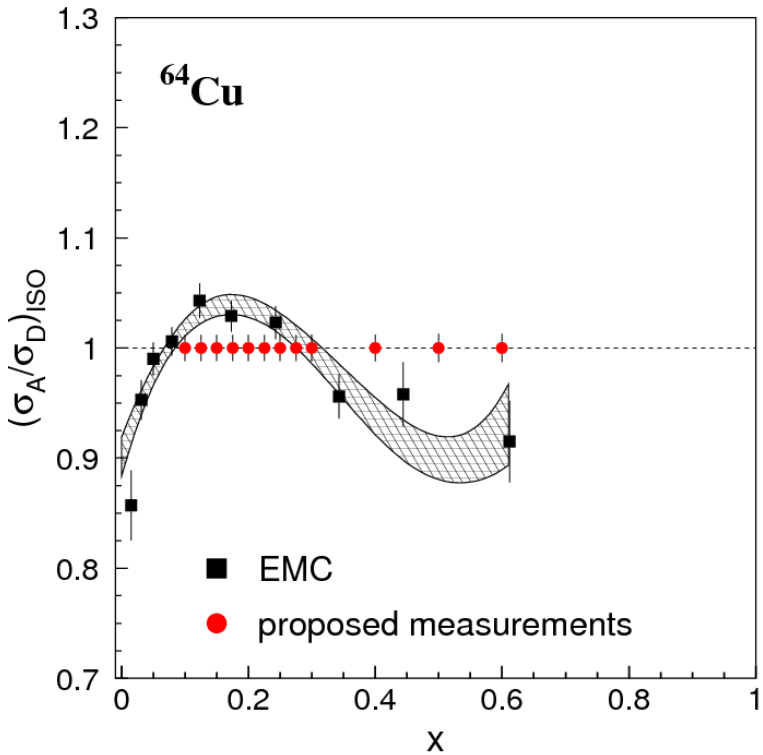
- The quality/quantity of existing data is not sufficient to pin down nuclear effects with a high level of precision as needed

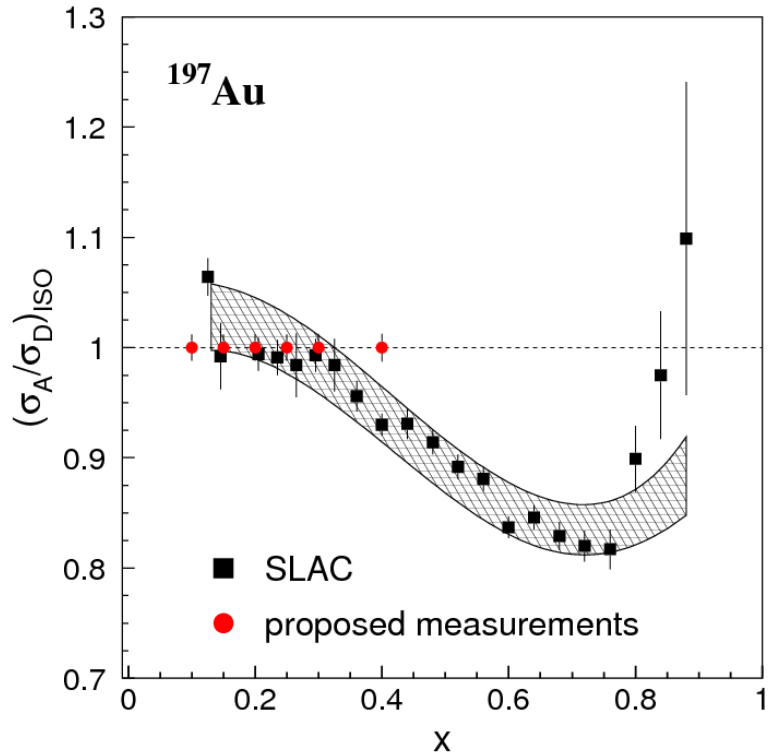
- E12-14-002 will measure via true, model-independent Rosenbluth L/Ts R_A-R_D in one dedicated experiment and set the most precise constraints to date on possible nuclear medium modifications of R

S.P. Malace - Spokesperson and contact
E. Christy, D. Gaskell, C. Keppel, P. Solvignon spokespeople

E12-14-002: Impact for σ_A/σ_D and F_L^A/F_L^D, F_1^A/F_1^D

- Constrain/verify the universality of nuclear modification in σ_A/σ_D
- Provide ***experimental constraints for nuclear PDF fits from separated structure functions***
- Are the separated structure functions modified differently by the nuclear medium?





Proposed measurements shown at central kinematics only; the large acceptance of SHMS/HMS will provide enhanced coverage (data will extend to lower and higher x than shown)

S.P. Malace - Spokesperson and contact
E. Christy, D. Gaskell, C. Keppel, P. Solvignon spokespeople

Summary

→ R_A-R_D has a direct impact on the way we interpret the observations of medium modifications in the antishadowing and in the EMC effect regions R_A-R_D → $\frac{F^A{}_1}{F^D{}_1} \neq \frac{F^A{}_2}{F^D{}_2}$

→ There are hints of a non-zero R_A-R_D from DIS analyses and resonance region preliminary measurements

→ The quality/quantity of existing data on nuclear separated structure functions and R is not sufficient to pin down nuclear effects with a high level of precision as needed

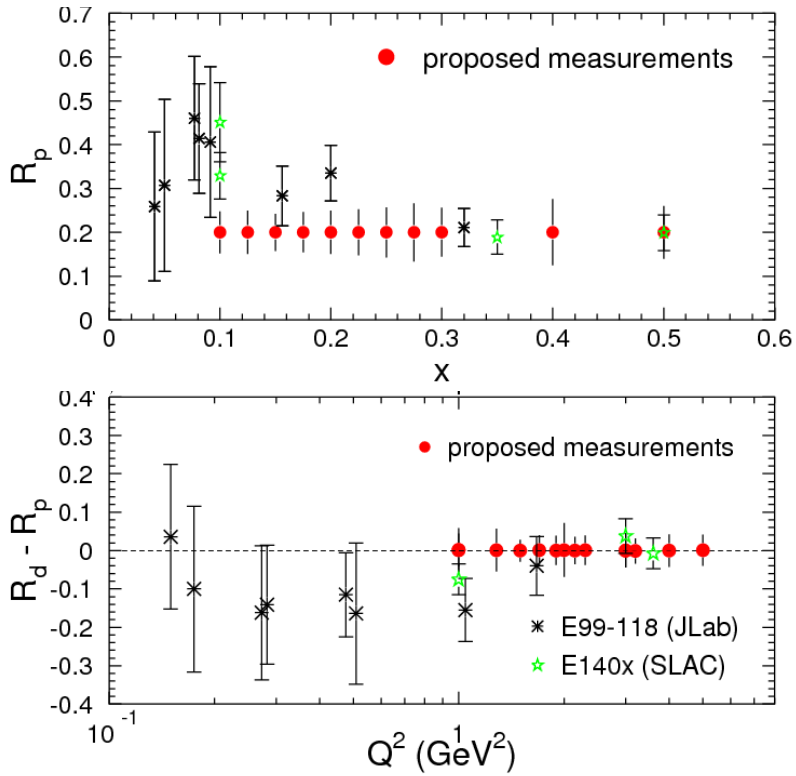
- **E12-14-002 at Jefferson Lab will** measure separated structure functions and R on the free nucleon and nuclei via model-independent true Rosenbluth L/Ts to address fundamental questions on the nuclear modifications of the nucleon structure functions
  - Origin of the antishadowing: are longitudinal photons playing a role?
  - EMC effect: is F_1 modified differently than F_2 by the nuclear medium?
  - Constraints for nuclear PDFs from separated structure functions
  - Experimental constraints on nuclear medium modifications of σ_A/σ_D

Backup Slides

Impact for R_p and R_d-R_p: Summary

- R_p (x and Q^2 dependence) in a kinematic region where its contribution to the structure functions is not negligible but measurements are scarce
- $R_d - R_p$ measurements, verify whether $R_d - R_p \sim 0$ at higher Q^2

