Experimental Investigation of the Transverse and Longitudinal Structure Functions of Bound Nucleons at Jlab

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

Presented at

Nuint 2017, Toronto

Tuesday June 27, 2017 - 11:45-12:05

Special thanks to
S. Malace, Jefferson Lab,
V. Mamyan, University of Virginia,
I. Albayrak and M. E. Christy Hampton University

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*

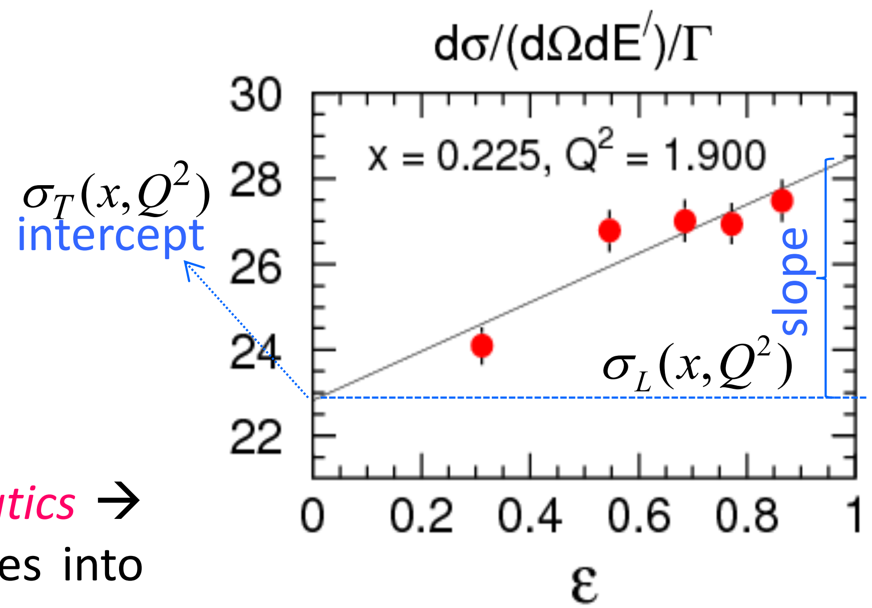
$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma(\sigma_T(x,Q^2) + \varepsilon\sigma_L(x,Q^2)) = \Gamma\sigma_T(1+\varepsilon R) \qquad \varepsilon = 1/(1+2(1+{}^{\nu^2}/_{Q^2})\tan^2({}^{\theta}/_{2}))$$

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

Requirements for precise R= σ_L/σ_T:

- 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 (**or 0.02 to 0.04 on R= σ_L/σ_T**)



Deep inelastic neutrino differential cross section are relatively well known.

The following are systematic errors in the high energy DIS total cross sections for W>1.8 GeV (Bodek-Yang)

$$\frac{d\sigma(\nu N)}{dx} \approx \frac{G_F^2 ME}{\pi}(Q+\overline{Q})\left[(1-f_{\overline{Q}})+\frac{1}{3}f_{\overline{Q}}-\frac{1}{6}\mathcal{R}\right], \quad (51)$$

and

$$\frac{d\sigma(\overline{\nu} N)}{dx} \approx \frac{G_F^2 ME}{\pi}(Q+\overline{Q})\left[\frac{1}{3}(1-f_{\overline{Q}})+f_{\overline{Q}}-\frac{1}{6}\mathcal{R}\right]. \quad (52)$$

How well do we know these for nuclear targets in the resonance region?

If ΔR in a nucleus Is 0.25 All these errors go up by x5

source	change (error)	change in σ_ν	change in $\sigma_{\overline{\nu}}$	change in $\sigma_{\overline{\nu}}/\sigma_\nu$
R	-0.05	+1.0%	+2.0%	+1%
$f_{\overline{q}}$	+5%	-0.7%	+1.4%	+2.1%
$K^{axial}-K^{vector}$	+ 50%	+1.3%	+1.9%	+1.2%
N	+3%	+3%	+3%	0
Total		±3.4%	±4.3%	±2.5%

Practically no existing data on R_A

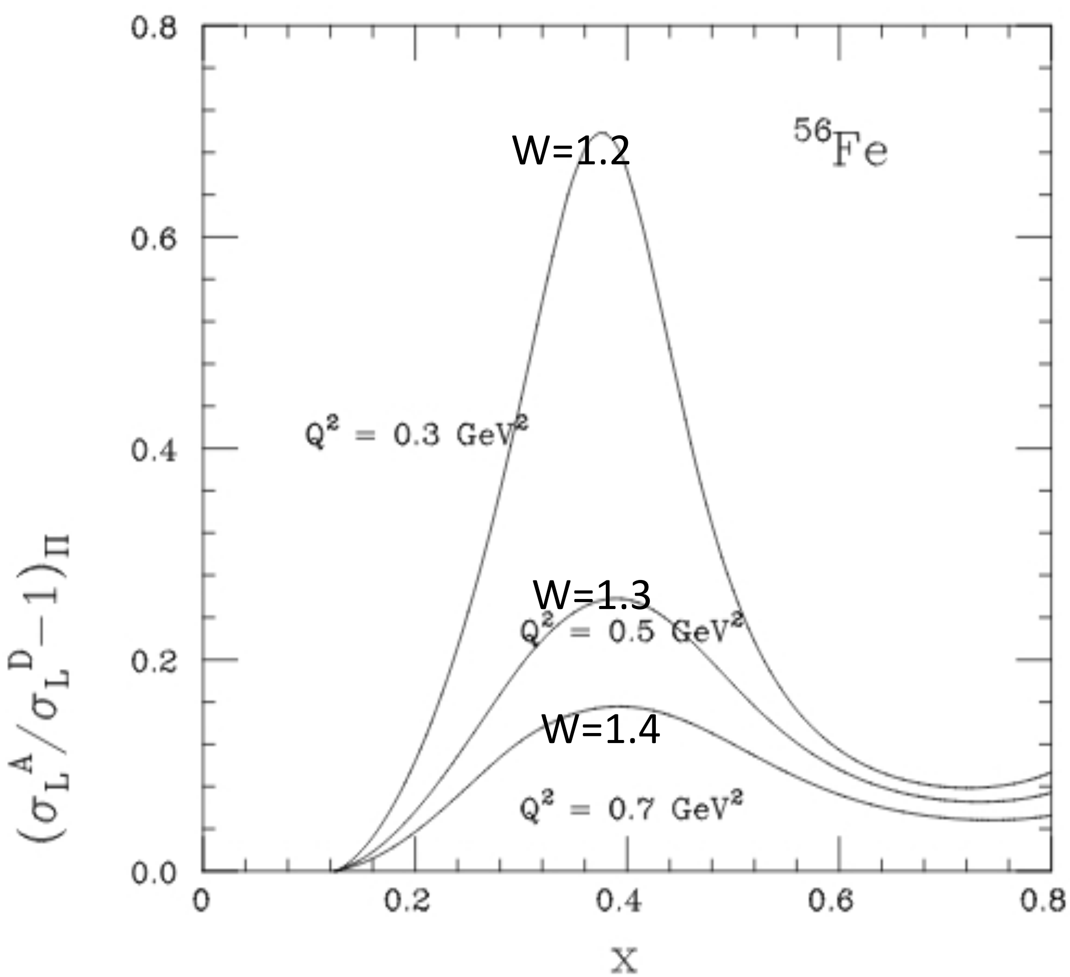
- F_{2A}, R_A in this region is input for modeling neutrino interactions
  → Neutrino oscillation experiments Requires good models
  for neutrino-A cross sections at low energy

At low Q^2 a model by Miller predicts significant *A*-dependent enhancement in F_L due to nuclear pions/mesons.
+0.25 increase in R at Q2=0.3 GeV2
Much smaller for Q2> 1 GeV2

This implies a reduction of
5% in neutrino and 10%
in antineutrino cross section at
The region of the Delta (1238).

(In addition to the normalization
Uncertainty in F2).

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



6 GeV L/T separation program in Hall C

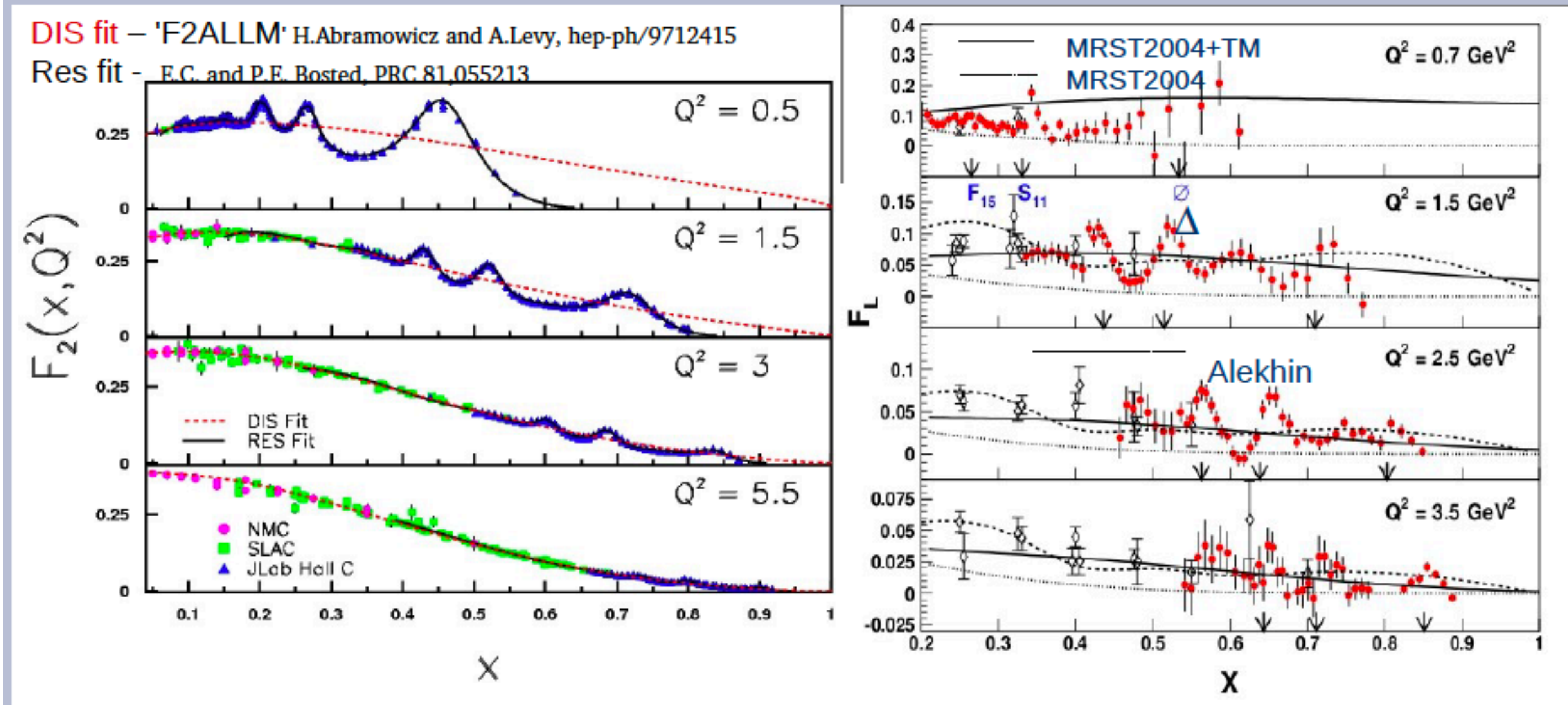
Experiment	*target(s)*	*W range*	*Q^2 range*	*Status*
E94-110	p	RR	0.3 - 4.5	nucl-ex/041002 -- low Q
E99-118	p,d	DIS+RR	0.1 - 1.7	PRL98:14301 -- low Q
E00-002 Publication submitted	p,d	DIS+RR	0.25 - 1.5	Analysis finalized-- low Q
E02-109	d	RR+QE	0.2 - 2.5	Finalizing cross section analysis -- low Q
E06-009	d	RR+QE	2.0 - 4.0	Cross section, F_L finalized -- high Q Non-singlet moments paper drafted.

