Hall C Inclusive Experiments:

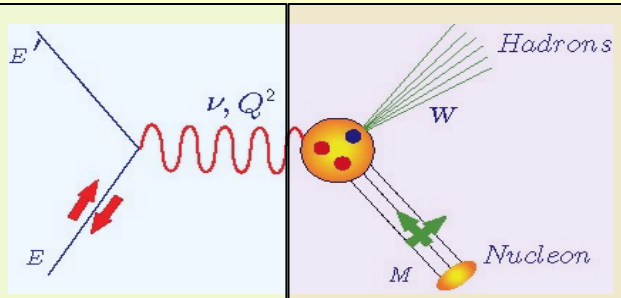
Experimental status of the longitudinal structure of the Protons, Neutrons, and Nuclei

Eric Christy

Hampton University

HallC Winter Workshop, January 14, 2012

Scattering with longitudinal photons



Calculable in Quantum Electrodynamics (QED)

Physics of interest (proton/neutron structure)

Polarization (Relative flux of longitudinal photons)

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

Flux of transverse photons

Transverse cross section

Longitudinal cross section

$$R = \sigma_L / \sigma_T$$

	$\sigma_T \propto$	$\sigma_L \propto$
Elastic scattering:	$G_M^2(Q^2)$	$G_E^2(Q^2)$
Inelastic scattering:	$F_1(x,Q^2)$	$F_L(x,Q^2)$

$Q^2 \to \infty$, $F_L \to 0$ (helicity conservation – spin ½ quarks, no transverse momentum)

$Q^2 \to 0$, $F_L \to Q^4$ (current conservation)

Lots of new F_L (R) data from Jlab Hall C

Experiment	target(s)	W range	Q^2 range	Status
E94-110	p	RR	0.3 - 4.5	nucl-ex/0410027
E99-118	p,d	DIS	0.1 - 1.7	PRL98:14301
E00-002	p,d	DIS+RR	0.25 - 1.5	Publication drafted
E02-109	d	RR+QE	0.2 - 2.5	Finalizing analysis
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Hope to publish all main physics results by 2012

Reminder: separation transverse from longitudinal structure

Reduced cross-section:

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

- **Fit linearly with ε at fixed W^2 and Q^2 (or x, Q^2).**

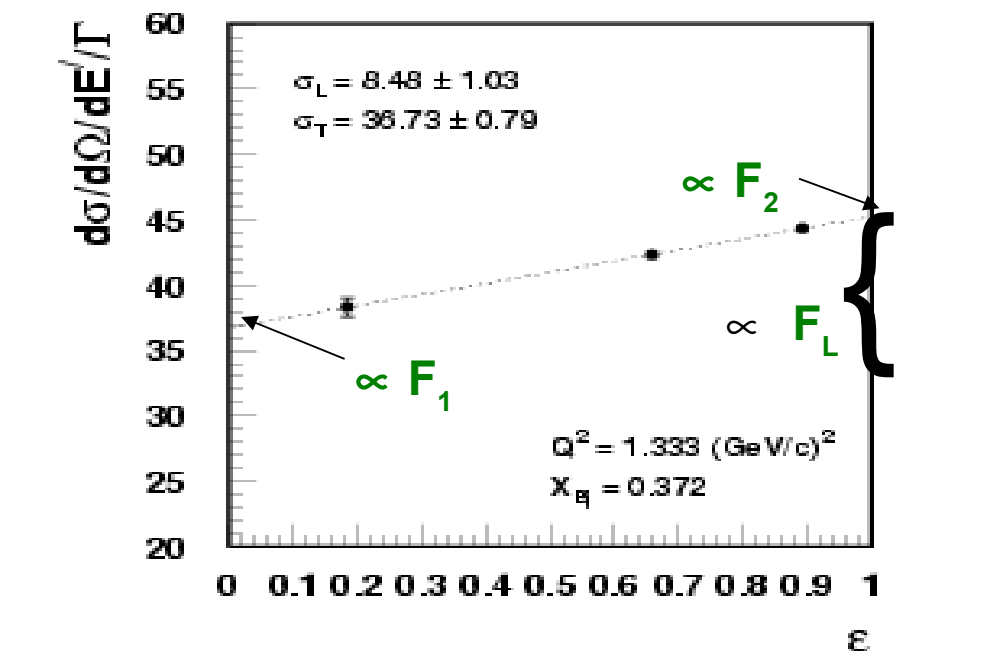
σ_L = Slope

σ_T = Intercept

$F_2 = (F_L + 2xF_1)/(1+\nu^2/Q^2)$

Extraction of F_2 depends on F_L and ε !