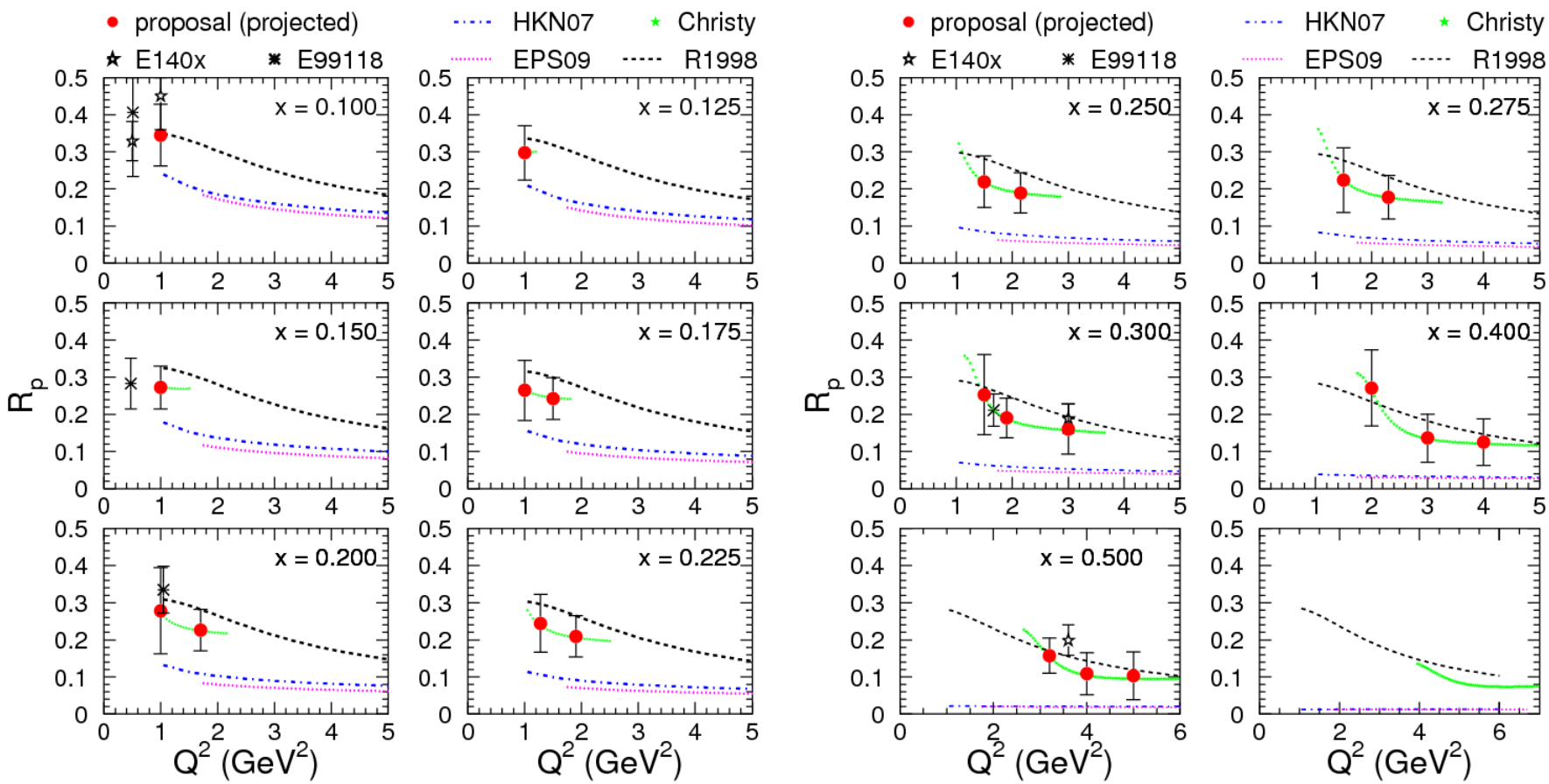
Model-independent Rosenbluth L/Ts from dedicated experiments (DIS)



- Model-independent F_L, F_1, F_2 for proton and deuteron: constrain moments of L/T separated structure functions; access non-singlet distributions

PR12-14-002: Impact for R_p

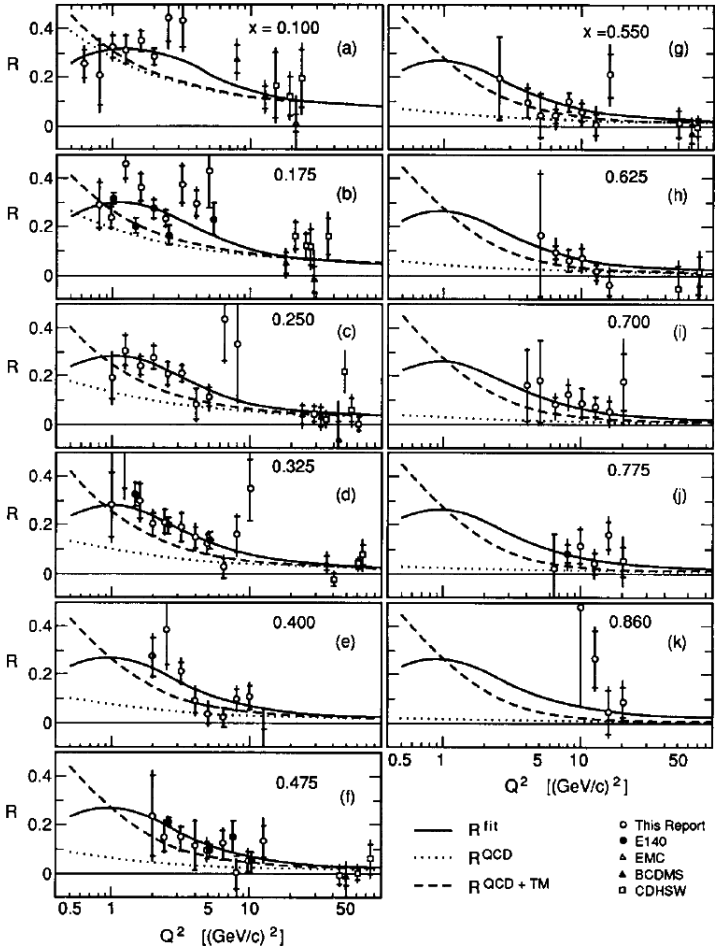
- Without our proposed measurements very few model-independent, true Rosenbluth L/Ts from dedicated experiments at low to moderate x and Q^2



- We have the same kinematic coverage for R_d-R_p but with smaller uncertainties

Existing L/Ts on proton in DIS

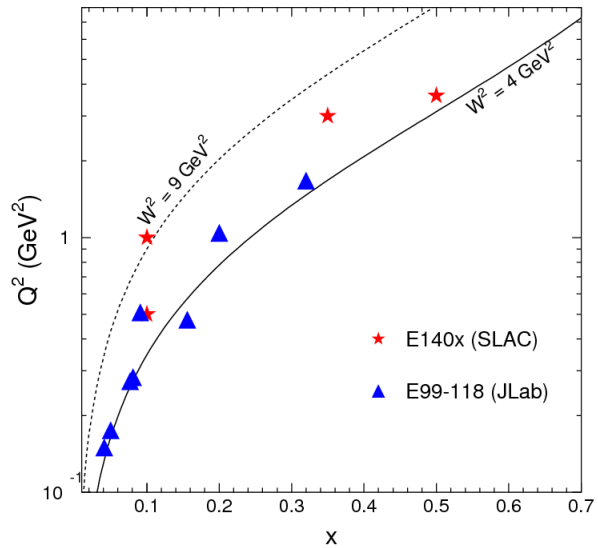
R from R1990 parametrization (SLAC)

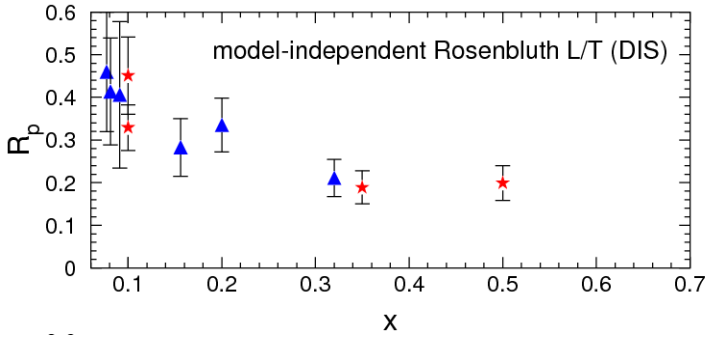


→ Data sets (on H and D) from 8 experiments (1970 - 1985), 7 of which normalized to E140

→ Corrections applied to bin-center data at the same x and Q^2 for a given L/T

- Model-independent L/Ts on proton from *dedicated experiments* in DIS surprisingly scarce: E140x and E99-118