==

E04-001 - I Phase I: low Q	**C, Al, Fe/Cu**	**RR+QE**	**0.2 - 2.5**	**Finalizing cross section analysis (Next)**
E04-001 - II Phase II high Q	**C, Al, Fe/Cu**	**RR+QE**	**2.0 - 4.0**	**Cross section, RA-Rd finalized for most targets (This talk)**

RR = Resonance Region

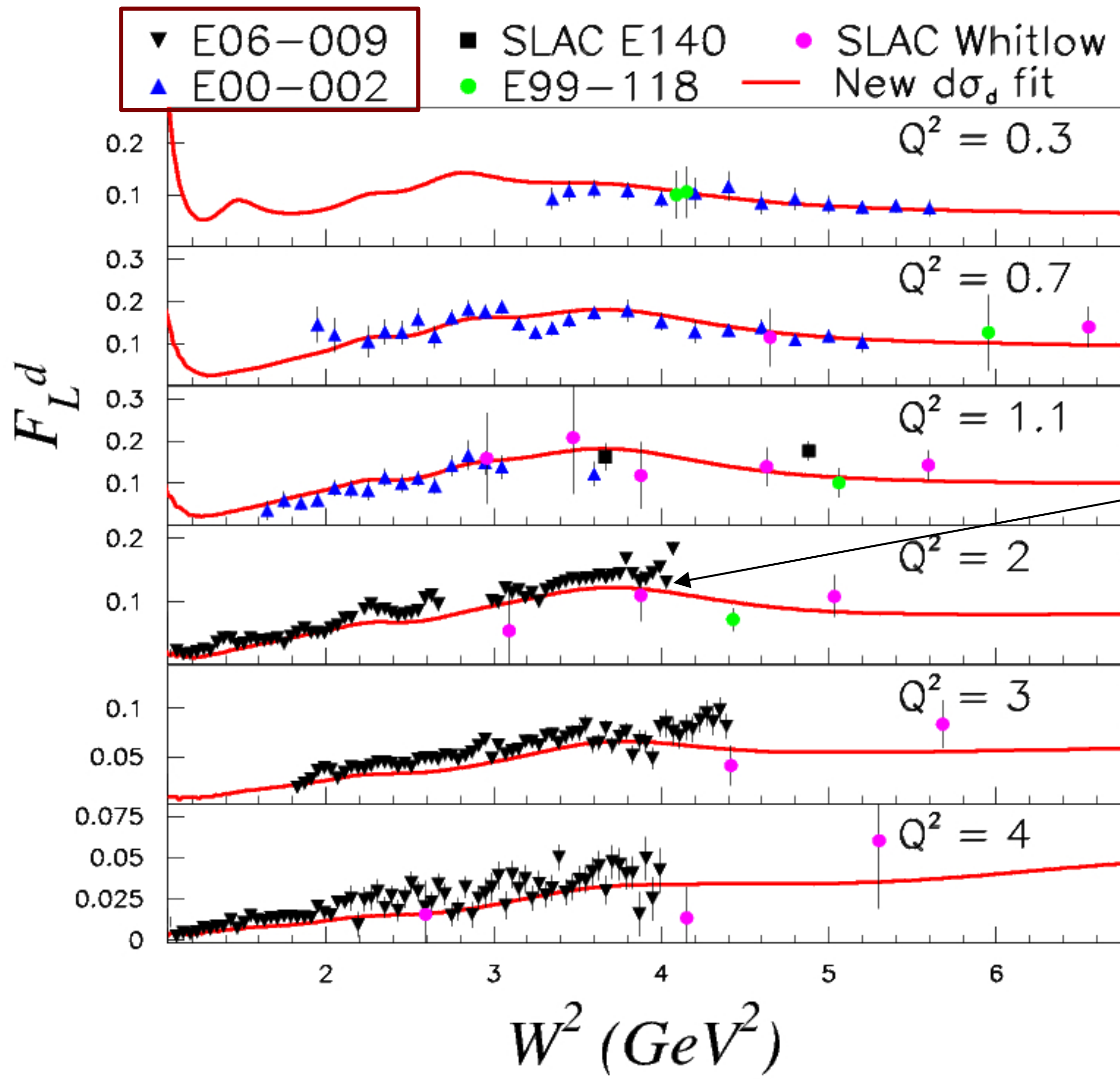
Proton F_2 , F_1, F_L well measured at 6 GeV



→ Used to study Q-H duality, structure function moments, and input for other physics studies

→ Deuteron and nuclear target data of similar quality to study
=> - duality and QCD moments of neutron and p-n
- Modifications of F_1, F_L in nuclear medium

Status of F_L deuteron data



→ Multiple new data sets

I. E00-002 (also proton data)
II. E06-009

→ Generally good agreement between data sets, but some tension in fit.

fit is Weak-binding approximation Smearing fit (proton input from Christy-Bosted fit)

M.E.C, N. Kalantarians, J. Ethier, W. Melnitchouk, In preparatiion

→ additional low Q^2 resonance region from phase-I (E02-109) expected to be finalized Winter of 2017.

F_L, R on Deuterium and heavier targets
JLab Hall C: E02-109, E04-001, E06-009

- Precision extraction separated structure functions on:

  d, Al, C, Fe/Cu

- Search for nuclear effects in F_L, R.

- Study quark-hadron duality in separated structure functions for neutron and nuclei.

THIS TALK

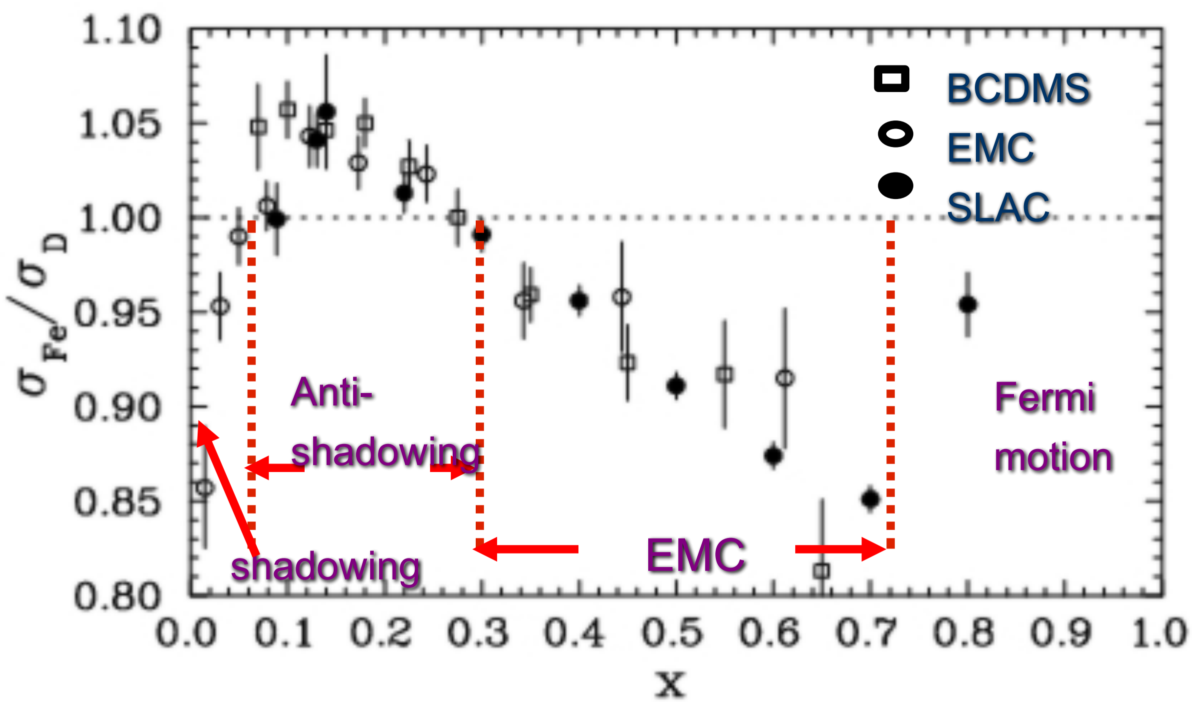
F_L^A (R_A) in Nuclei (E04-001)

Jupiter Collaboration

*Well known since the EMC experiment that the nuclear medium modifies nucleon structure functions.

→ However, after 25 years the mechanism is *still* not fully understood.

→ Is the effect different in F_1 and F_2?



* The latter => nuclear dependence of R and F_L !

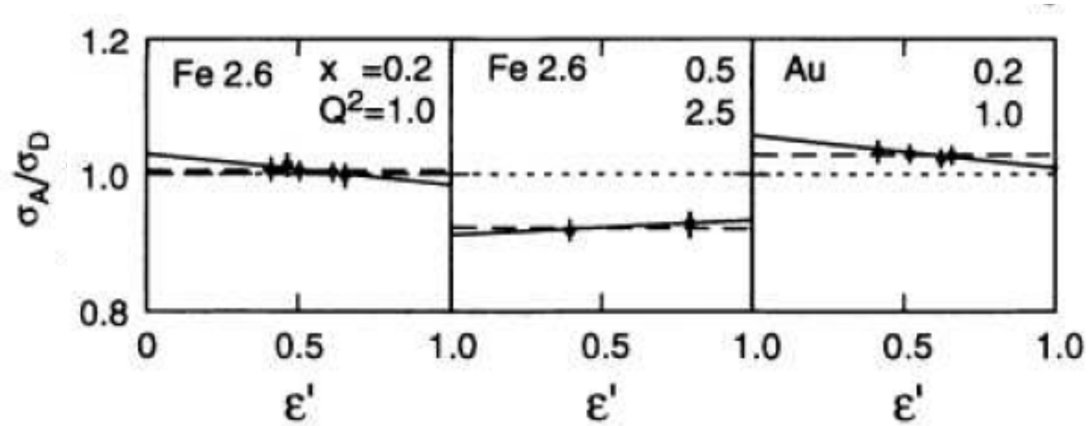
Need to know if *A* dependence exists in F_L for full understanding of EMC effect.

Most existing data at intermediate x from SLAC E140

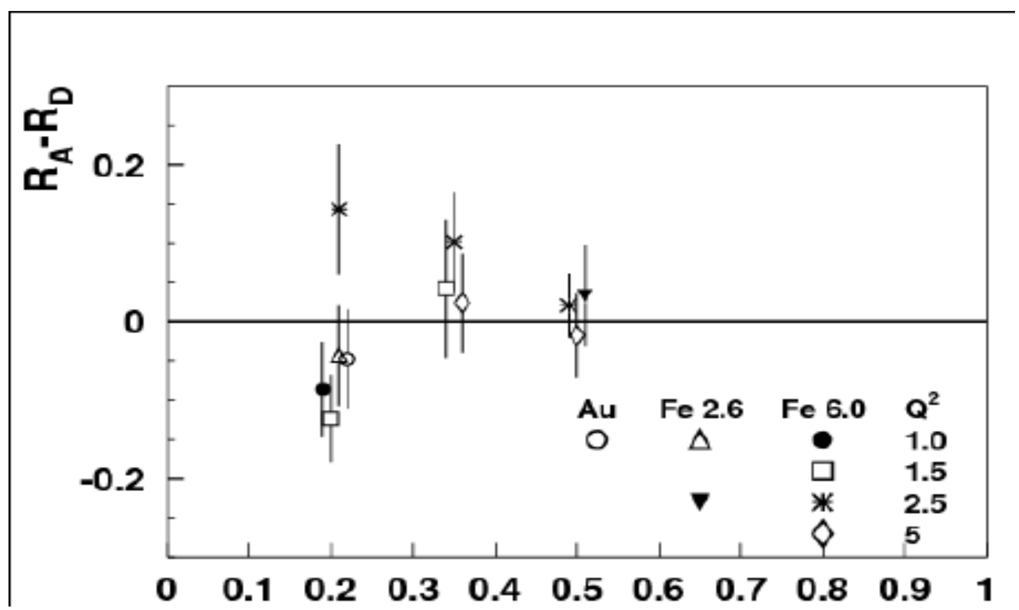
(Dasu *et.al Phys. Lett. D 49 (1993*)

→ Much of systematics drop out in cross section ratio

Reduction in errors in R_A-R_D

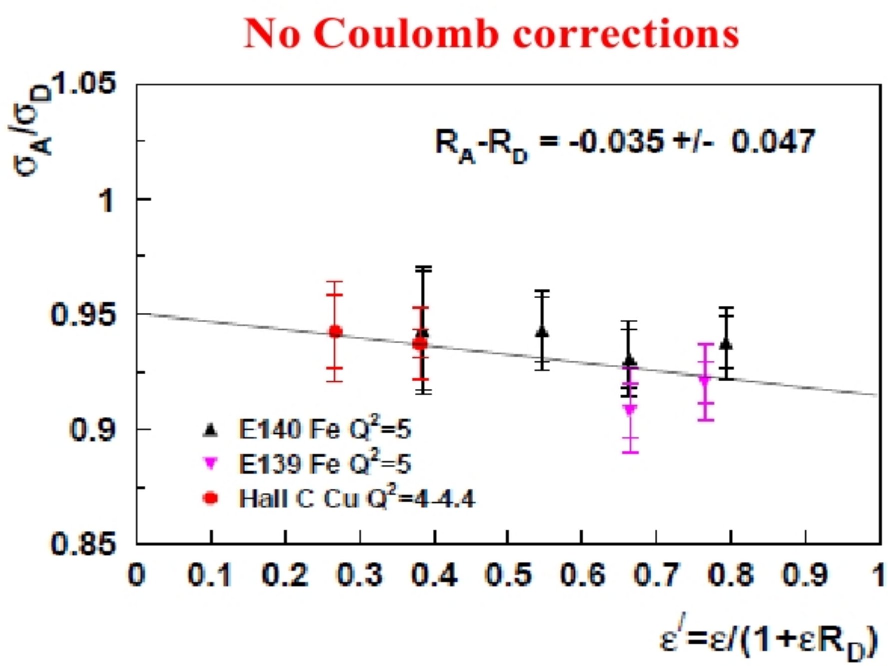


R_A-R_d found to be consistent with zero



Re-analysis of L/T separations (P. Solvignon, J. Arrington, D. Gaskell,ArXiv:0906.0512) including neglected Coulomb effects for electron entering and exiting nucleus