Important for Jlab kinematics

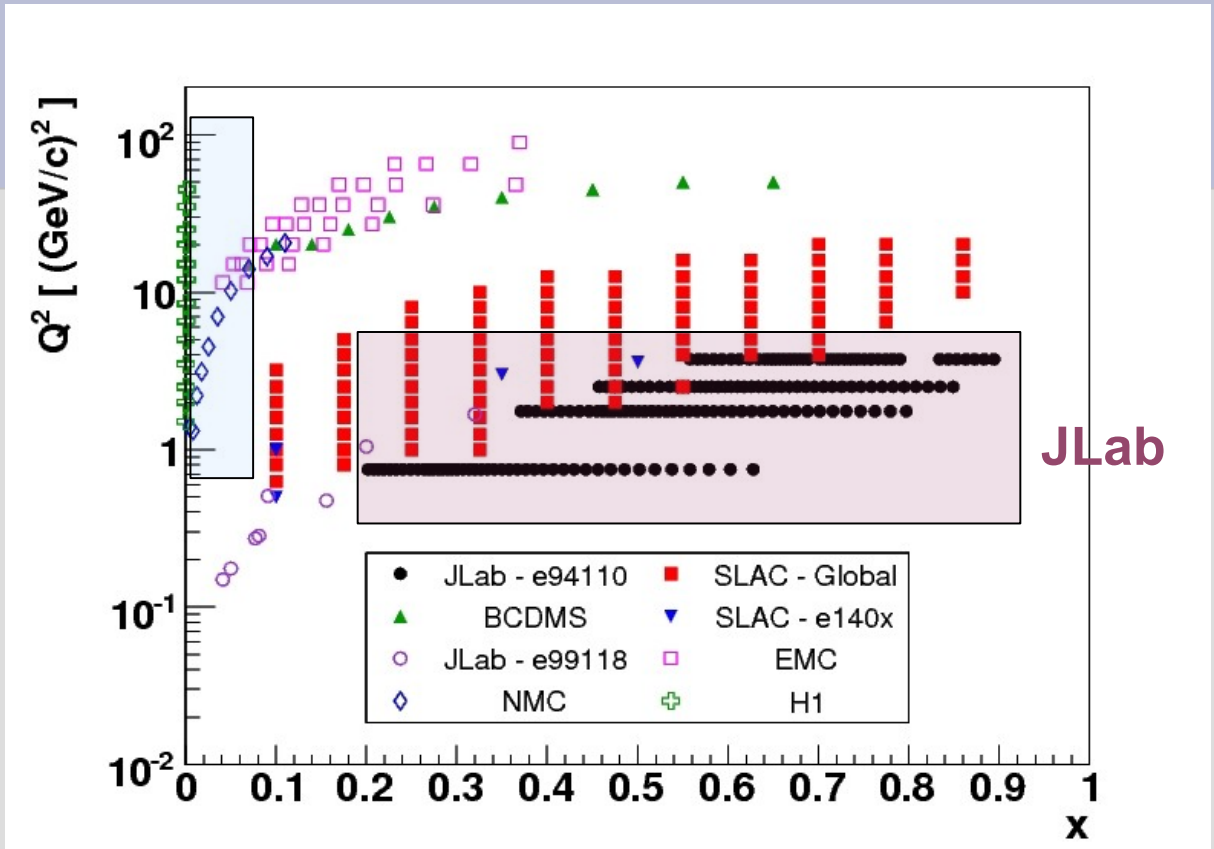


→ need 1-2% uncertainties pt-pt in ε to provide 15-20% δR ($\delta F_L/F_L$)

→ also requires multiple beam energies and spectrometer settings for multiple ε.