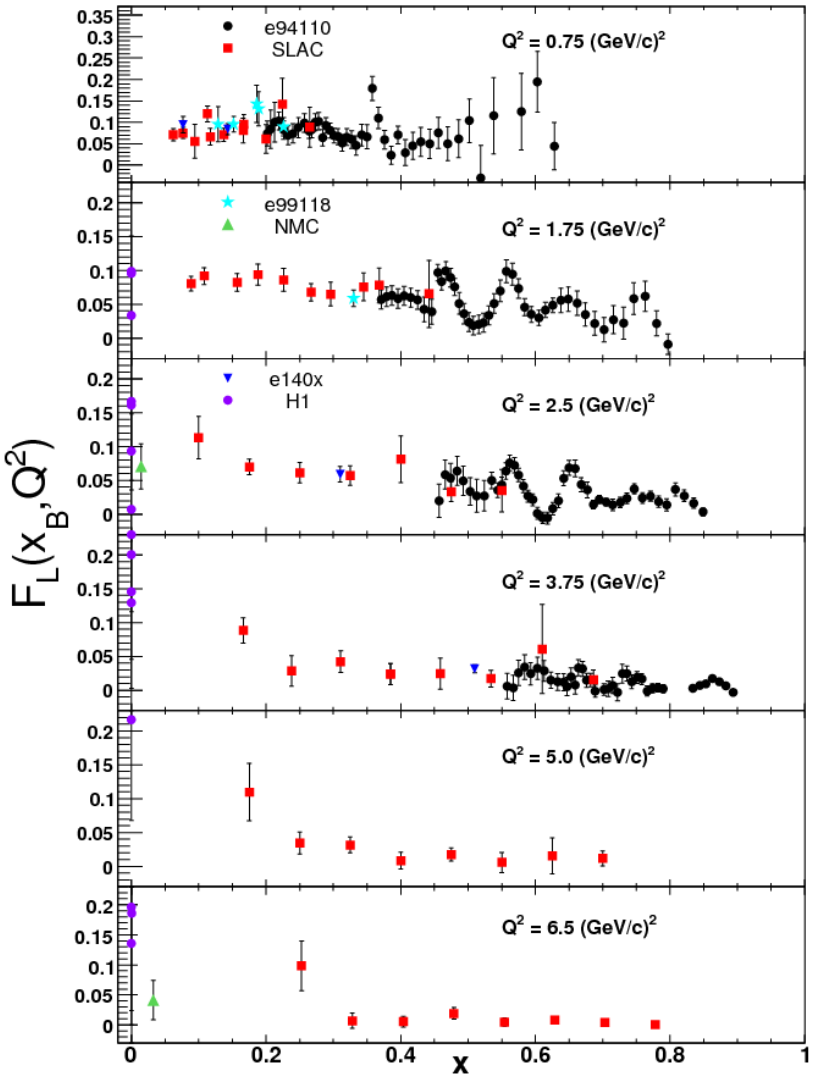


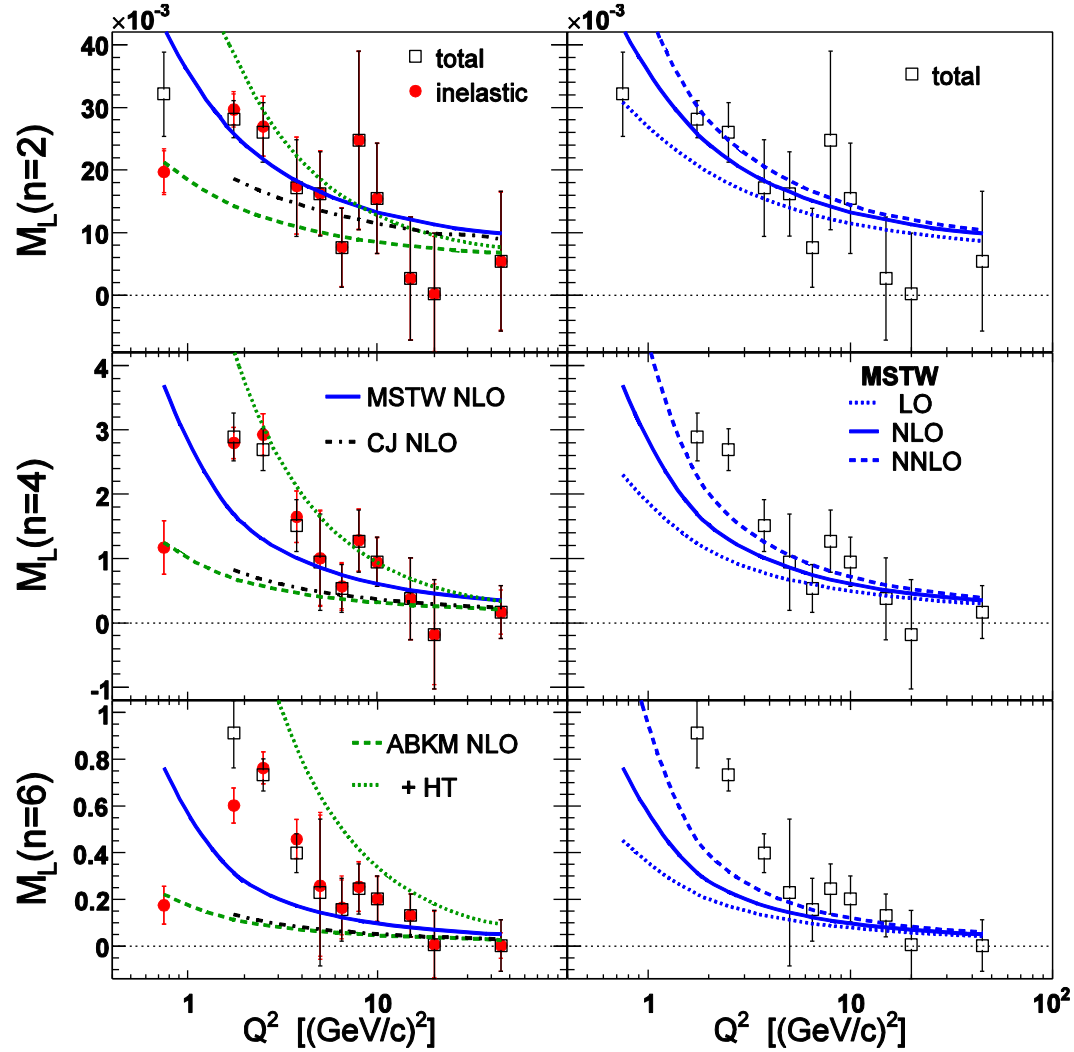


→ Uncertainties on R translate directly into uncertainties on structure functions

Moments of Structure Functions

- Moments of the F_L structure function: tests of pQCD fits

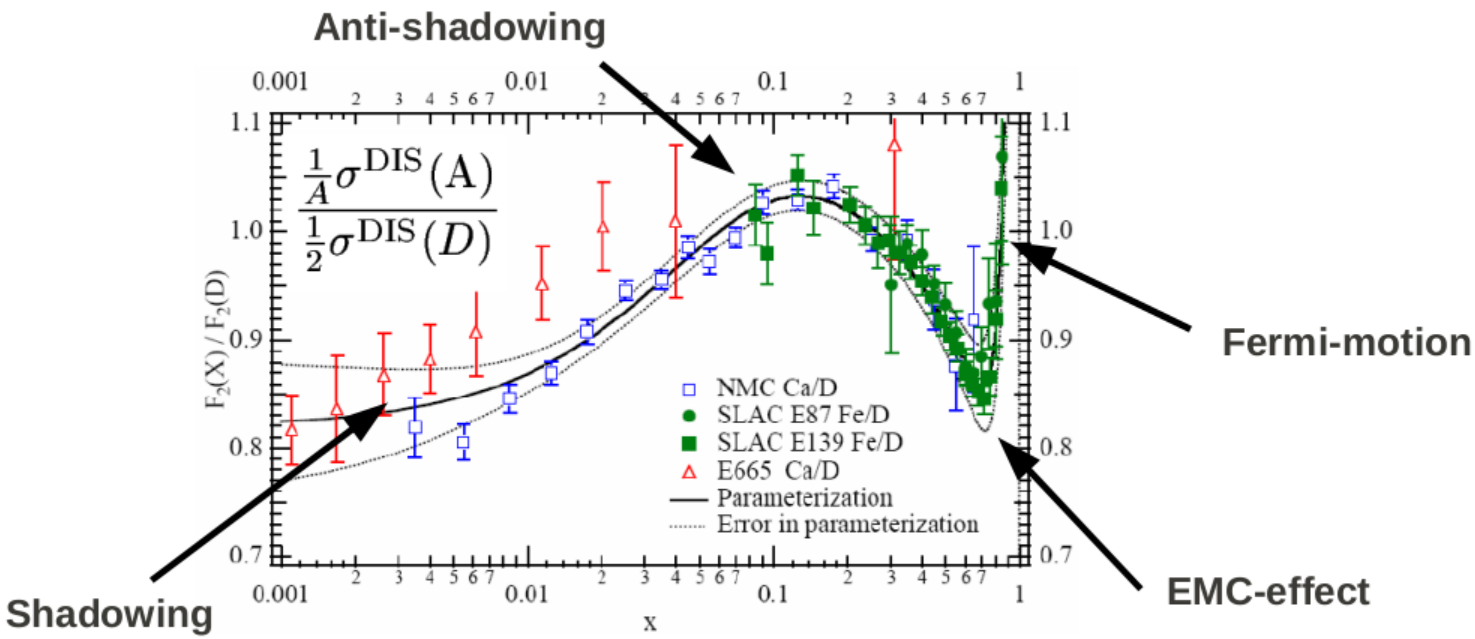




P. Monaghan et al. Phys. Rev. Lett. 110 (2013) 15, 152002

Formalism: Nuclear PDFs

- Nuclear PDFs: the free proton framework is typically used to analyze nuclear data in search of process-independent nuclear PDFs (nPDFs)



Assumptions:

- Factorization
- nPDFs obey the same evolution equations and sum rules as free PDFs
- Isospin symmetry: $u^{n/A}(x) = d^{p/A}(x), d^{n/A}(x) = u^{p/A}(x)$
- Some collaborations: neglect nuclear modifications in deuterium
- ….