This is for Q2 = 5 GeV2



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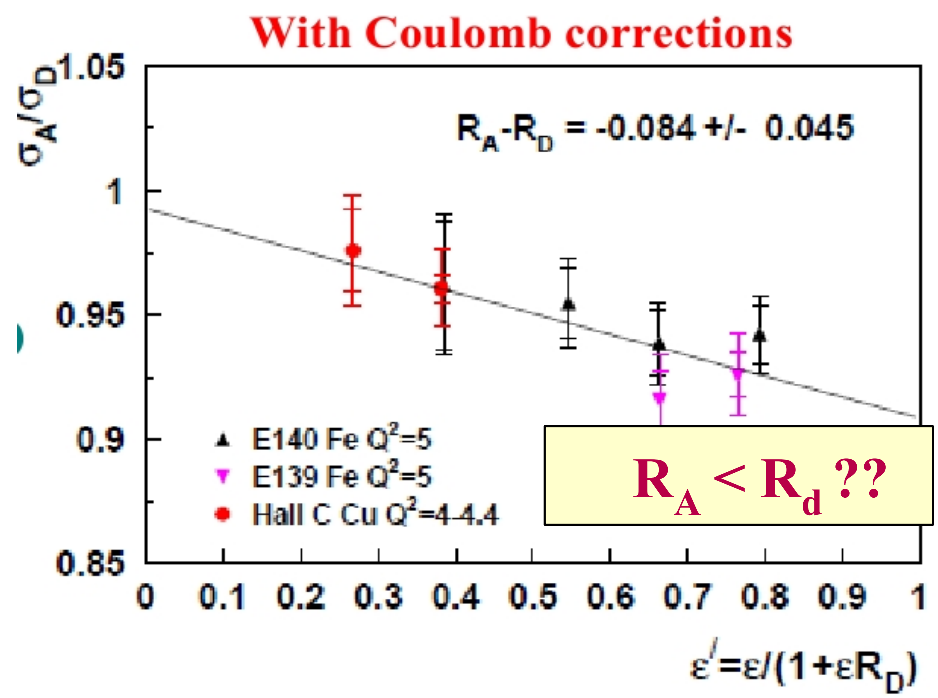
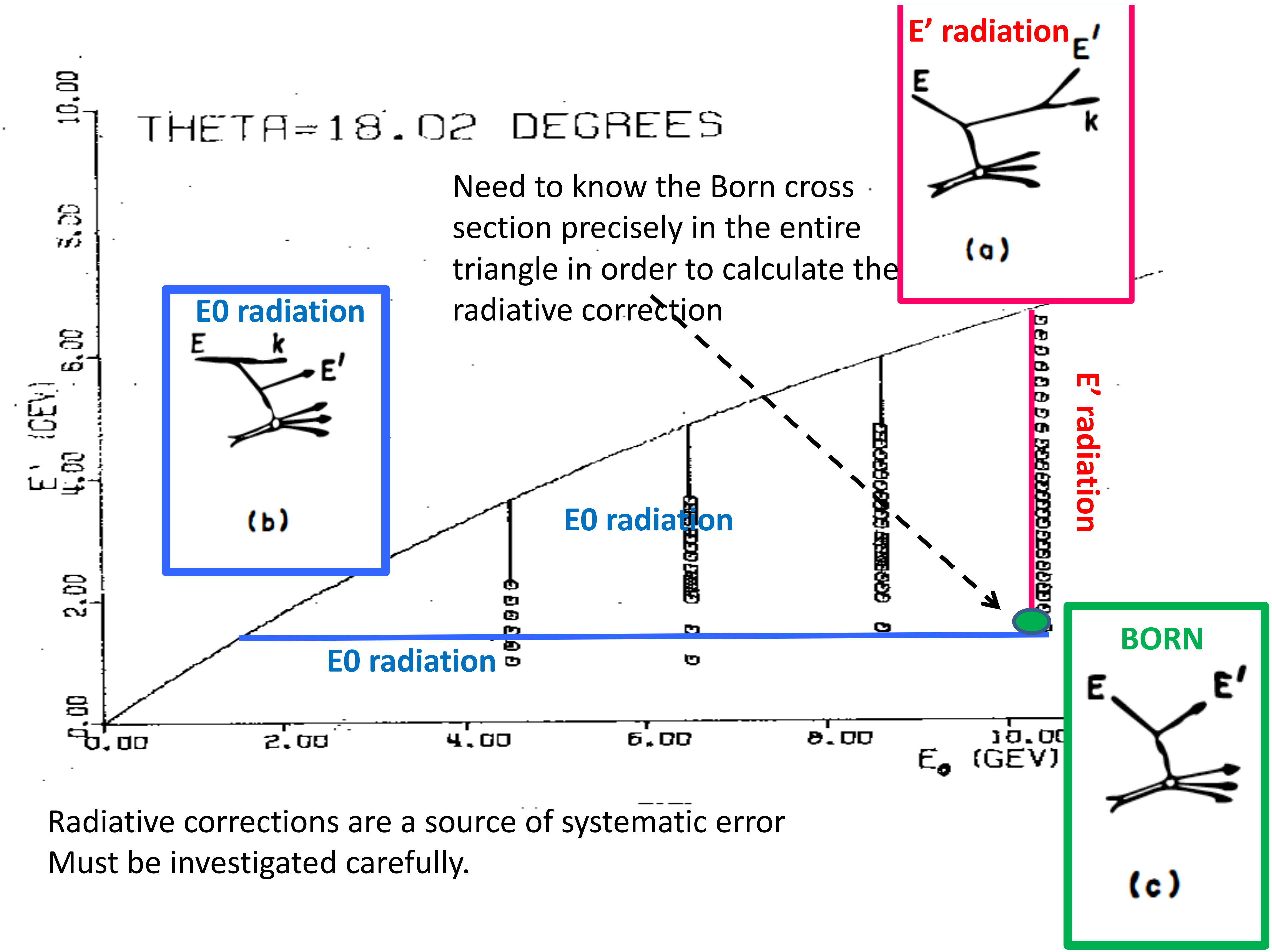




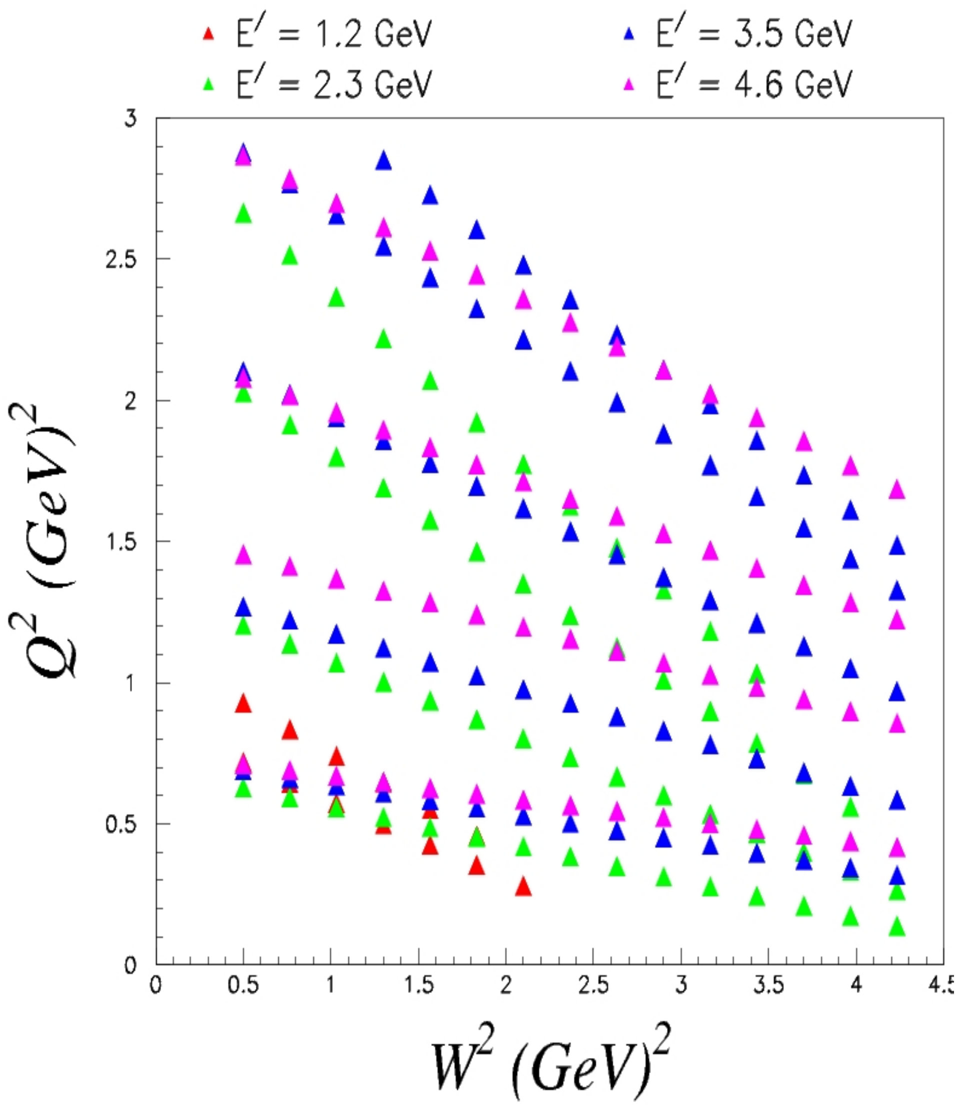
Radiative corrections are a source of systematic error
Must be investigated carefully.

L/T kinematics (d, C, Al, Cu, Fe)

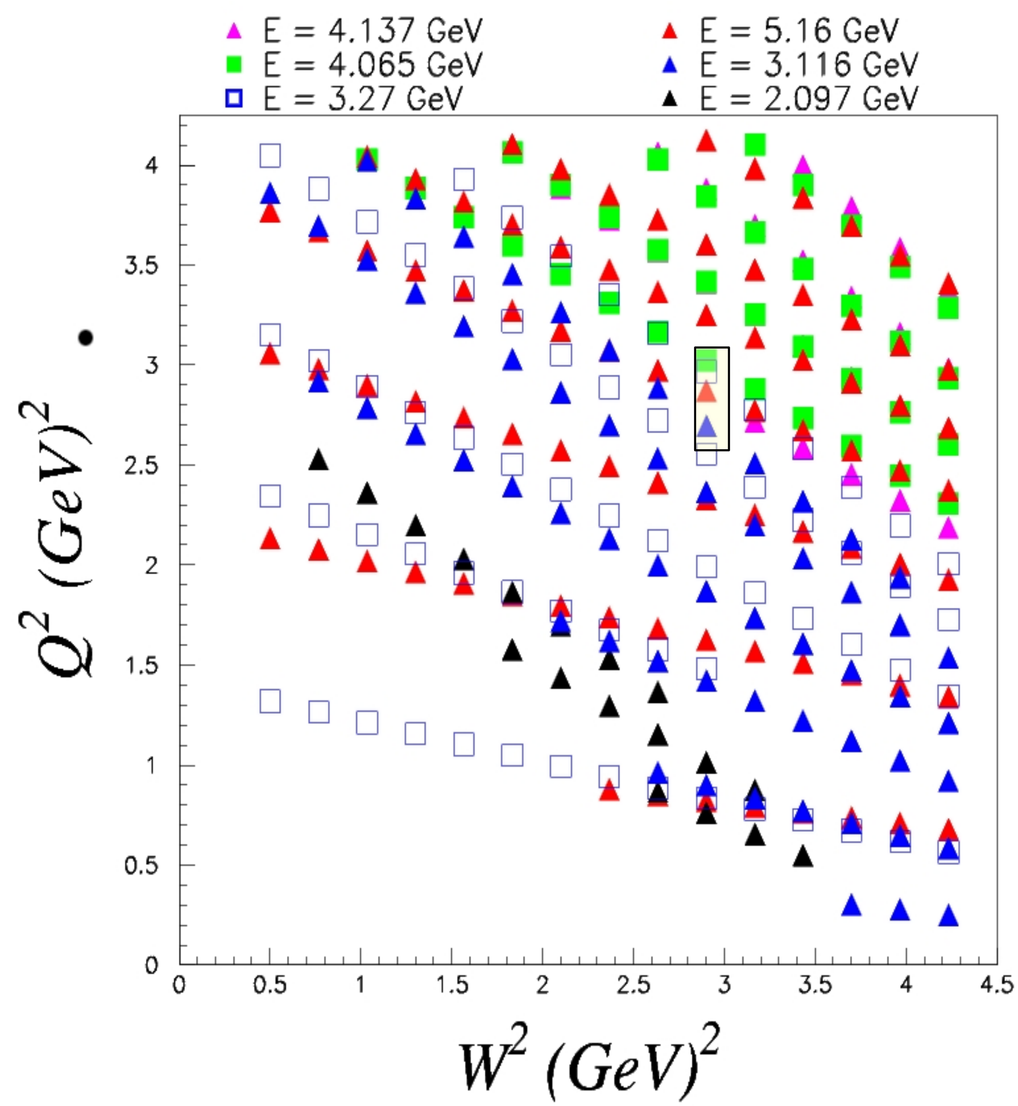
RR+QE Q^2: 0.2 - 2.5 in analysis

RR+QE Q^2: 2 – 4 THIS TALK

Phase-I



Phase-II

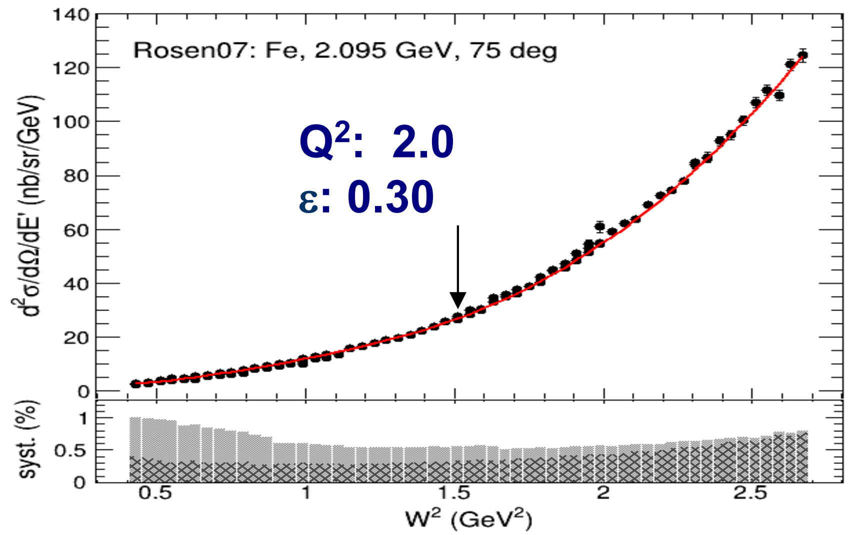


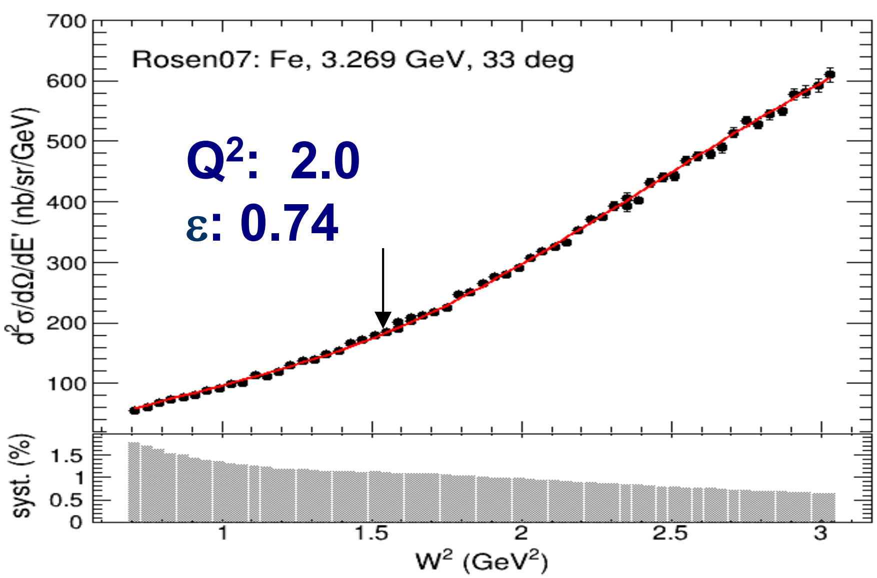
Final E04-001 Phase II ^{56}Fe cross sections
(no Couloumb corrections)