Very challenging experimentally!

Status of F_L proton data



→ Nearly all experiments (with exception of HERA H1 / Zeus) has **deuterium** data.

→ Good coverage in x below Q^2 ~40 GeV/c^2

→ New **HERA** (H1 shown + Zeus) data at small x and **JLab** at low Q^2 large x
(mainly resonance region at 6 GeV)

E94-110: proton F_L in resonance region

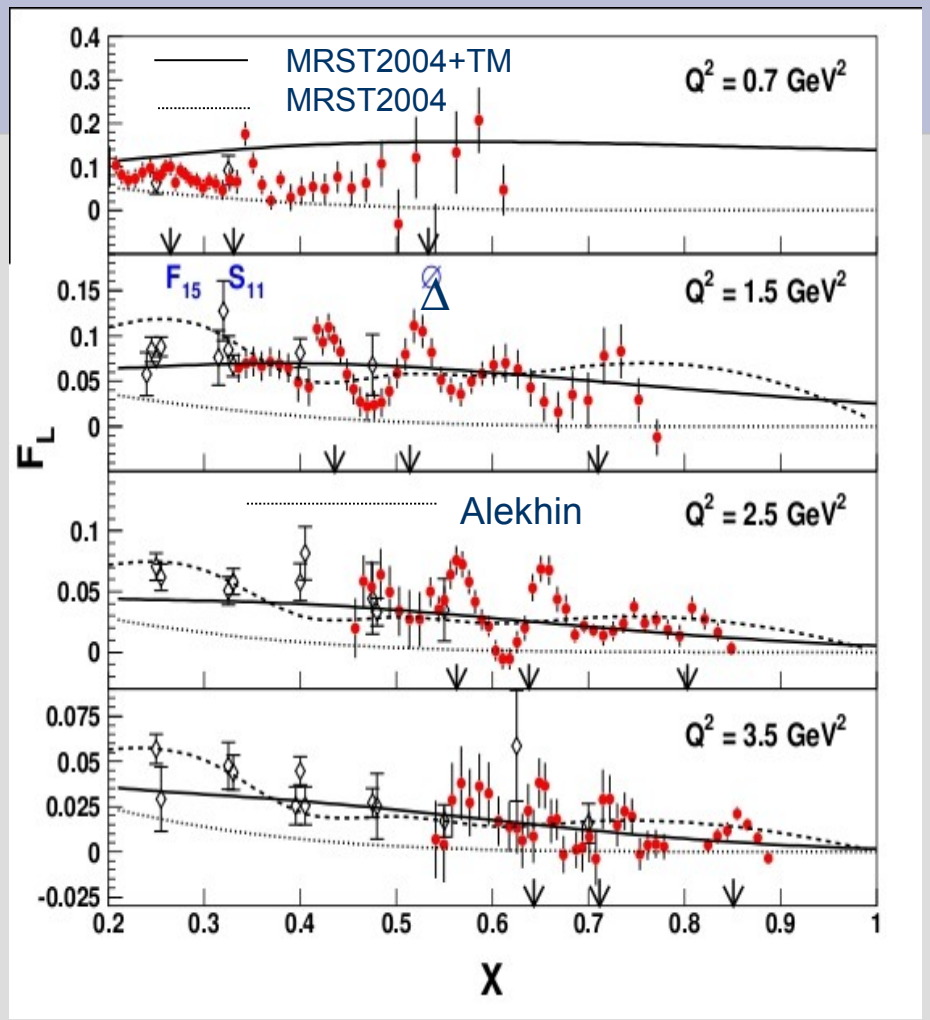
→ ~200 individual L/T separations.

→ Among most precise ever performed.