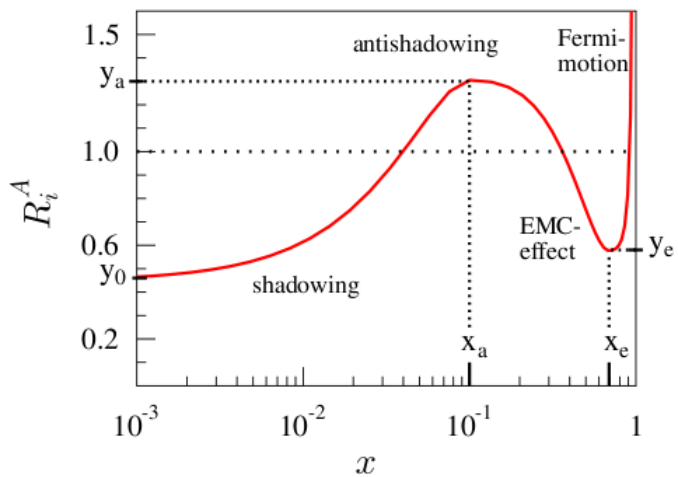
Formalism: Nuclear PDFs

- **Nuclear PDFs**: the free proton framework is typically used to analyze nuclear data in search of process-independent nuclear PDFs (nPDFs)

Example: EPS09

Factorization: $$\sigma^{l+A\to l+X} = \sum_{i=q,\bar{q},g} \overbrace{f^A{}_i(\mu^2)}^{\text{nPDF obeying standard DGLAP}} \otimes \underbrace{\hat{\sigma}^{l+i\to l+X}(\mu^2)}_{\text{usual hard scattering cross section}}$$

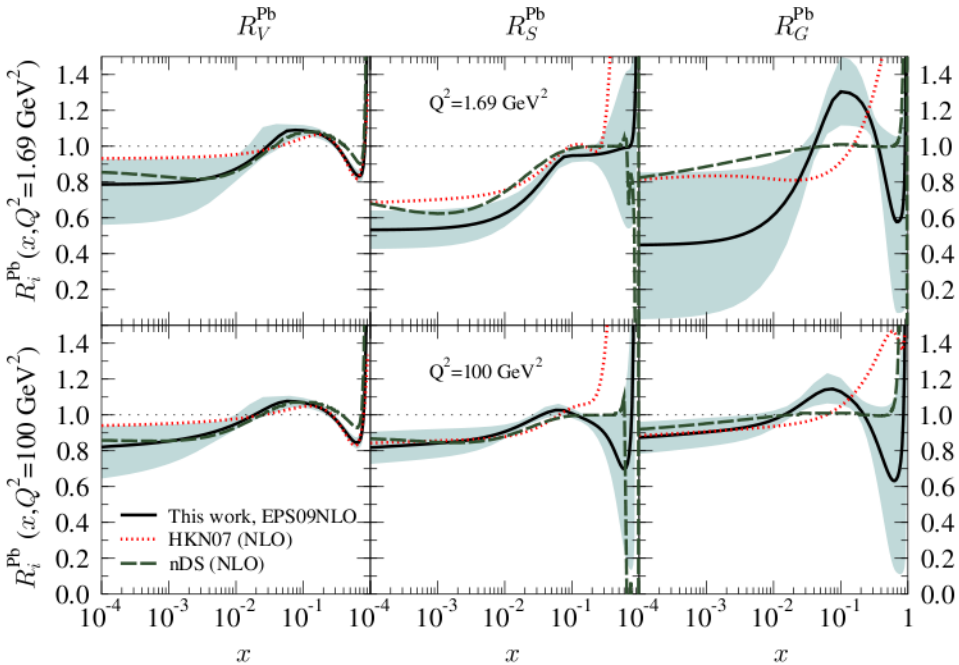
nPDF: $$f^A{}_i(x,Q^2) = \underbrace{R^A{}_i(x,Q^2)}_{\text{Nuclear modifications to the free proton PDFs}} \overbrace{f^p{}_i(x,Q^2)}^{\text{free proton PDFs}}$$

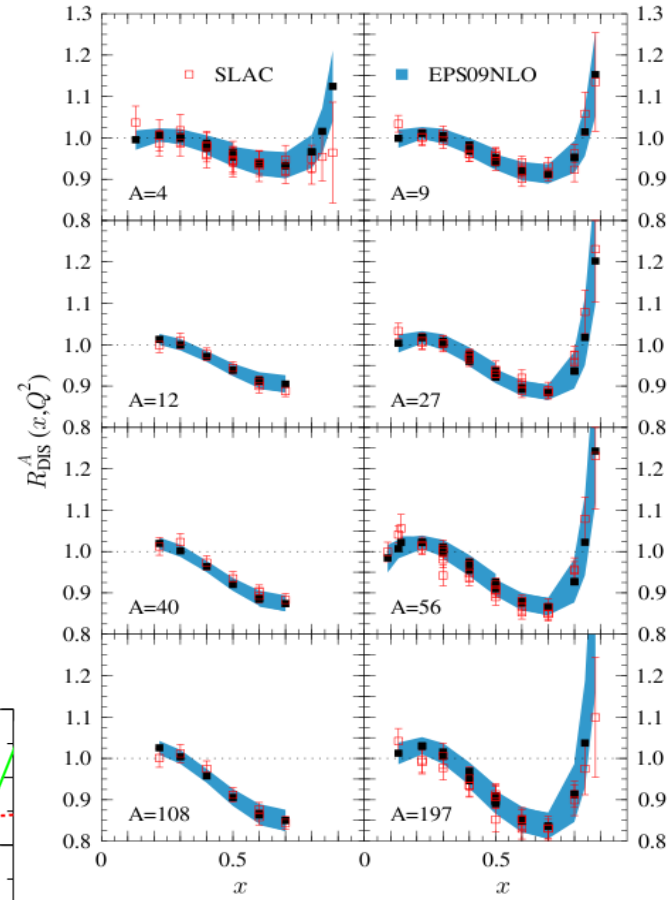


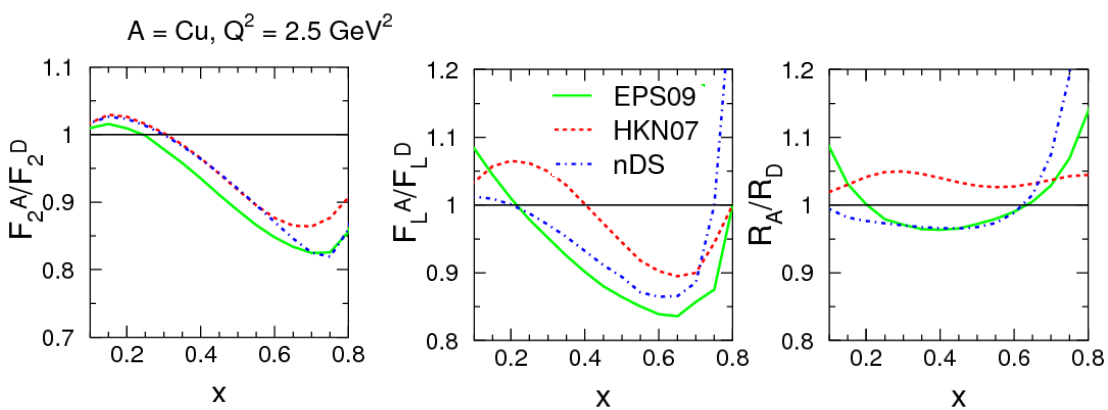
Data: most constraints from charged lepton scattering DIS (F_2^A/F_2^D) but few also from Drell-Yan dilepton production on p+A and from neutral pion production on dAu and pp

Nuclear PDFs: EPS09

- Not enough data to allow for an independent extraction of each parton flavor; no constraints from separated structure functions; working in the limit of $R_A=R_D$







open circles: data on $\sigma_2^A/A/\sigma_2^D/2$ from SLAC

ΔR: Model-Dependent Extractions

NMC: R_{Sn} - R_C Nucl. Phys. B 481, 23 (1996)

→ 3 muon beam energies but ΔR extracted using Q^2 dependent fit at fixed x

From published paper

The function R is sensitive to the differences in cross sections measured at different incident muon energies. For a given (x, Q^2) bin the cross section ratio σ^{Sn}/σ^{C} for an incident muon energy E_i can be written as

$$\boxed{\frac{\sigma^{Sn}}{\sigma^{C}}(E_i)} = \frac{F_2^{Sn}}{F_2^{C}} \frac{1+R^{C}}{1+R^{Sn}} \frac{1+z_i R^{Sn}}{1+z_i R^{C}} \approx \boxed{\frac{F_2^{Sn}}{F_2^{C}}\left[1 - \frac{1-z_i}{(1+\bar{R})(1+z_i\bar{R})}\Delta R\right]}, \qquad (6)$$

where

$$z_i = \frac{1}{1+\frac{1}{2}(y_i^2 + Q^2/E_i^2)/(1-y_i-Q^2/4E_i^2)}, \qquad (7)$$

with $y_i = \nu/E_i$ and $\bar{R} = \frac{1}{2}(R^{Sn} + R^{C})$; the z_i coefficients are always smaller than unity and mainly depend on y_i.

For each x bin a parametrisation with the form of Eq. (6) was fitted simultaneously to the data at each incident muon energy for all values of Q^2. The parametrisation had four free parameters: the mean value of ΔR in the bin, and the three parameters a_1, a_2 and a_3 of the function $F_2^{Sn}/F_2^{C} = (a_1 + a_2 \ln Q^2)(1 + a_3/Q^2)$ describing the Q^2 dependence of the structure function ratio in this x bin. The quantity $\bar{R}$ was taken to be equal to the SLAC parametrisation [18] with artificially large errors.