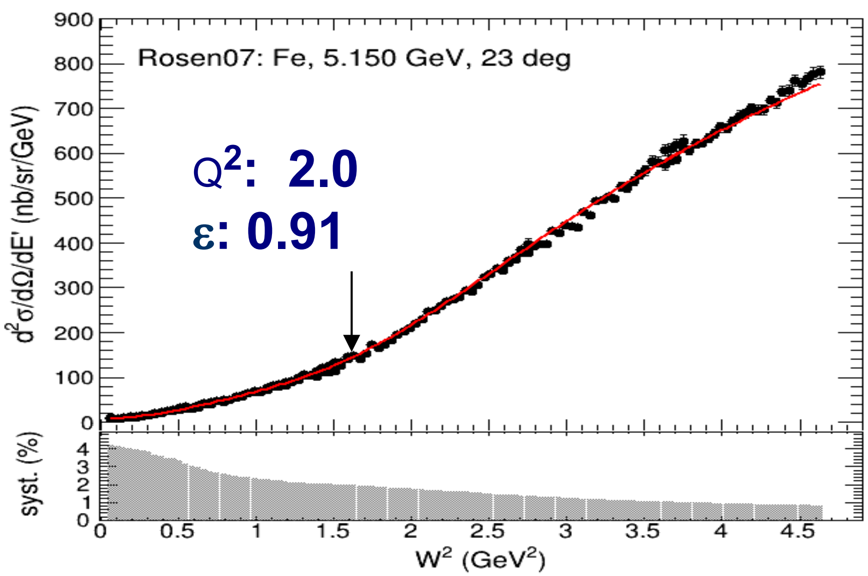
→ Example scans utilized in L/T Separations at Q^2 =2 near Delta(1232)

→ Correlated systematics at bottom

→ Red curve represents fit to global data set using p, n (d) fits as input.







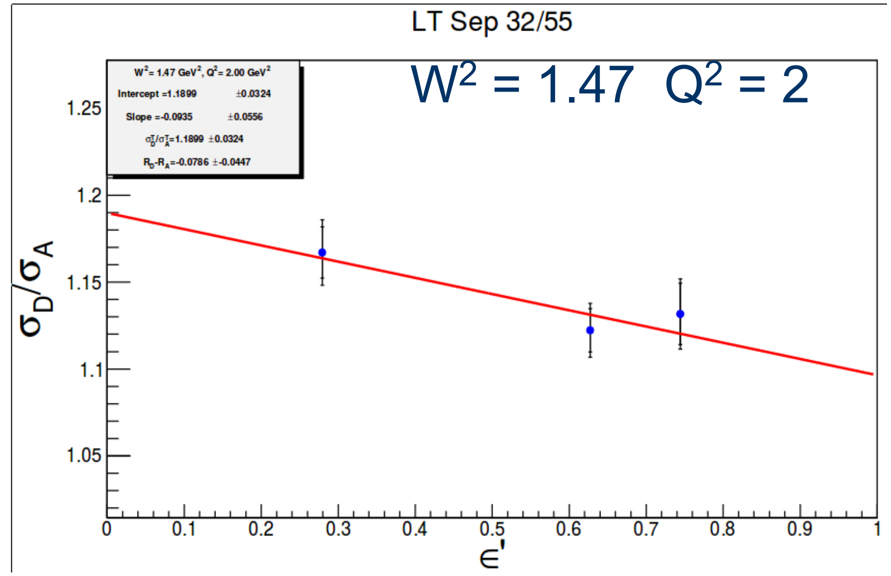
Example E04-001 Phase II L/T Separations

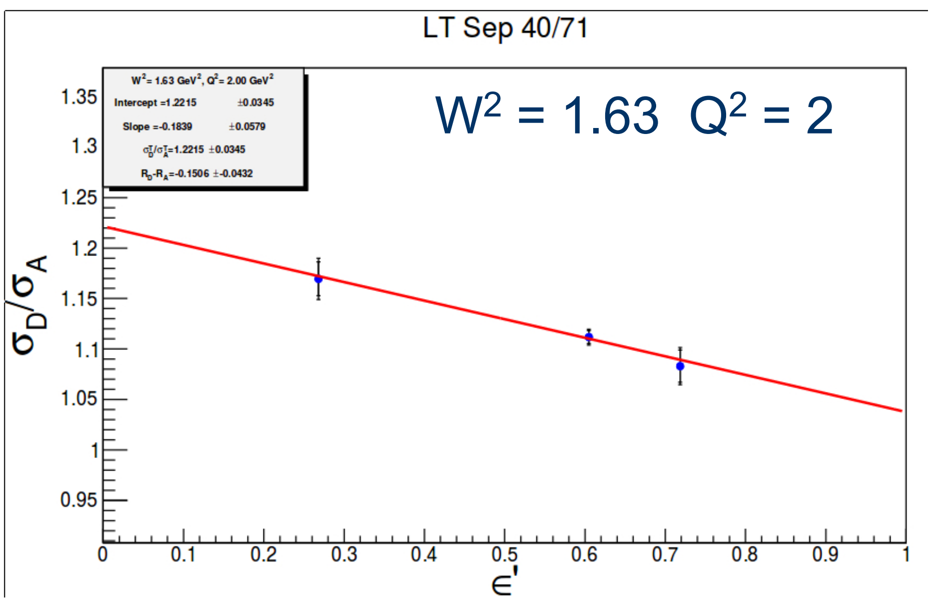
Note we now use $\sigma_T^d \;/\; \sigma_T^A$

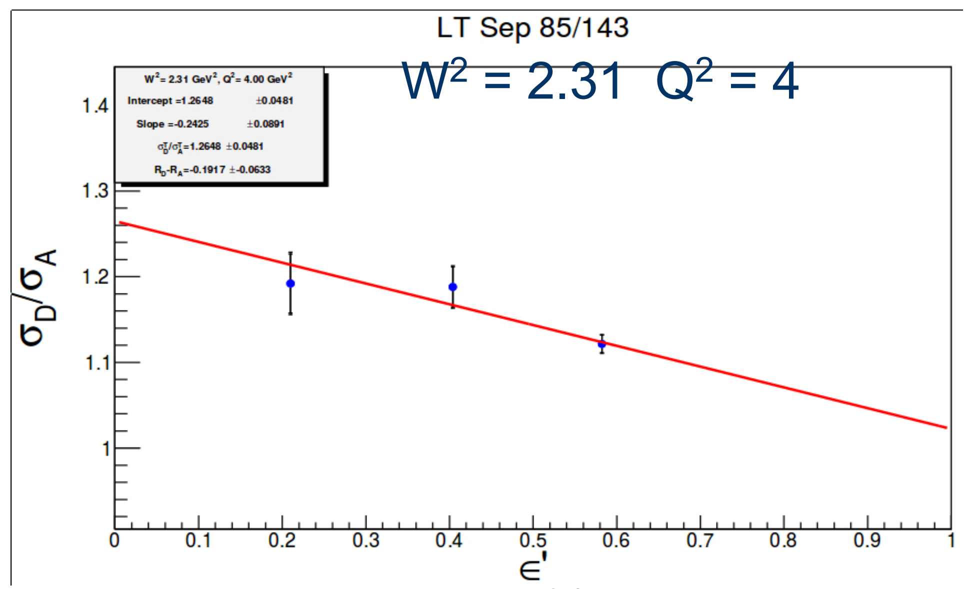
→ Example L/T Separations for ^{12}C

~300 separations for ^{12}C, ^{27}Al
About 100 each for ^{56}Fe, ^{64}Cu

→ Statistical + pt-pt systematic in shown

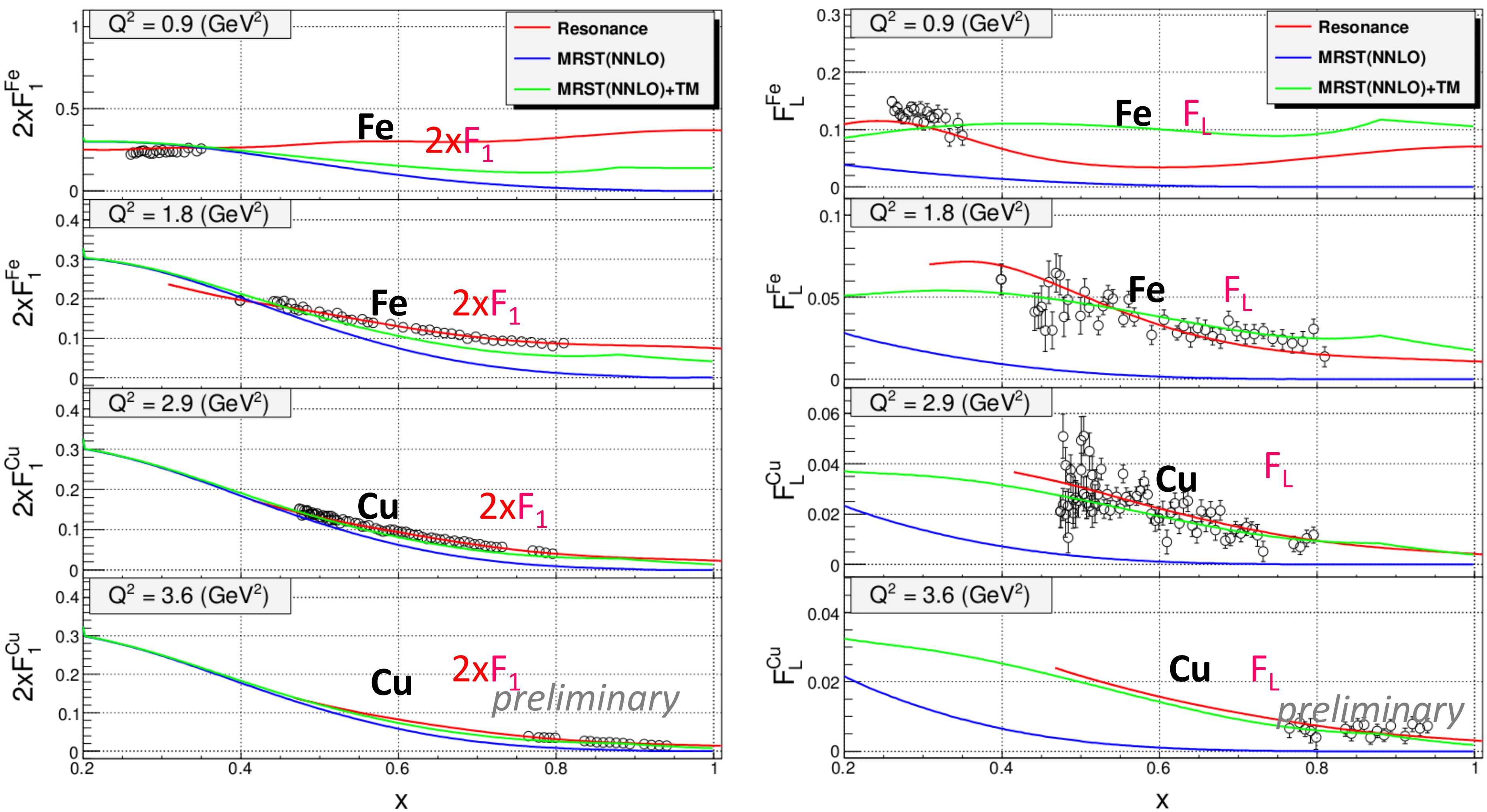






The experiment also measures absolute $2xF_1$, F_2, F_L in the Res. Region for several nuclear targets **C, Al, Fe, Cu as well as R_A-R_D**