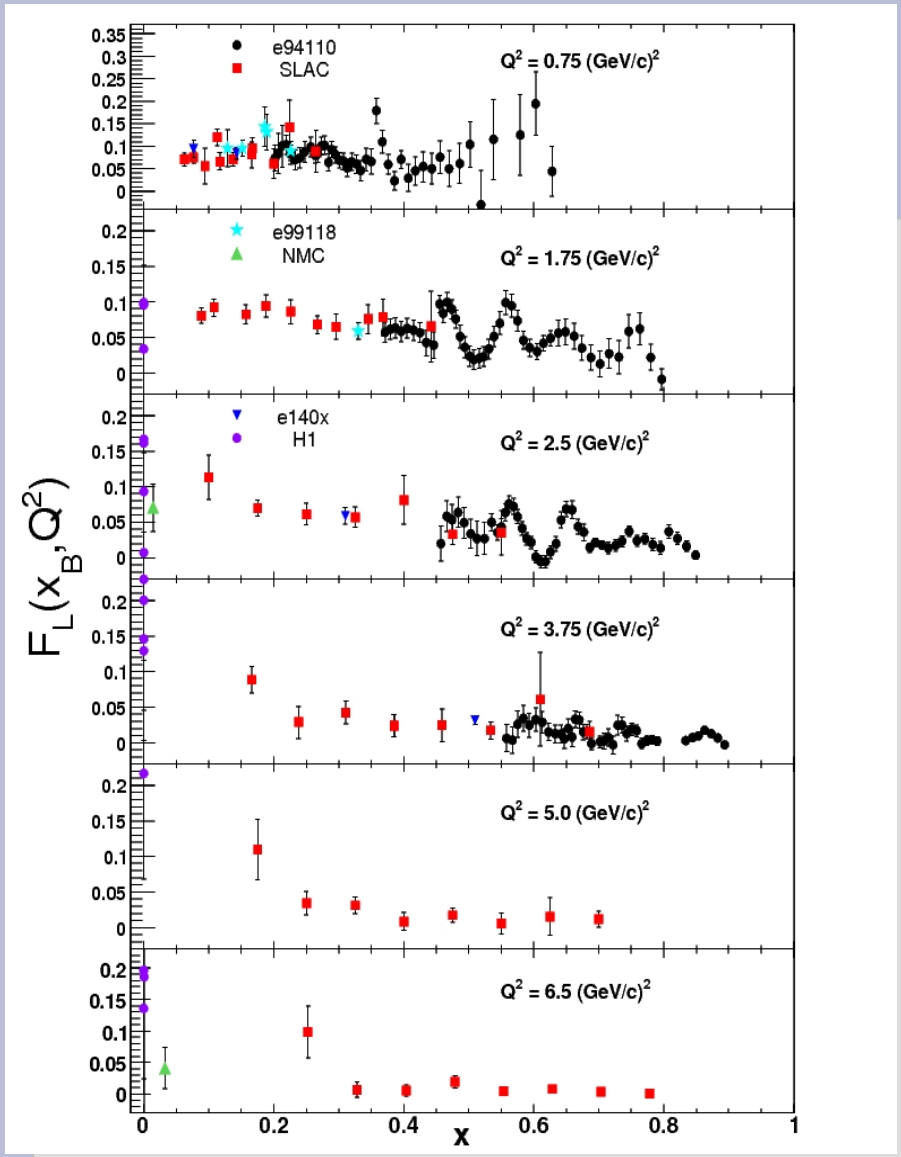
→ First observation of quark-hadron duality in F_L.