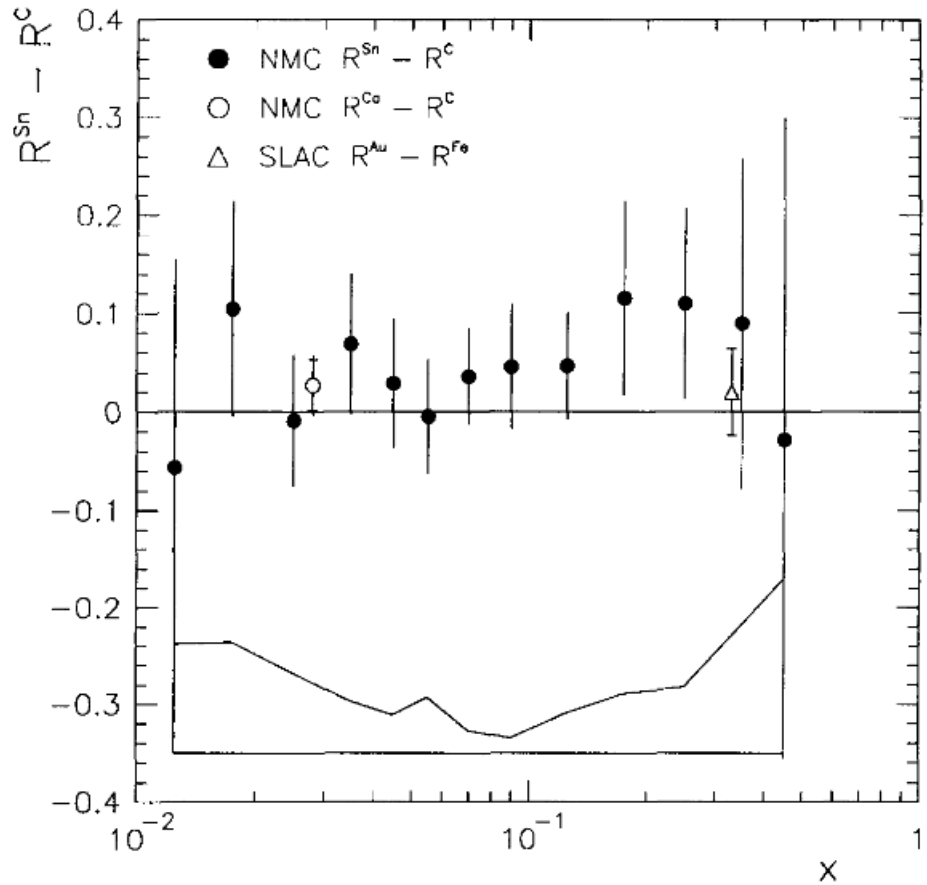
ΔR: Model-Dependent Extractions

NMC: R_{Sn} - R_C Nucl. Phys. B 481, 23 (1996)

From published paper

Fit results at fixed x (and running Q^2)

x	$\langle Q^2 \rangle$ [GeV^2]	$\Delta R \pm$ stat. $\pm$ syst.
0.0125	3.3	$-0.06 \pm 0.21 \pm 0.11$
0.0175	4.3	$0.10 \pm 0.11 \pm 0.11$
0.025	5.6	$-0.01 \pm 0.07 \pm 0.08$
0.035	7.2	$0.07 \pm 0.07 \pm 0.05$
0.045	8.6	$0.03 \pm 0.07 \pm 0.04$
0.055	9.9	$0.00 \pm 0.06 \pm 0.06$
0.070	11.4	$0.04 \pm 0.05 \pm 0.02$
0.090	13.1	$0.05 \pm 0.06 \pm 0.02$
0.125	15.2	$0.05 \pm 0.05 \pm 0.04$
0.175	17.9	$0.12 \pm 0.10 \pm 0.06$
0.25	20.8	$0.11 \pm 0.10 \pm 0.07$
0.35	26.6	$0.09 \pm 0.17 \pm 0.13$
0.45	35.1	$-0.03 \pm 0.33 \pm 0.18$



Since no significant x dependence of ΔR was observed, we averaged the measurements over x and obtained at a mean Q^2 of 10 GeV^2

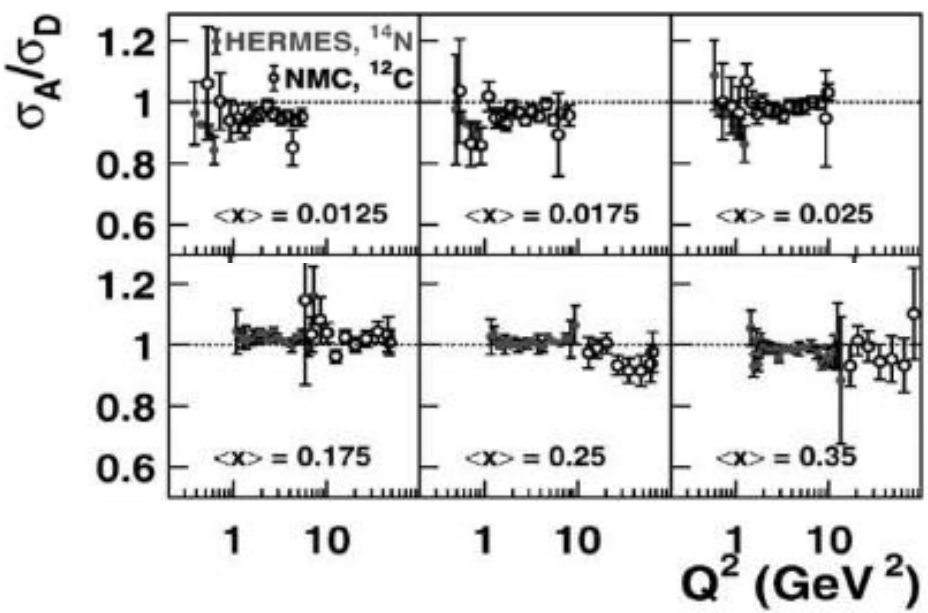
$$\Delta R = R^{Sn} - R^C = 0.040 \pm 0.021 \text{ (stat.)} \pm 0.026 \text{ (syst.)}. \quad (8)$$

ΔR: Model-Dependent Extractions

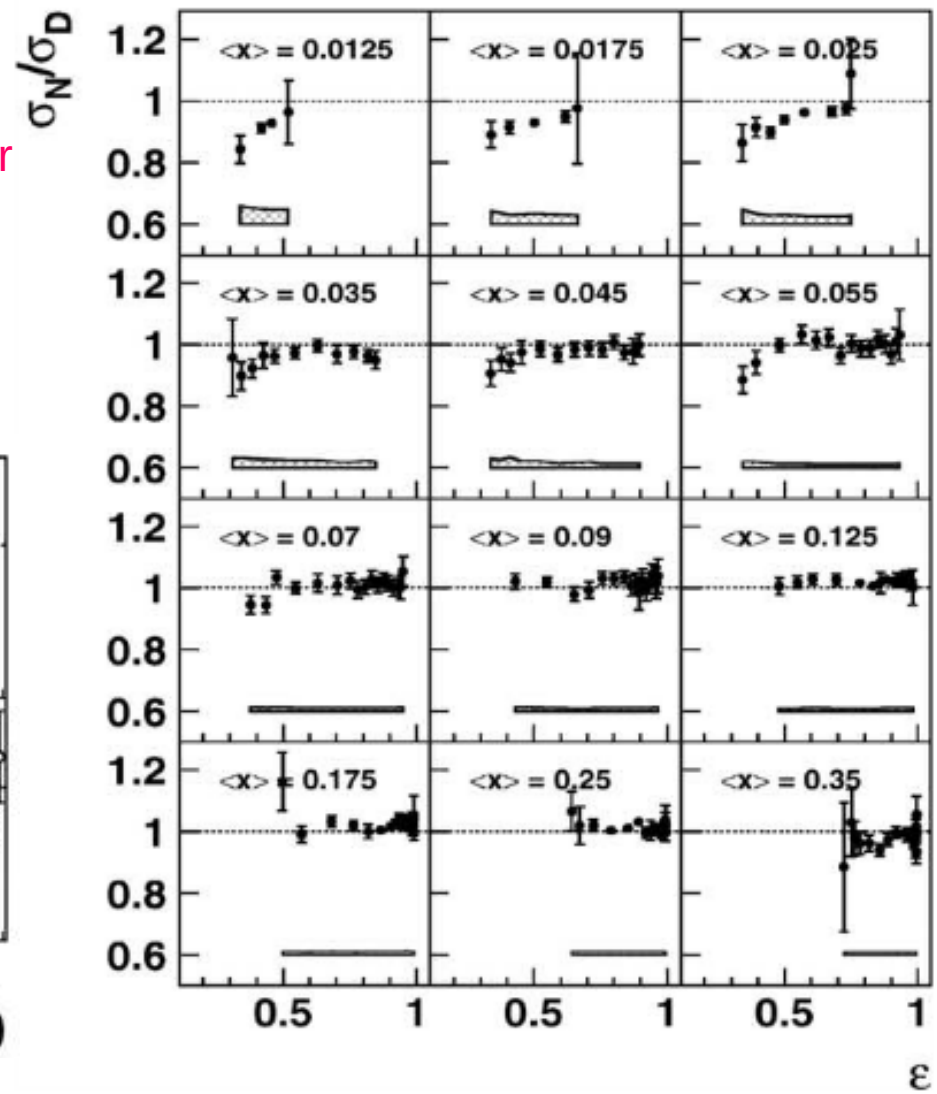
HERMES: ^{3}He/D, N/D, Kr/D Phys. Lett. B 567, 339 (2003)