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



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

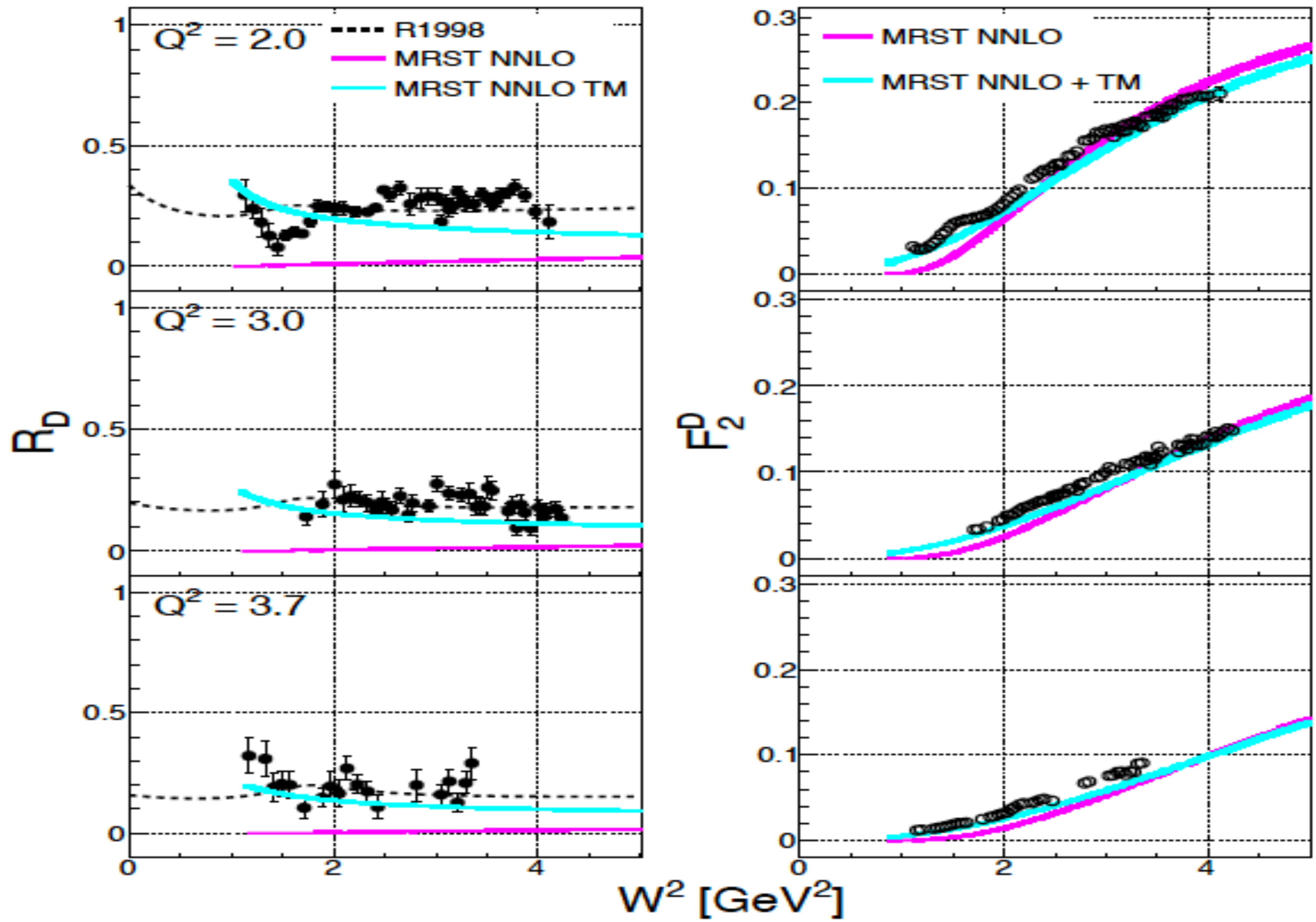
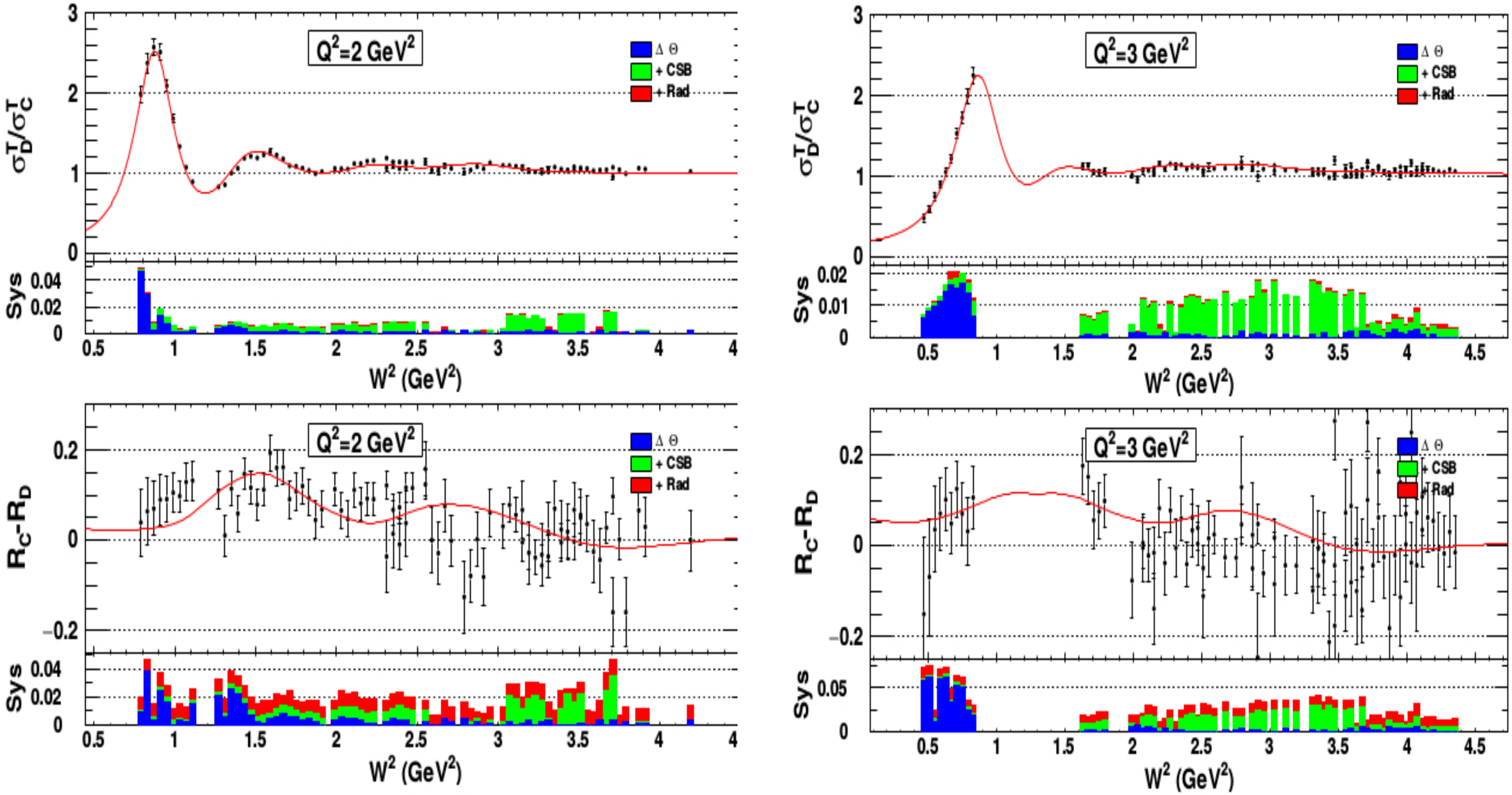


FIG. 1: Fig.1 Extracted values of R_D and F_{2D} in fine bins of W for three values of Q^2 compared to the theoretical expectation for R_D from NNLO QCD, from NNLO QCD including target mass corrections, and from a fit to the world's previous measurements of R for free protons (R_{1998}).

$Q^2 = 2\ \mathrm{GeV}^2$ Results for $\mathbf{R_A - R_d}$ and $\boldsymbol{\sigma_T^d / \sigma_T^A}$ ^{12}C



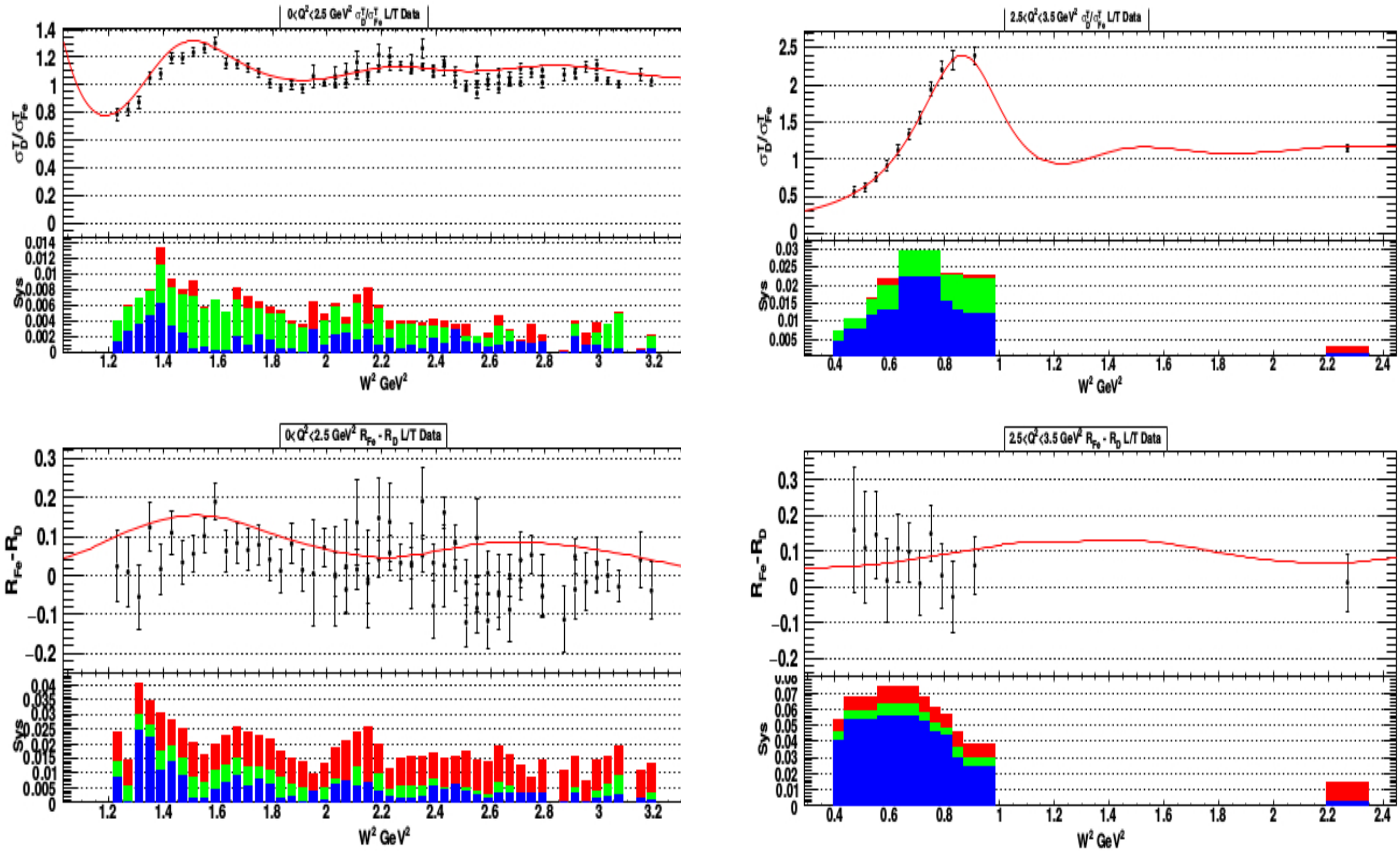
- Correlated systematics determined by shifting cross sections and repeating L/T separations
- Curve is fit to global cross sections with proton and neutron inputs

(M. E. Christy, T. Gautam, A. Bodek, in preparation)

- (note that QE has not been subtracted)

$Q^2 = 2\ \mathrm{GeV}^2$ Results for $\mathbf{R_A - R_d}$ and $\boldsymbol{\sigma_T^d} / \boldsymbol{\sigma_T^A}$

^{56}Fe



** ^{27}Al and ^{64}Cu coming soon

$R_C - R_d$: Compare **to Fermi motion calculation Bodek and Cai**
(to be published 2017). Uses effective spectral function (ESF): simulates Psi scaling includes SRC

2. A. Bodek, M. E. Christy and B, Coppersmith, Eur. Phys. J. C (2014) 74:3091

High momentum components affect R In a nucleus

$$W_{\mu\nu} = -W_1(\nu, q^2)\left[g_{\nu\mu} - \frac{q_\mu q\nu}{q^2}\right] + \frac{W_2(\nu, q^2)}{M^2}\left[p_\mu - \frac{M\nu}{q^2}q_\mu\right]\left[p_\mu - \frac{M\nu}{q^2}q_\mu\right]$$

$$W_1^S(q^2,\nu) = \int [W_1(q^2,\nu_w) + \frac{k_T^2}{2M^2}W_2(q^2,\nu_w)]|\phi(k)|^2\, d^3k$$

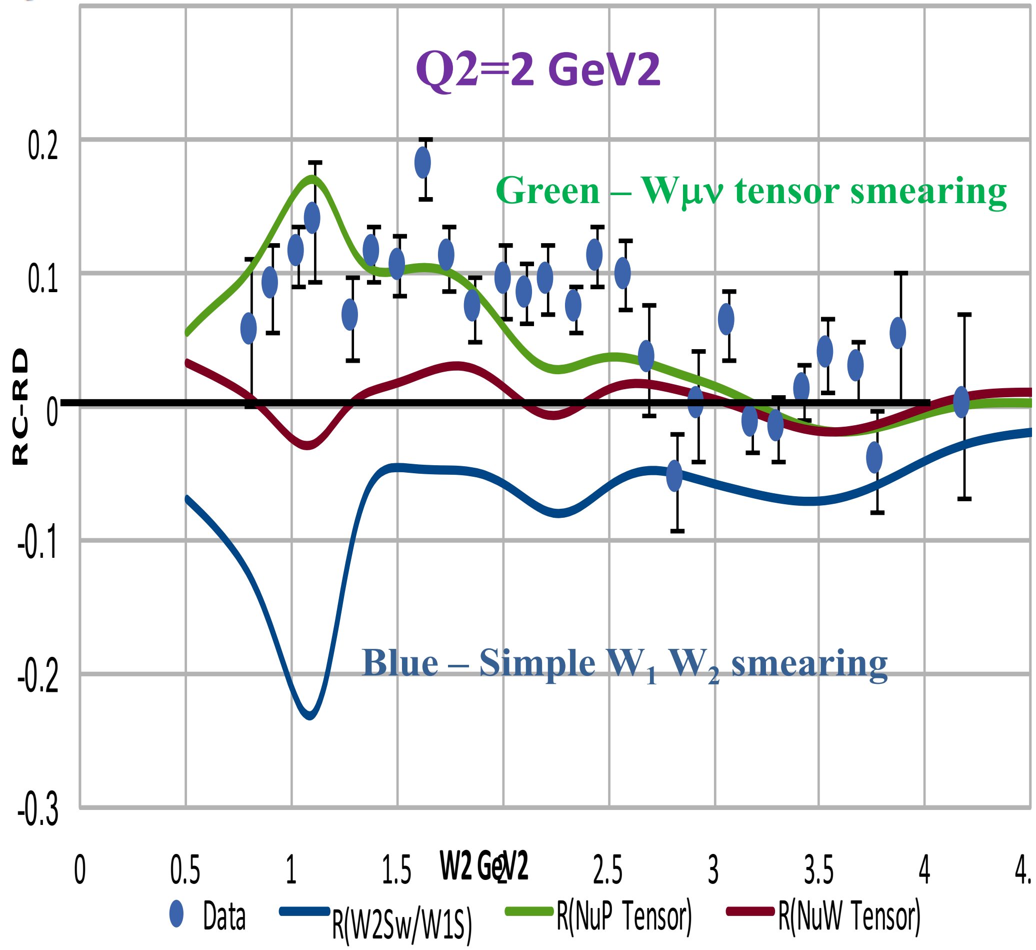
$$W_2^S(q^2,\nu) = \int W_2(q^2,\nu_w)\left[\left(\frac{\nu'}{\nu}\right)^2\left(1-\frac{k_z^2 q^2}{M\nu'|q|}\right)^2 - \frac{k_T^2}{2M^2}\frac{q^2}{|q|^2}\right]|\phi(k)|^2\, d^3k$$

$$W_3^S(q^2,\nu) = \int W_3(q^2,\nu_w)\left[\frac{Ei}{M} - \frac{k_z\nu}{M|q|}\right]|\phi(k)|^2\, d^3k$$