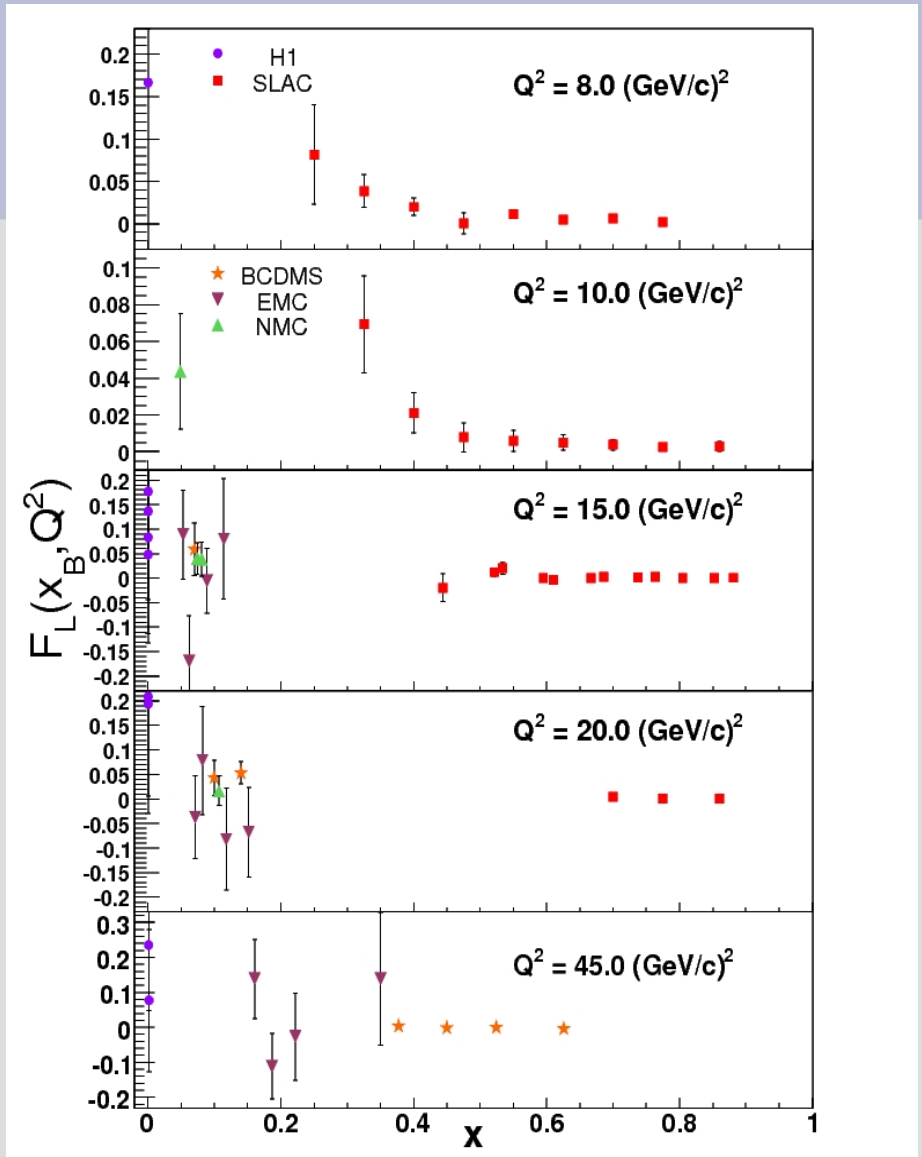
While resonance structure is clearly observed, resonance dips and peaks oscillate about scaling curve describing DIS.

- pQCD curves from MRST2004 and Alekhin parton distribution function (PDF) fits +TM.