→ 1 beam energy
→ R_A/R_D extracted at fixed x by fitting the cross section ratio as a function of ε with R_A/R_D and F_2^A/F_2^D as free parameters under the assumption that:

R_A/R_D and F_2^A/F_2^D are constant over the Q^2 range covered by the data



Cross section ratio at fixed x, running Q^2 and ε



R1990

SLAC: Whitlow *et al.* Phys. Lett. B 250 (1990)

→ Combined re-analysis of 8 SLAC experiments to extract R_p, R_D and R_D - R_p

→ The data from the other 7 experiments were normalized to E140 by fitting cross sections to a model with normalization factors as free parameters

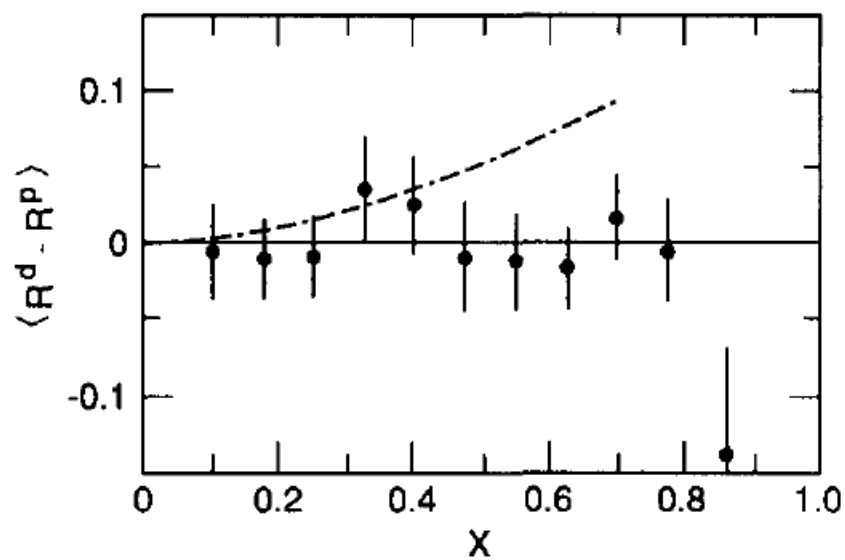
→ The normalized cross sections were binned in intervals of x and Q^2 and bin-centering corrections was applied. R was extracted at the center of each bin by doing a linear regression of cross sections with ε

→ It was observed that $R_p \sim R_d$ thus the 2 values in each bin were averaged to yield R

→ A global parametrization of R (R1990) was obtained by fitting these extractions with world data: E140, EMC, BCDMS, CDHSW…

Experiment	Hydrogen normalization	Deuterium normalization
E49a [1]	1.012 ± 0.005 ± 0.003	1.001 ± 0.006 ± 0.002
E49b [3]	0.981	0.981 ± 0.005 ± 0.002
E61 [4]	1.011 ± 0.008 ± 0.004	1.033 ± 0.007 ± 0.003
E87 [2]	0.982 ± 0.005 ± 0.011	0.986 ± 0.004 ± 0.010
E89a [5]	0.989 ± 0.020 ± 0.020	0.985 ± 0.021 ± 0.020
E89b [6]	0.953 ± 0.004 ± 0.004	0.949 ± 0.004 ± 0.001
E139 [7]		1.008 ± 0.004 ± 0.002
E140 [8,9]		1.000

E140: the only L/T experiment (on D, Fe, Au)



Why as Many Beam Energies as Possible?

E94-110 (Hall C)

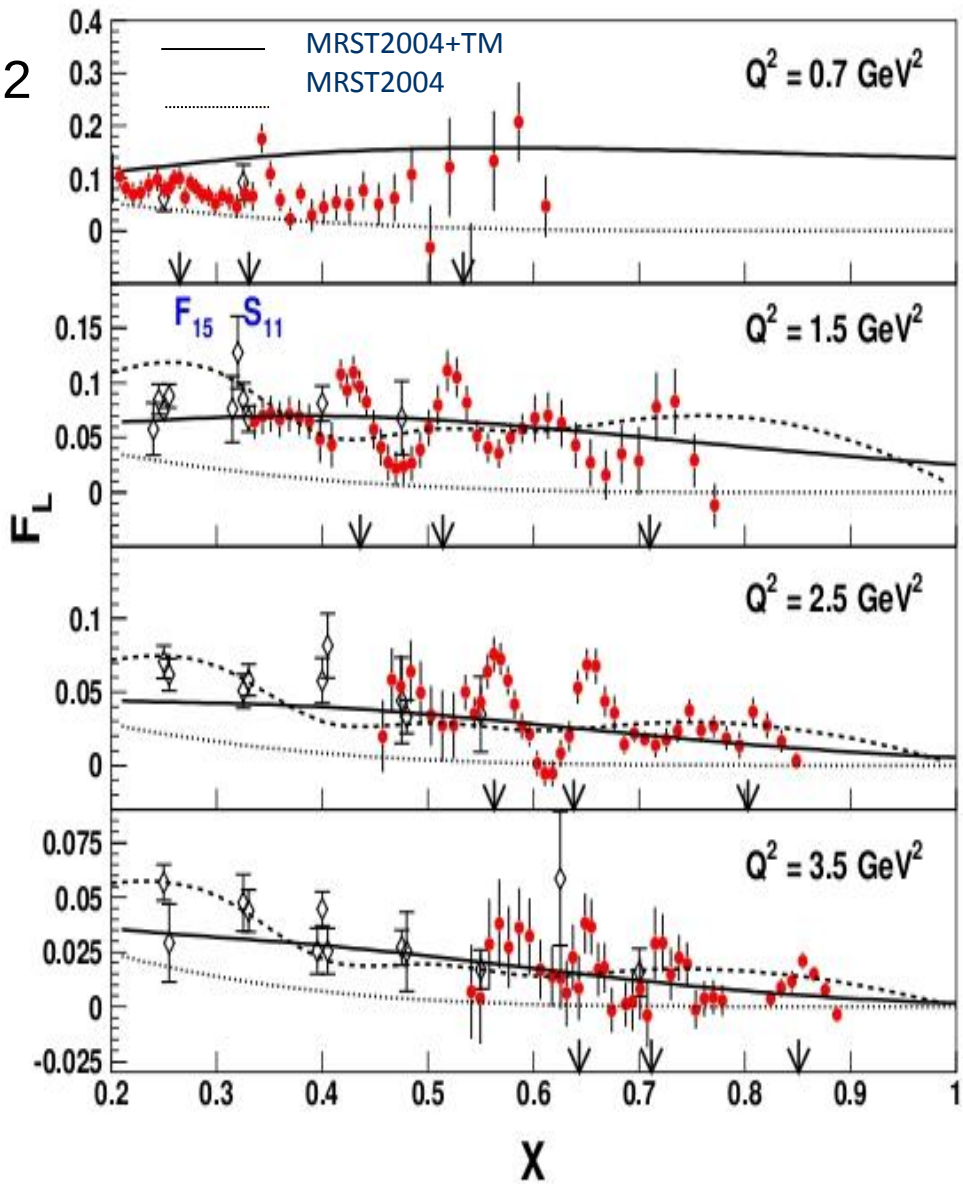
Y. Liang, Ph.D. Thesis, Hampton 2002

→ ~ 200 individual L/T separations

→ one of the most precise L/T ever performed: it became a benchmark for this type of experiments

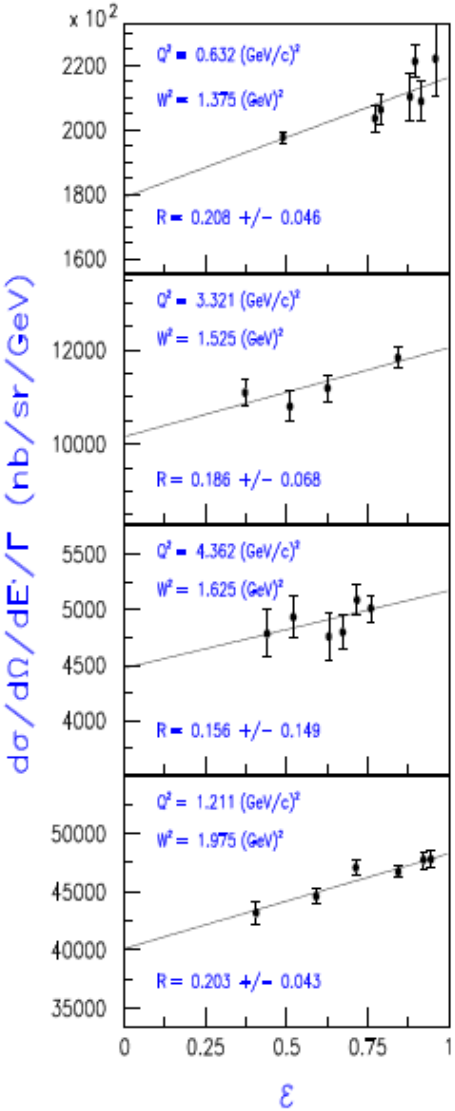
→ data have been since included in global fits of F_1, F_L, R, F_2 and used for F_L moments calculations

7 beam energies



Why as Many Beam Energies as Possible?