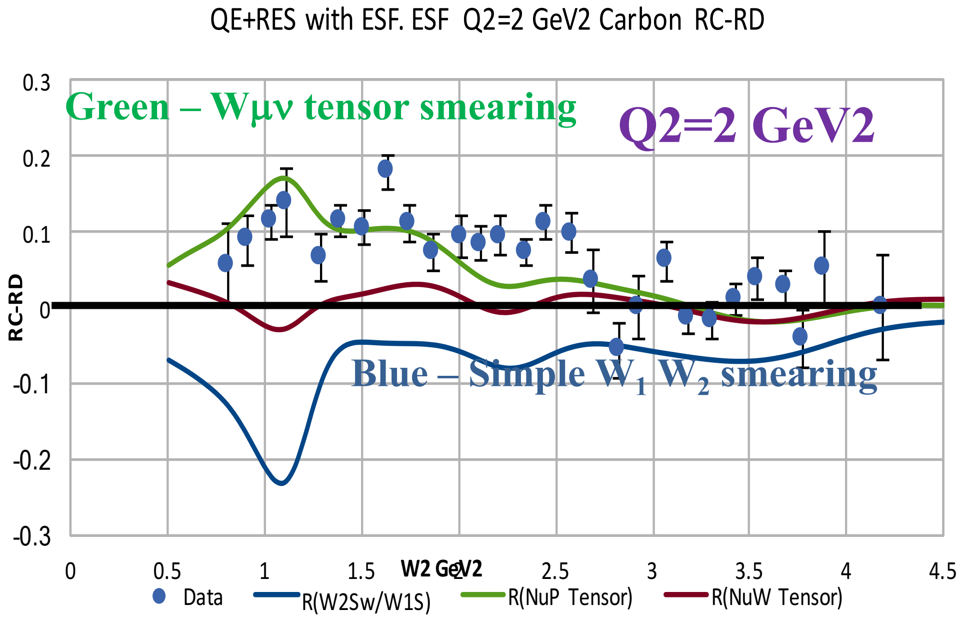
A. Bodek and J. L. Ritchie, Phys.Rev. D23, 1070 (1981).

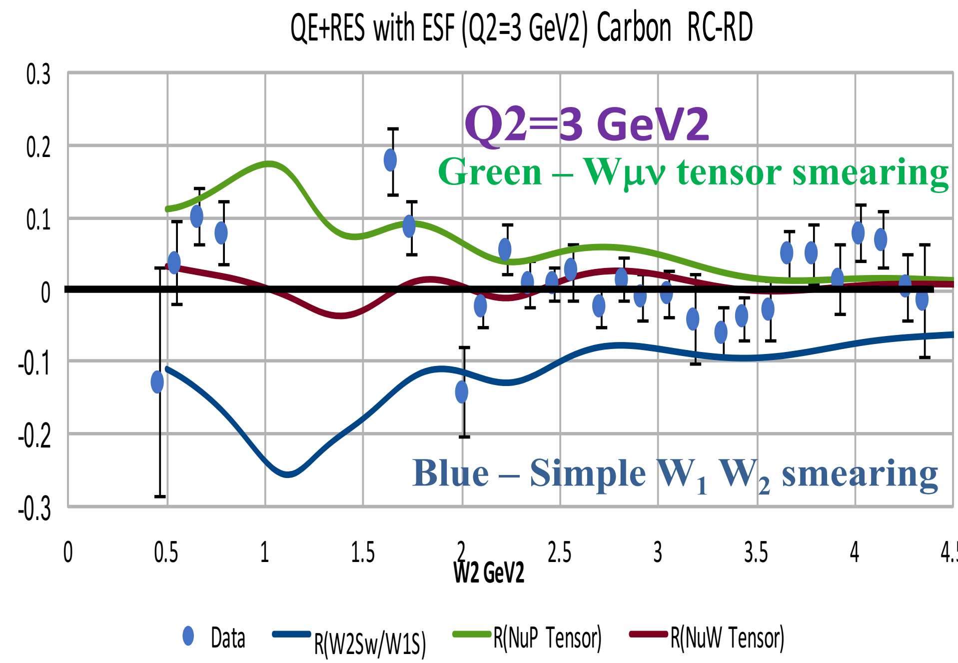
^{12}C

QE+RES with ESF. ESF Q2=2 GeV2 Carbon RC-RD



Green – Wμν tensor smearing
purple - Wμν tensor smearing with off-shell correction (from Q2=0)
Blue – Simple W_1 W_2 smearing





Green – Wμν tensor smearing

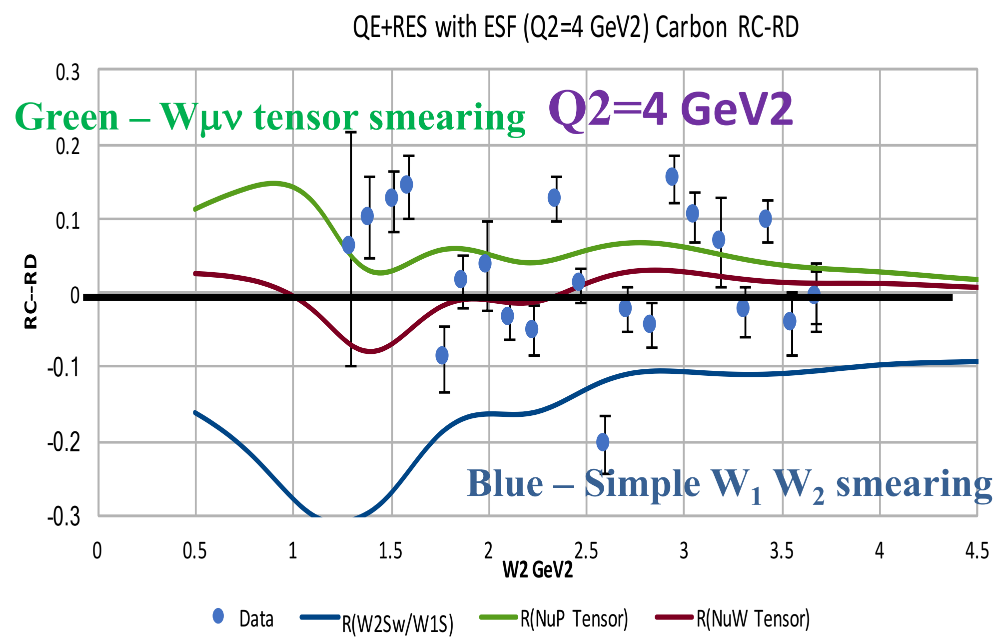
purple - Wμν tensor smearing
with off-shell correction (from Q2=0)

Blue – Simple W_1 W_2 smearing

Conclusion: Simple Fermi smearing does not work:

Low Q2 analysis –coming soon

^{12}C



RC-RD

Table 3. Sources of systematic error in the predicted inelastic contribution to the total cross section on iron (for $W > 1.8 GeV$). The change (positive or negative) in the neutrino, antineutrino and the $\sigma_{\bar{\nu}}/\sigma_\nu$ ratio that originate from a plus one standard deviation change in the ratio of transverse to longitudinal structure functions (R), the fraction of antiquarks ($f_{\bar{q}}$), the axial quark-antiquark sea, and the overall normalization of the structure functions (N).

source	change (error)	change in σ_ν	change in $\sigma_{\bar{\nu}}$	change in $\sigma_{\bar{\nu}}/\sigma_\nu$
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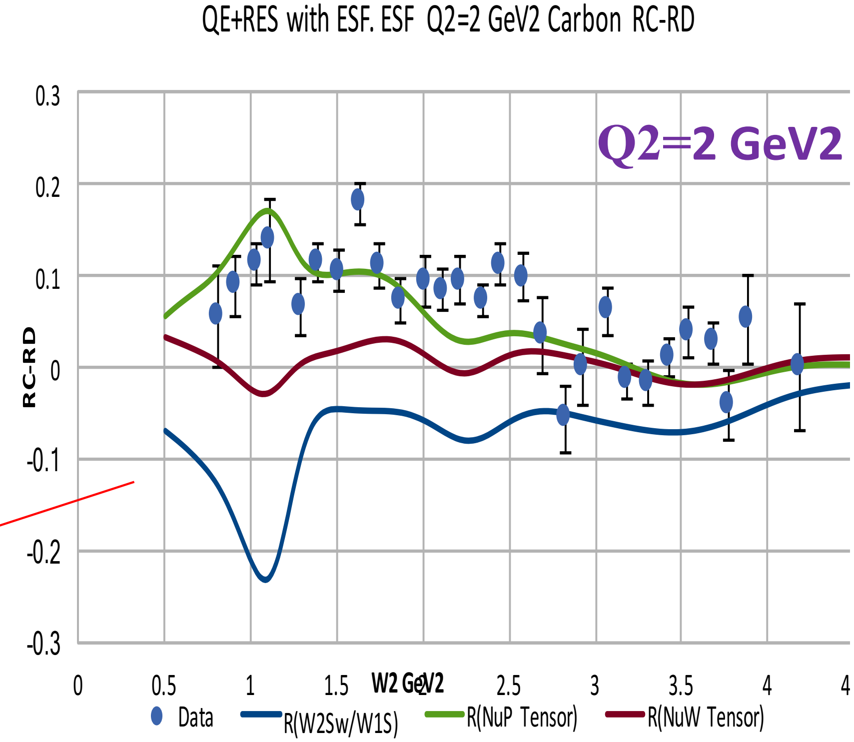
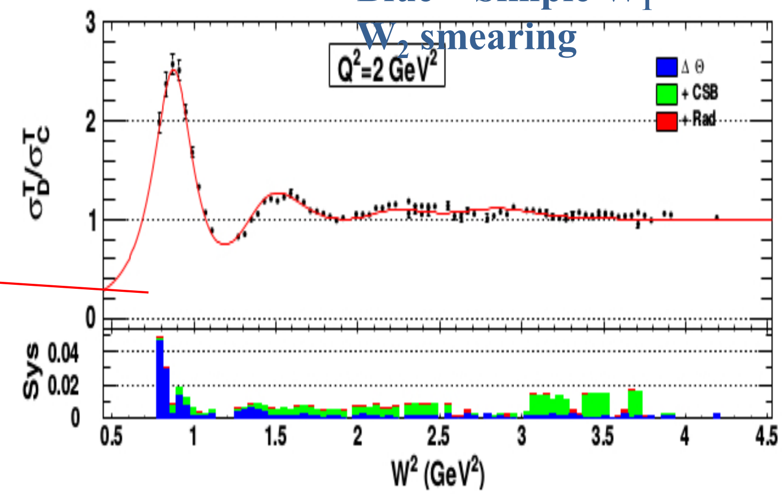
$f_{\bar{q}}$	+5%	-0.7%	+1.4%	+2.1%
$K^{axial} - K^{vector}$	+ 50%	+1.3%	+1.9%	+1.2%
N	+3%	+3%	+3%	0
Total		±3.4%	±4.3%	±2.5%





Future Plans

1. Publish higher Q^2 Phase II data. (Q^2 =2, 3, 4 GeV^2)
2. Study separation of QE and inelastic on R_A-R_d

3. Finalize low Q^2 Phase I data (**Q^2: 0.2 to 2.5**) near end of 2017.

→ adds additional ε points at $2 < Q^2 < 3$

=> reduced systematics in higher Q^2 data

→ allows study of Q^2 dependence for R_A-R_d

→ Look for evidence of Miller's nuclear pions

4 Precise measurement of absolute W1 and W2 and ratio to Deuterium.

Extra Slides

Experimental Investigation of the Structure Functions of Bound Nucleons

V. Mamyan,[27] I. Albayrak,[11] A. Ahmidouch,[22] J. Arrington,[1] A. Asaturyan,[31] A. Bodek,[24] P. Bosted,[29] R. Bradford,[1,24] E. Brash,[3] A. Bruell,[5] C Butuceanu,[23] M. E. Christy,[11] S. J. Coleman,[29] M. Commisso,[27] S. H. Connell,[9] M. M. Dalton,[27] S. Danagoulian,[22] A. Daniel,[12] D. B. Day,[27] S. Dhamija,[7] J. Dunne,[18] D. Dutta,[18] R. Ent,[8] D. Gaskell,[8] A. Gasparian,[22] R. Gran,[17] T. Horn,[8] Liting Huang,[11] G. M. Huber,[23] C. Jayalath,[11] M. Johnson,[1,21] M. K. Jones,[8] N. Kalantarians,[12] A. Liyanage,[11] C. E. Keppel,[11] E. Kinney,[4] Y. Li,[11] S. Malace,[6] S. Manly,[24] P. Markowitz,[7] J. Maxwell,[27] N. N. Mbianda,[9] K. S. McFarland,[24] M. Meziane,[29] Z. E. Meziani,[26] G. B Mills,[15] H. Mkrtchyan,[31] A. Mkrtchyan,[31] J. Mulholland,[27] J. Nelson,[29] G. Niculescu,[10] I. Niculescu,[10] L. Pentchev,[29] A. Puckett,[16,15] V. Punjabi,[20] I. A. Qattan,[13] P. E. Reimer,[1] J. Reinhold,[7] V. M Rodriguez,[12] O. Rondon-Aramayo,[27] M. Sakuda,[14] W. K. Sakumoto,[24] E. Segbefia,[11] T. Seva,[32] I. Sick,[2] K. Slifer,[19] G. R Smith,[8] J. Steinman,[24] P. Solvignon,[1] V. Tadevosyan,[31] S. Tajima,[27] V. Tvaskis,[30] G. R. Smith,[8] W. F. Vulcan,[8] T. Walton,[11] F. R Wesselmann,[20] S. A. Wood,[8] and Zhihong Ye[11]
(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?