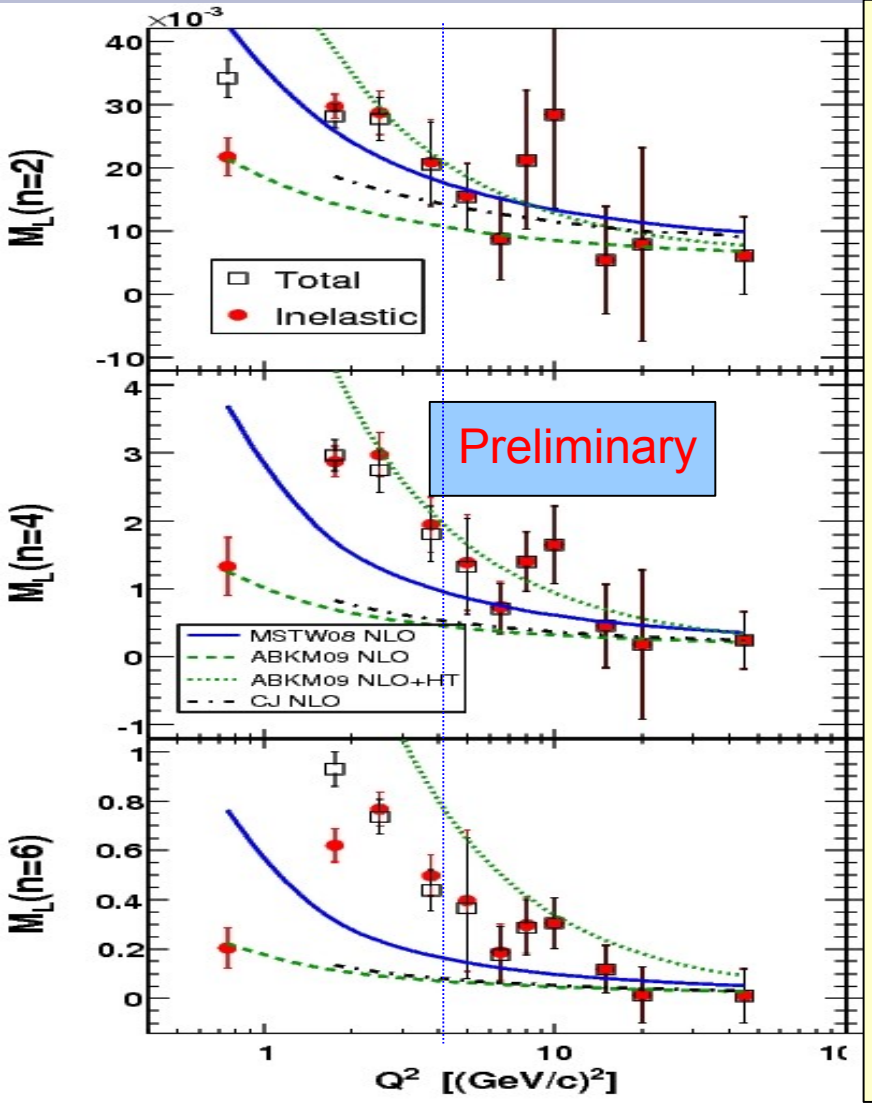
Global status of the Proton F_L data





Proton F_L Nachtmann Moments to low Q^2

P. Monaghan, A. Accardi, M.E.C, C.E. Keppel, W. Melnitchouk, L. Zhu (*in preparation*)



→ Inclusion of precision JLab data results in small uncertainties at $Q^2 < 4$.

→→ Contribution at x=1 ($\xi < 1$) from elastic form factors is increasingly large for small Q^2, but small above $Q^2 = 2$.

→ Turn over at low Q^2 due to pion production threshold appearing at smaller x for small Q^2.

Proton Results utilized by many other experiments and physics studies

→ R results utilized in extracting spin structure functions from asymmetries.

→ quantitative duality studies.