E94-110 (Hall C) Y. Liang, Ph.D. Thesis, American University 2002



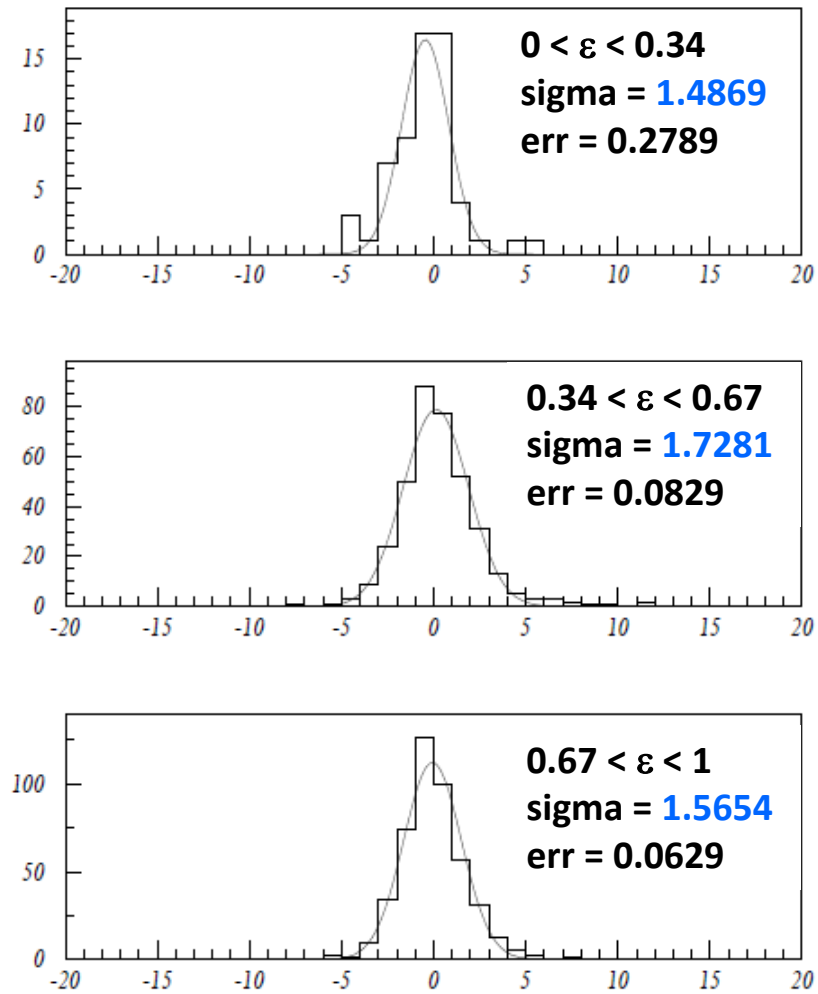
7 (many) beam energies

↓

many ε points

↓

It could be checked that the average deviation of the data used to perform the Rosenbluth L/Ts from the linear fit was consistent with the estimated point-to-point uncertainty of 1.6 %



$(\sigma_{data} - \sigma_{fit})*100/\sigma_{data}$ (%)

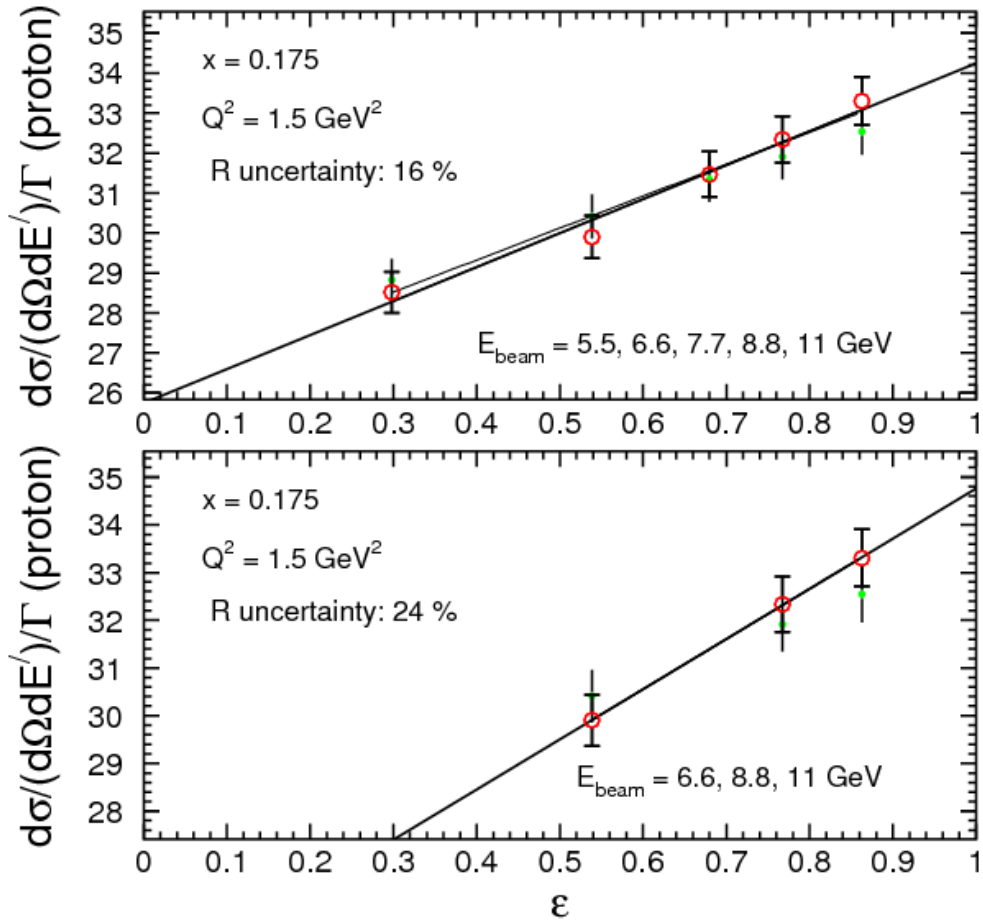
Why as Many Beam Energies as Possible?

PR12-14-002

Example:

Without non-standard beam energies: uncertainty on R extraction larger

Out of 23 central L/Ts, 9 have the lowest ε point provided by a 5.5 GeV beam energy setting



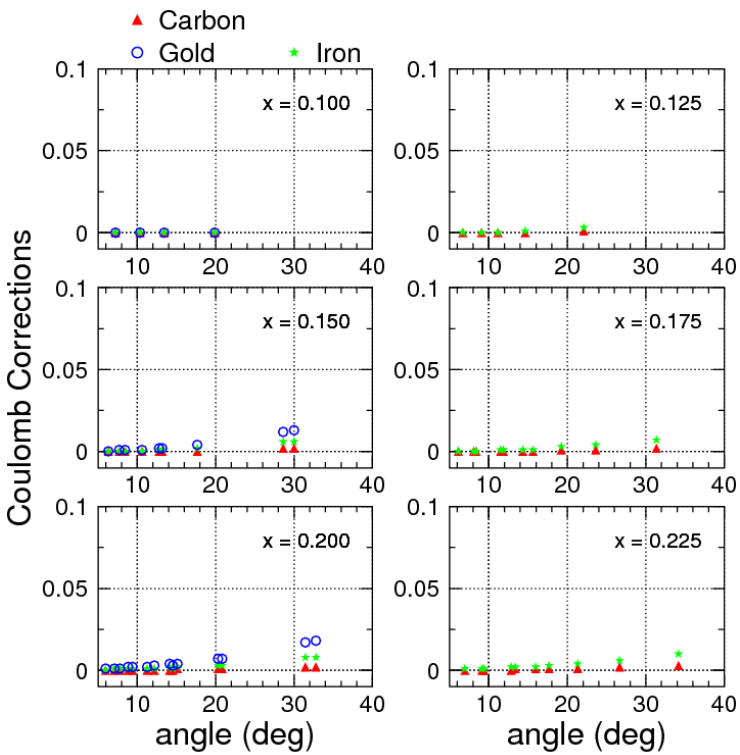
PR12-14-002: Backgrounds and Corrections