special thanks to
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V. Mamyan,, University of Virginia,
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Focus of this talk will be the 6 GeV program in JLab Hall C to separate all unpolarized structure functions: **F_1, F_2, F_L**

Kinematic coverage: **$0.3 < Q^2 < 4$**

$W^2 < 4$ (Resonance Region, RR)

Targets: **proton, deuteron, ^{12}C, ^{27}Al, ^{56}Fe, ^{64}Cu**

Electron scattering

$$\frac{d^2\sigma}{d\Omega dE'}(E_0, E', \theta) = \frac{4\alpha^2 E'^2}{Q^4}\cos^2(\theta/2)$$

$$\times\left[\mathcal{F}_2(x,Q^2)/\nu + 2\tan^2(\theta/2)\mathcal{F}_1(x,Q^2)/M\right],$$

$$\frac{d^2\sigma}{d\Omega dE'} = \Gamma\left[\sigma_T(x,Q^2) + \epsilon\sigma_L(x,Q^2)\right],$$

where

$$\Gamma = \frac{\alpha K E'}{4\pi^2 Q^2 E_0}\left(\frac{2}{1-\epsilon}\right)$$

$$K = \frac{Q^2(1-x)}{2Mx} = \frac{2M\nu - Q^2}{2M}$$

$$\epsilon = \left[1 + 2\left(1+\frac{Q^2}{4M^2x^2}\right)tan^2\frac{\theta}{2}\right]^{-1}.$$

$$\epsilon = \frac{1 - y - Q^2/(4E_0^2)}{1 - y + y^2/2 + Q^2/(4E_0^2)},$$

which in the limit of $Q^2 << E_0^2$ is approximately

$$\epsilon = \frac{2(1-y)}{2(1-y)+y^2}.$$

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

Electron scattering continued

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

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

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

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

or

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

In addition, $2x\mathcal{F}_1$ is given by

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

or equivalently

$$\mathcal{W}_1(x,Q^2) = \mathcal{W}_2(x,Q^2) \times \frac{1+\nu^2/Q^2}{1+\mathcal{R}(x,Q^2)}.$$

Neutrino Vector quark-hadron duality

ing expressions: $\mathcal{F}_2 = 2x[q(x,Q^2)+\overline{q}(x,Q^2)]$ and $x\mathcal{F}_3 = 2x[q(x,Q^2)-\overline{q}(x,Q^2)]$. We define $Q = \int_0^1 2x[q(x,Q^2)]dx$

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2ME}{\pi} \times \left(\left[1-y(1+\frac{Mx}{2E})+\frac{y^2}{2}\frac{1+Q^2/\nu^2}{1+\mathcal{R}(x,Q^2)}\right]\mathcal{F}_2 \pm \left[y-\frac{y^2}{2}\right]x\mathcal{F}_3\right). \quad (48)$$

or

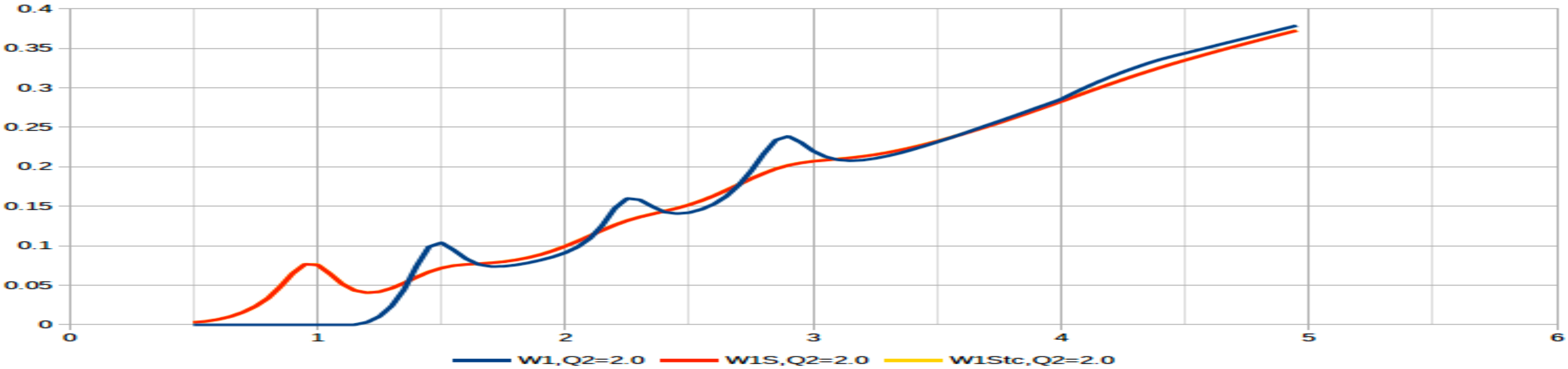
$$\frac{d^2\sigma^{\nu}}{dxdy} = \frac{G_F^2ME}{\pi}\Big(Q(x,Q^2)+(1-y)^2\overline{Q}(x,Q^2) - \frac{y^2}{2}\frac{\mathcal{R}(x,Q^2)}{1+\mathcal{R}(x,Q^2)}(Q+\overline{Q}) + \left[-\frac{Mxy}{2E}+\frac{Mxy/E}{1+\mathcal{R}(x,Q^2)}\right](Q+\overline{Q})\Big). \quad (49)$$

and

$$\frac{d^2\sigma^{\overline{\nu}}}{dxdy} = \frac{G_F^2ME}{\pi}\Big(\overline{Q}(x,Q^2)+(1-y)^2 Q(x,Q^2) - \frac{y^2}{2}\frac{\mathcal{R}(x,Q^2)}{1+\mathcal{R}(x,Q^2)}(Q+\overline{Q}) + \left[-\frac{Mxy}{2E}+\frac{Mxy/E}{1+\mathcal{R}(x,Q^2)}\right](Q+\overline{Q})\Big). \quad (50)$$

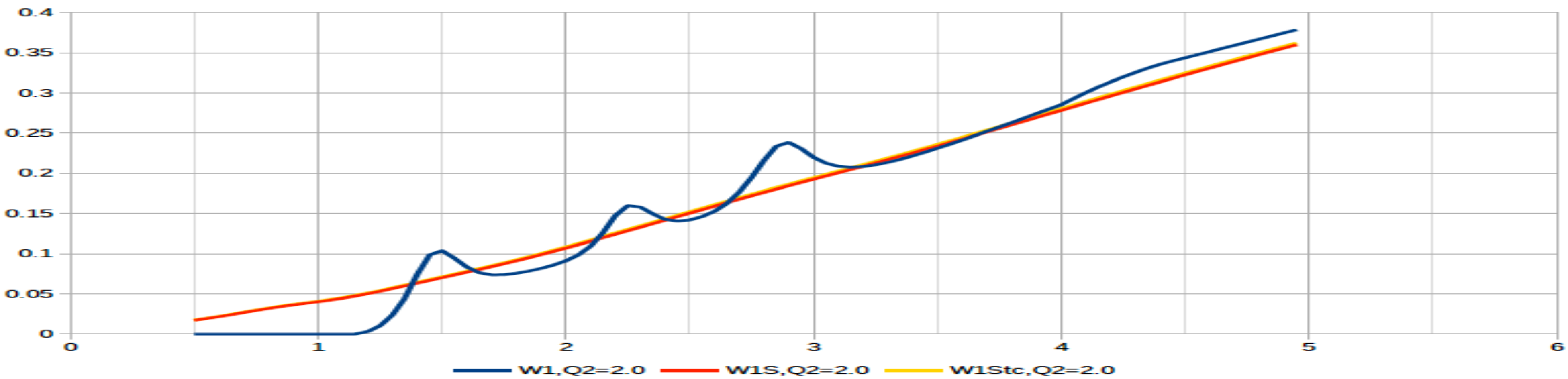
QE_ESF:D

RedLDeuterium W1
Q2=2 GeV2



QE_ESF:C12

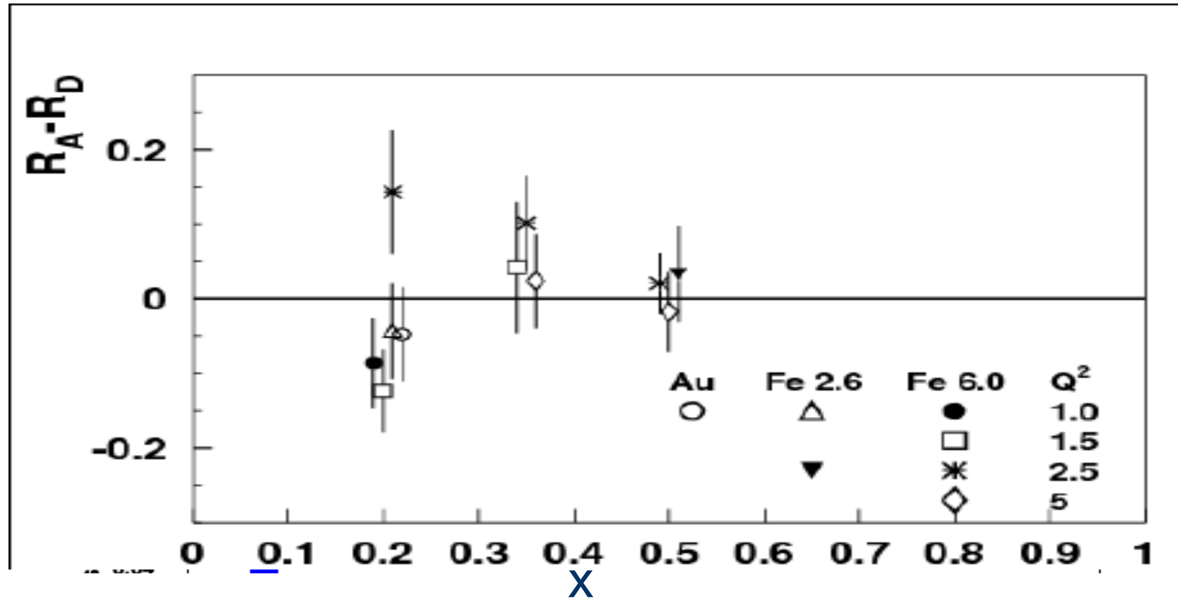
Red: Carbon W1
Q2=2 GeV2



New Hall C data provides
1^{st} determination of R_A-R_d
In resonance region

→ Large # of data points
Comparable to E140

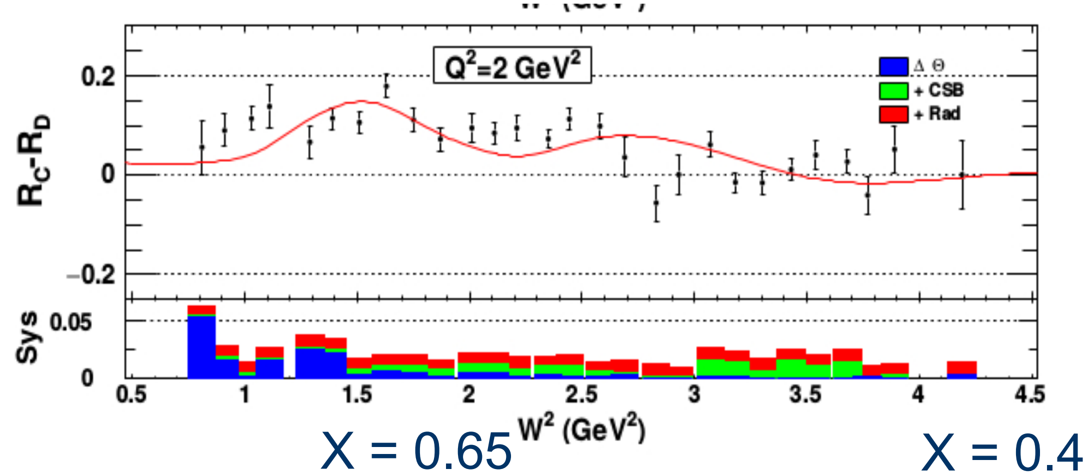
→ Improved extractions
at $Q^2 < 3$ in future
Including phase I data



Future studies:

- Duality in separated SFs
and EMC effect

- Moments of nuclar SFs



Deep inelastic neutrino total cross section are relatively well known. The following are systematic errors in the high energy DIS total cross sections for W>1.8 GeV (Bodek-Yang)

Integrating over y, The cross sections for neutrino (anti-neutrino) can then be approximately expressed in terms of (on average) the fraction antiquarks $f_{\overline{Q}} = \overline{Q}/(Q+\overline{Q})$ in the nucleon, and (on average) the ratio of longitudinal to transverse cross sections $\mathcal{R}$ as follows:

$$\frac{d\sigma(\nu N)}{dx} \approx \frac{G_F^2 ME}{\pi}(Q+\overline{Q})\left[(1-f_{\overline{Q}})+\frac{1}{3}f_{\overline{Q}}-\frac{1}{6}\mathcal{R}\right], \quad (51)$$

and

$$\frac{d\sigma(\overline{\nu} N)}{dx} \approx \frac{G_F^2 ME}{\pi}(Q+\overline{Q})\left[\frac{1}{3}(1-f_{\overline{Q}})+f_{\overline{Q}}-\frac{1}{6}\mathcal{R}\right]. \quad (52)$$

With $\langle\mathcal{R}\rangle = 0.2$ and $\langle f_{\overline{Q}}\rangle = 0.1725$, we obtain $\langle\sigma_{\overline{\nu}}/\sigma_{\nu}\rangle = 0.487$, which is the world's experimental average value in the 30-50 GeV energy range. The above expressions are used to estimate the systematic error in the cross section originating from uncertainties in $\mathcal{R}$ and $f_{\overline{q}}$ (as shown in Table 3).