→ Global fits to resonance region F_2, F_L

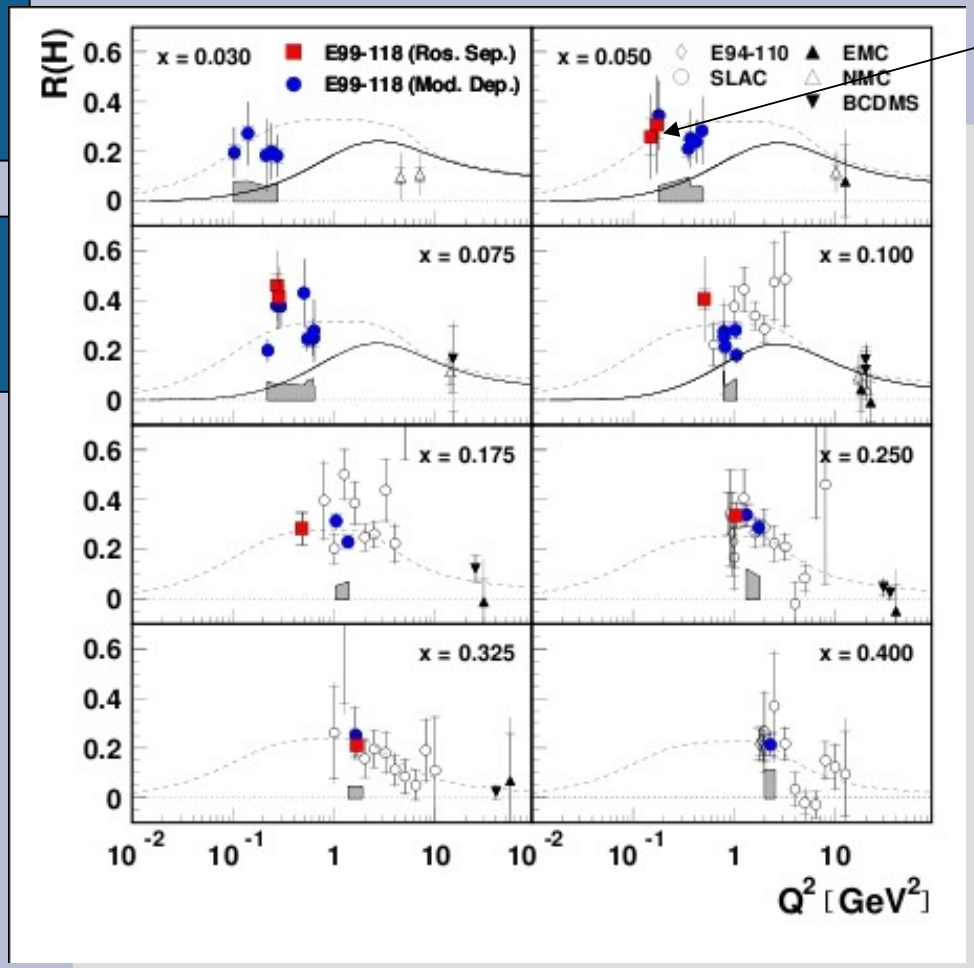
I. Input for radiative corrections

II. Structure function moments

III. BONUS extraction of F_2^n

Proton F_L and R_d-R_p small $Q^2 \rightarrow 0$ and x

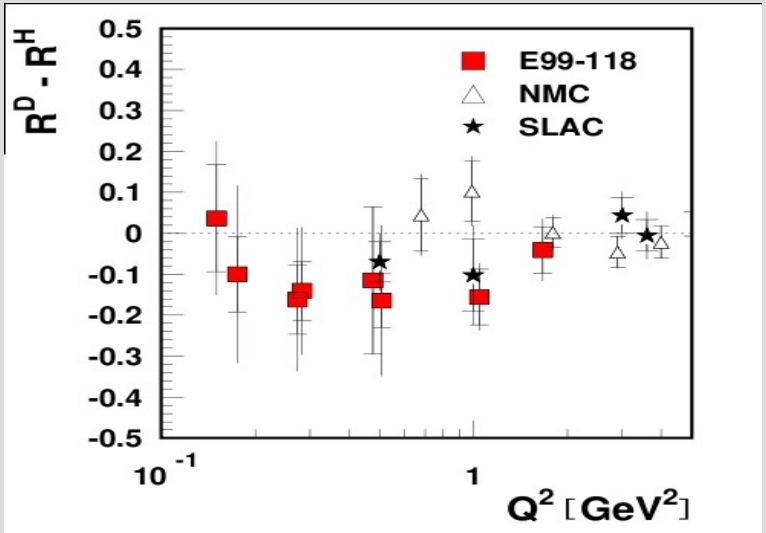
E99-118



From current conservation

$R \rightarrow Q^2$ for $Q^2 \rightarrow 0$

But this behavior is not yet observed.