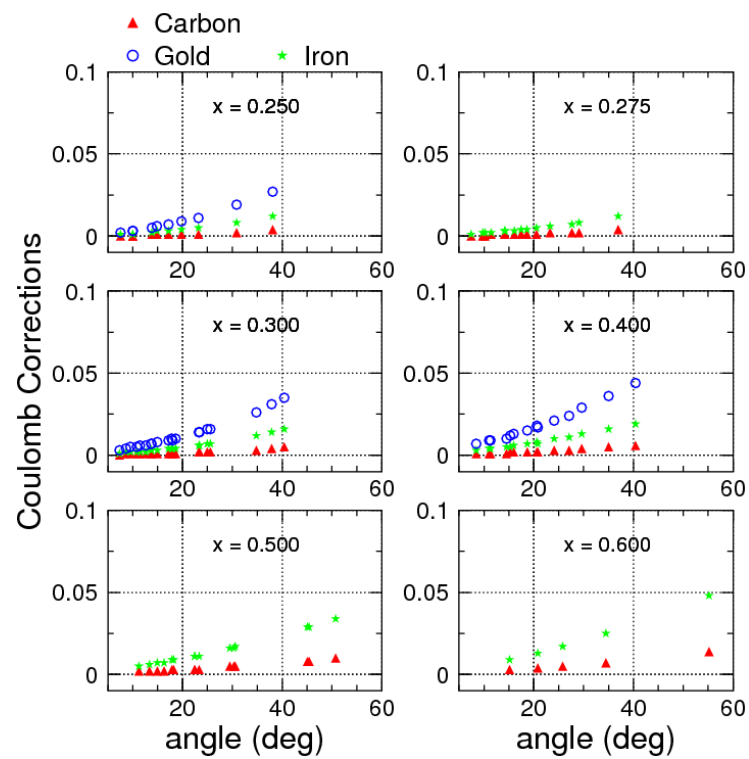
Coulomb Corrections

→ We will take additional measurements to constrain/verify Coulomb corrections procedure

Q^2	x_b	E	E'	θ	ϵ	y	W	C^{Au}_{Coulomb}
3.48	0.50	4.4	0.69	64.6	0.20	0.84	2.08	11.6%
9.03	0.50	11.0	1.38	45.5	0.20	0.88	3.10	6.2%
2.15	0.50	4.4	2.11	27.9	0.70	0.52	1.74	3.5%
5.79	0.50	11.0	4.83	19.0	0.70	0.56	2.58	1.9%

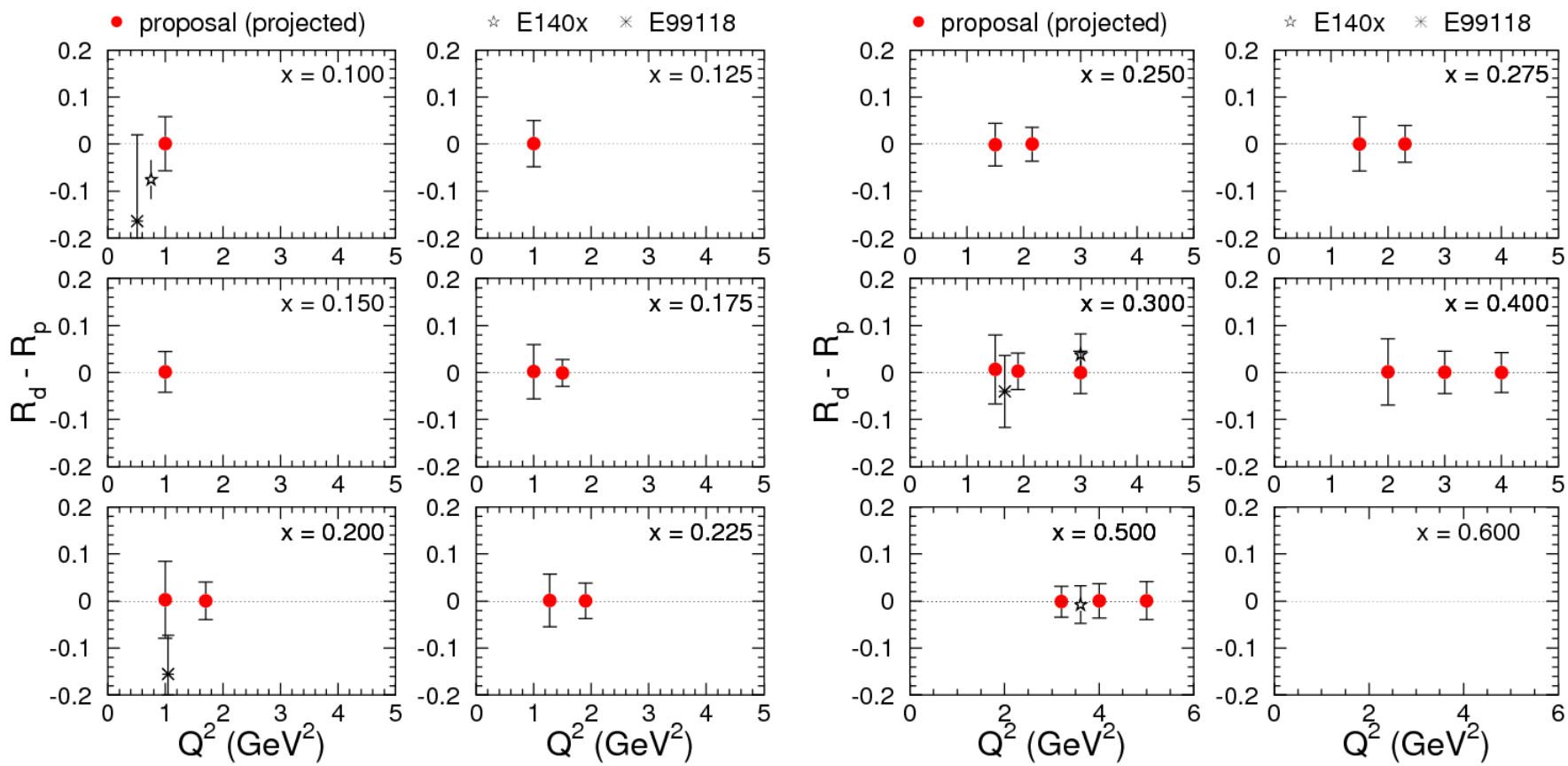
At fixed ε we expect σ_{Au}/σ_D to scale with Q^2, any measured variation would be mostly due to Coulomb corrections





PR12-14-002: Impact for R_d-R_p

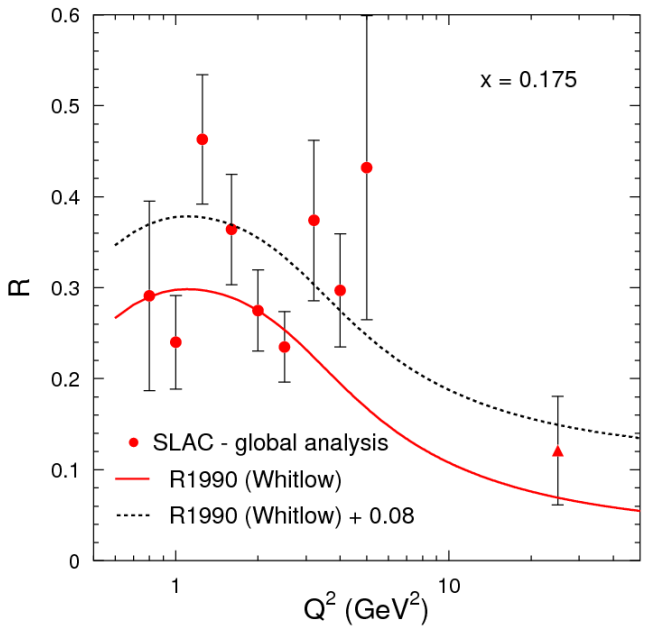
- We plan to map the x and Q^2 dependence of **R_d-R_p** independently

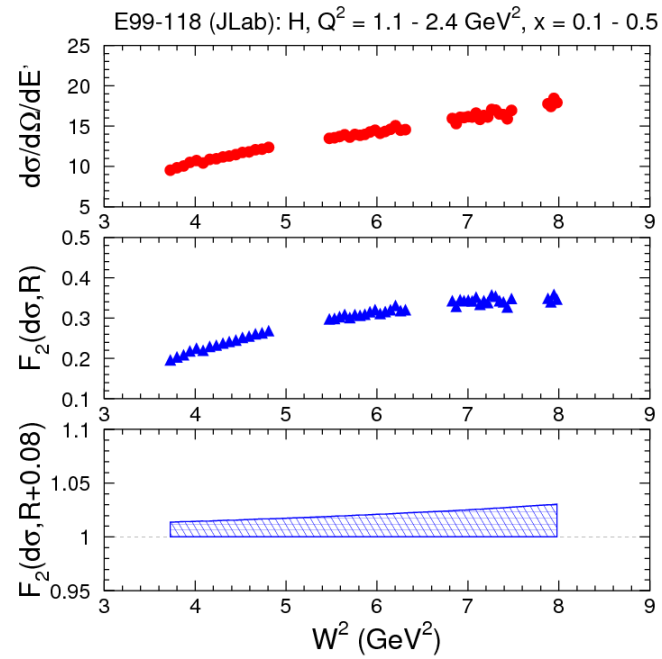


- We will extend measurements of $R_d - R_p$ to larger Q^2

Impact of R_p uncertainties on F_2 extractions

- When transitioning from cross sections to F_2 at low to intermediate Q^2 even a small offset in R can lead to a non-negligible uncertainty in the structure function extraction





Example: At low Q^2 (between 1.1 and 2.4 GeV^2), and moderate x (between 0.1 and 0.5), a ~25% (0.08 in absolute value) change in R allowed by the precision of current data, leads to up to 4% change in F_2