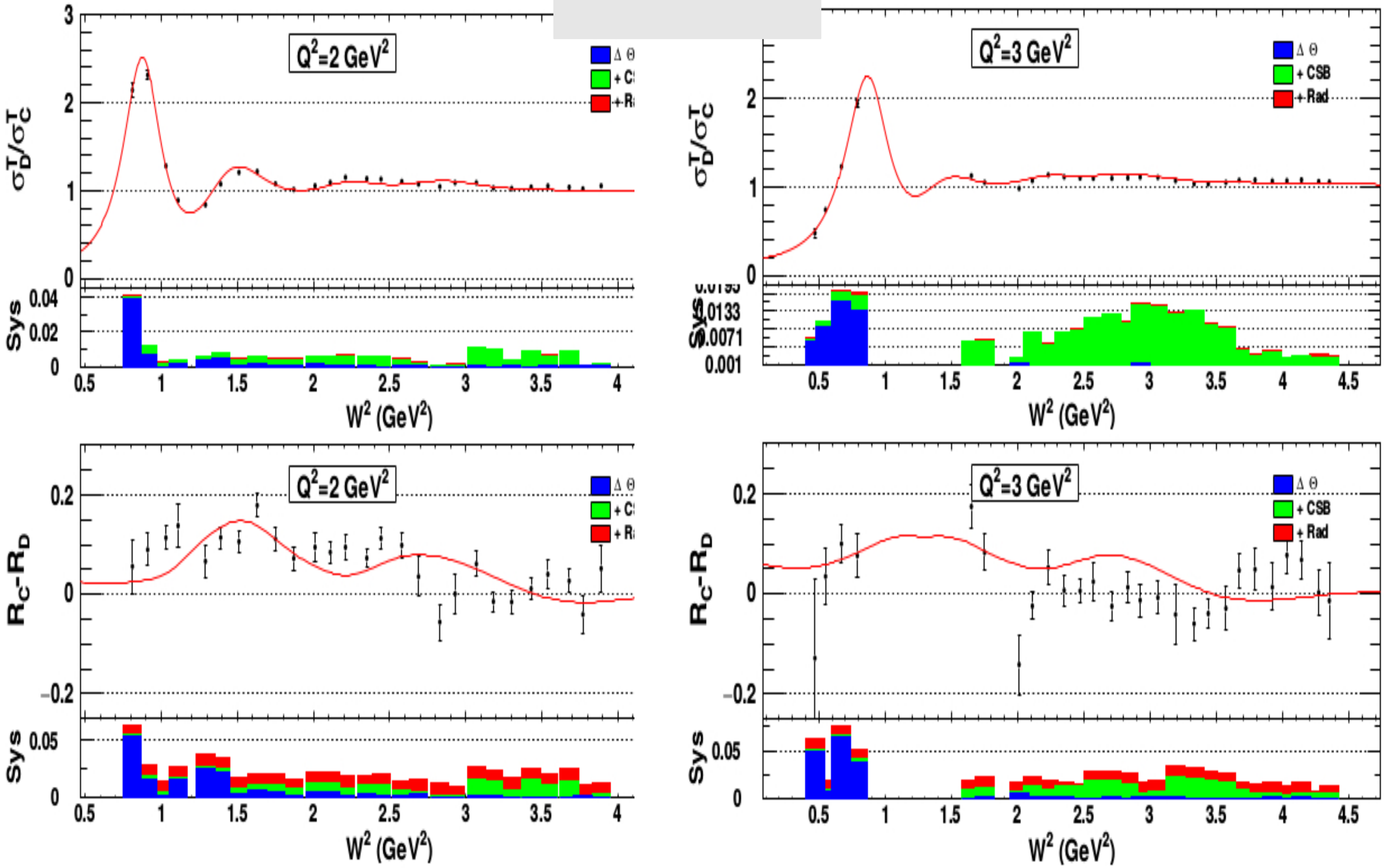
Table 3. Sources of systematic error in the predicted inelastic contribution to the total cross section on iron (for $W > 1.8GeV$). The change (positive or negative) in the neutrino, antineutrino and the $\sigma_{\overline{\nu}}/\sigma_{\nu}$ ratio that originate from a plus one standard deviation change in the ratio of transverse to longitudinal structure functions (R), the fraction of antiquarks ($f_{\overline{q}}$), the axial quark-antiquark sea, and the overall normalization of the structure functions (N).

source	change (error)	change in σ_{ν}	change in $\sigma_{\overline{\nu}}$	change in $\sigma_{\overline{\nu}}/\sigma_{\nu}$
R	-0.05	+1.0%	+2.0%	+1%
$f_{\overline{q}}$	+5%	-0.7%	+1.4%	+2.1%
$K^{axial}-K^{vector}$	+ 50%	+1.3%	+1.9%	+1.2%
N	+3%	+3%	+3%	0
Total		±3.4%	±4.3%	±2.5%

We want to achieve similar precision in the resonance region (RR) on H, D and nuclear targets, and also low Q inelastic,

$Q^2 = 2\ GeV^2$ Results for $\mathbf{R_A - R_d}$ and $\boldsymbol{\sigma_T}^{d}$ / $\boldsymbol{\sigma}\ _{T}^{A}$ ^{12}C

Rebinned



Fermi motion and off-shell corrections to nucleons bound in nuclei

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A. Bodek, Phys. Rev. D8 (1973) 2331**;** A. Bodek et al., Phys. Rev. D 20, 1471 (1979).
- off-shell corrections

Impulse approximation

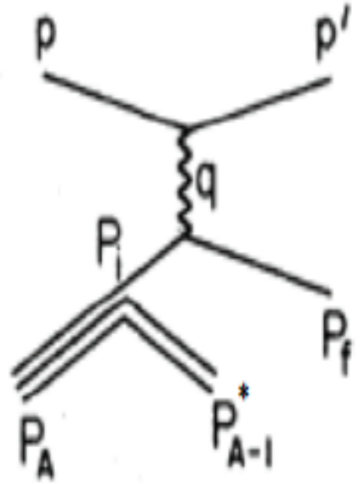

Fig. 1. 1p1h process: Scattering from an off-shell bound proton of momentum $\mathbf{P_i} = \mathbf{k}$ in a nucleus of mass A. The on-shell recoil excited $[A-1]^*$ spectator nucleus has a momentum $\mathbf{P^*_{A-1}} = \mathbf{P_s} = -\mathbf{k}$. The off-shell energy of the interacting nucleon is $E_i = M_A - \sqrt{(M_{A-1}*)^2 + k^2} = M_A - \sqrt{(M_{A-1} + \mathbf{E_x})^2 + k^2}$, where $\mathbf{E_x}$ is the excitation energy of the $[A-1]^*$ spectator nucleus.

$$P_i = (E_i, \boldsymbol{k}) = (M - \epsilon, \boldsymbol{k})$$

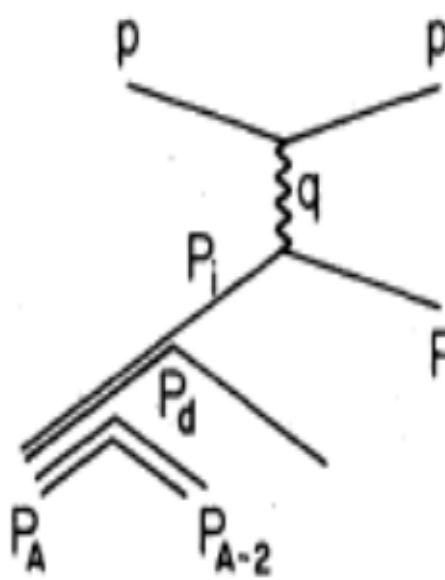

Fig. 2. 2p2h process: Scattering from an off-shell bound neutron of momentum $\mathbf{P_i} = -\mathbf{k}$ from two nucleon short range correlations (quasi-deuteron). There is an on-shell spectator (A-2)* on-shell nucleus and an on-shell spectator recoil nucleon with momentum $\mathbf{P_s} = \mathbf{k}$. The energy of the interacting off-shell nucleus is $E_i^P(SRC) = M_D - \sqrt{M_N + k^2} - \Delta^{N+P}_{SRC}$

The hadronic tensor for a target of mass M is given by:

$$W_{\mu\nu} = -\mathcal{W}_1(\nu, q^2)\Big[g_{\nu\mu} - \frac{q_\mu q_\nu}{q^2}\Big] + \frac{\mathcal{W}_2(\nu, q^2)}{M^2}\Big[p_\mu - \frac{M\nu}{q^2}q_\mu\Big]\Big[p_\mu - \frac{M\nu}{q^2}q_\mu\Big] \quad (16)$$

Where $g_{\mu\mu} = (-1, -1, -1, +1)$.

We use the Atwood-West[2] Fermi smearing formalism for electron scattering on deuterium which has been extended to neutrino scattering on nuclear targets by Bodek and Ritchie[3]. We starts with the following relation between the hadronic tensor for a nucleus and the hadron tensor of bound nucleons.

$$W^A_{\mu\nu}(q^2,\nu) = Z\ W^{p-S}_{\mu\nu}(q^2,\nu) + N\ W^{n-S}_{\mu\nu}(q^2,\nu) \quad (17)$$

$$W^S_{\mu\nu}(q^2,\nu) = \int W_{\mu\nu}(q^2,\nu_w)|\phi(k)|^2\ d^3k$$

Equating the xx (11) components of the smeared tensor we get the following expression for the smeared structure function $\mathcal{W}_1$.

$$\mathcal{W}_1^S(q^2,\nu) = \int [\mathcal{W}_1(q^2,\nu_w) + \frac{k_T^2}{2M^2}\mathcal{W}_2(q^2,\nu_w)]|\phi(k)|^2\ d^3k \quad (18)$$

Where, k_T is the transverse momentum of the nucleon with respect to the virtual photon ($|\boldsymbol{q}| = q_z = q_3$) direction.

Equating the 33 (zz) component and also using equation 18 we get the following expression for the smeared structure function $\mathcal{W}_2$.

large -->

$$\mathcal{W}_2^S(q^2,\nu) = \int \mathcal{W}_2(q^2,\nu_w)\Big[\big(\frac{\nu'}{\nu}\big)^2\Big(1 - \frac{k_z^2 q^2}{M\nu'|\boldsymbol{q}|}\Big)^2 - \frac{k_T^2}{2M^2}\frac{q^2}{|\boldsymbol{q}|^2}\Big]|\phi(k)|^2\ d^3k \quad (19)$$

Small -->

For neutrino scattering one can derive[3] the following expression for $\mathcal{W}_3$.

$$\mathcal{W}_3^S(q^2,\nu) = \int \mathcal{W}_3(q^2,\nu_w)\Big[\frac{Ei}{M} - \frac{k_z\nu}{M|\boldsymbol{q}|}\Big]|\phi(k)|^2\ d^3k$$

Identifying the bound structure functions as functions of (Q^2, W') or equivalently (Q^2, ν_w) ensures energy conservation. However, gauge conservation is violated. One can restore gauge conservation by adding off-shell corrections to the structure functions, but there is no unique way of doing it. The above expressions yield a non-zero value of $R_{nucleus}=\sigma_L/\sigma_T$ at $Q^2 = 0$. Bodek (1973) showed introducing an off-shell correction to W_2 (e.g. replacing ν' with ν_W the above equations) results in $R_{nucleus}=0$ at $Q^2 = 0$.

We investigate three cases: (1) No tensor corrections, (2) With tensor corrections using ν', and (3) Applying off-shell corrections by replacing ν' with ν_w in the smearing equations.

Here, $P_i = (E_i, \boldsymbol{k}) = (M - \epsilon, \boldsymbol{k})$

$$
\begin{aligned}
P_i^2 &= E_i^2 - k^2 \qquad (20)\\
W'^2 &= P_i^2 + 2P_i * q - Q^2\\
\nu' &= P_i * q/M = (E_i\nu - |\boldsymbol{q}|k_3)/M\\
\nu' &= \frac{W'^2 - P_i^2 + Q^2}{2M}\\
\nu_w &= \frac{W'^2 - M^2 + Q^2}{2M}\\
\nu_w &= \nu' + \frac{P_i^2 - M^2}{2M}
\end{aligned}
$$

$$
\mathcal{W}_1^S(q^2,\nu) = \int [\mathcal{W}_1(q^2,\nu_w) + \frac{k_T^2}{2M^2}\mathcal{W}_2(q^2,\nu_w)] |\phi(k)|^2 \, d^3k
$$

$$
\mathcal{W}_2^S(q^2,\nu) = \int \mathcal{W}_2(q^2,\nu_w)\Big[(\frac{\nu'}{\nu})^2\Big(1 - \frac{k_z^2 q^2}{M\nu'|\boldsymbol{q}|}\Big)^2 - \frac{k_T^2}{2M^2}\frac{q^2}{|\boldsymbol{q}|^2}\Big] |\phi(k)|^2 \, d^3k
$$

Our studies indicate:

(1) The tensor corrections are essential at all Q2.

(2) The off-shell corrections are large at low Q2, and are smaller at higher Q2.

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

$$\mathcal{F}_{2,LO}^{e/\mu}(x,Q^2) = \Sigma_i e_i^2 \left[x q_i(x,Q^2) + x\overline{q}_i(x,Q^2) \right].$$

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 ν) is EXACT for the Adler sum rule down to Q2=0 only for the Structure Function F2.

F2 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 F2.

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 ν_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 Q2.
- Target mass effects (+ quark transverse momentum) which dominate at high x and intermediate Q2 (Jlab energy range).
- Higher twist effects which dominate near Q2=0.
- **In QCD 2XF1 is derived from F2 by the subtraction of FL.**

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

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

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 F2, R and F1 (and also in F3 if we include neutrino scattering).