For first time, intriguing hint that

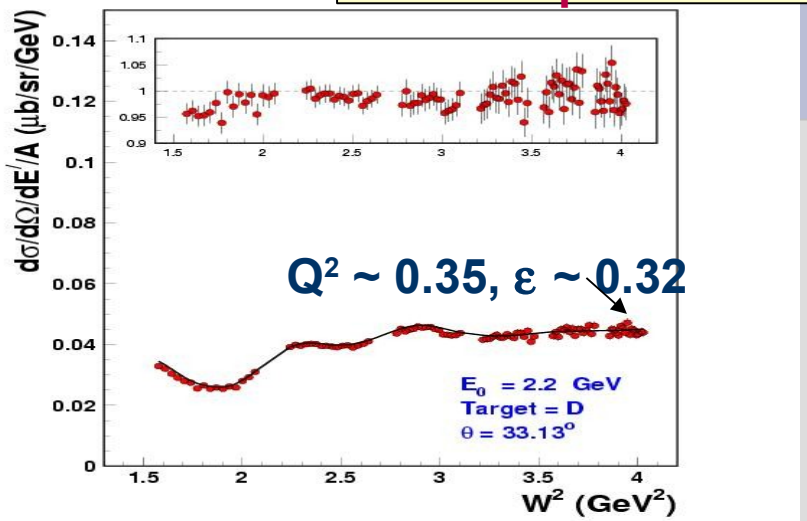
$R_d < R_p$

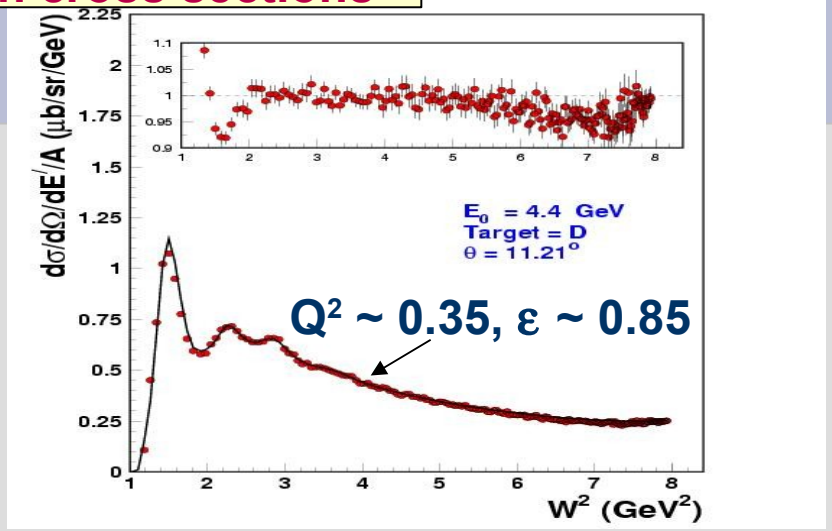
Difference in neutron?

New data from E02-109, E06-009, and E00-002 will help resolve these open questions.

E00-002 Results (in preparation)

Sample deuteron cross sections



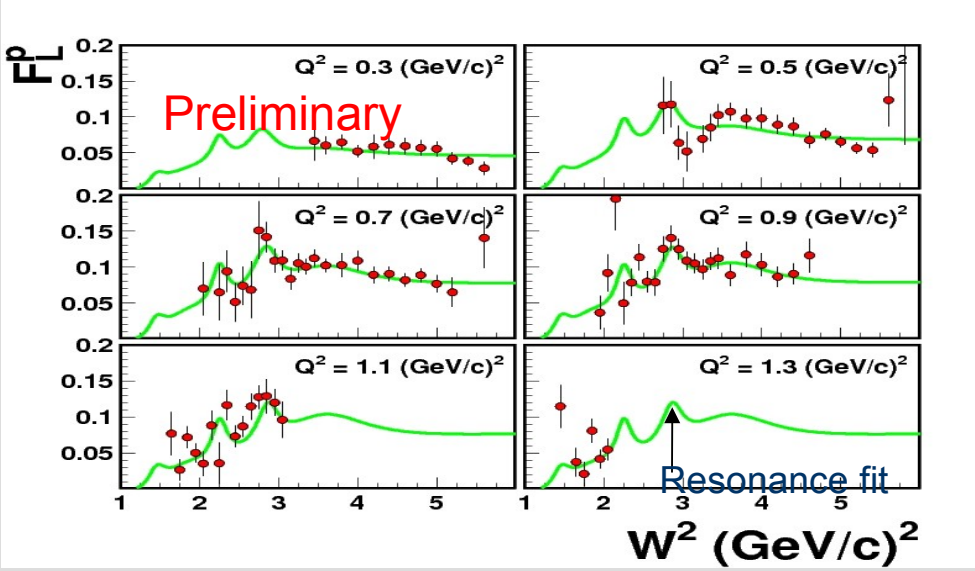


Preliminary results for F_L^p

Consistent with resonance global fit.

Results for deuteron shown in later slides

R_d-R_p coming soon.

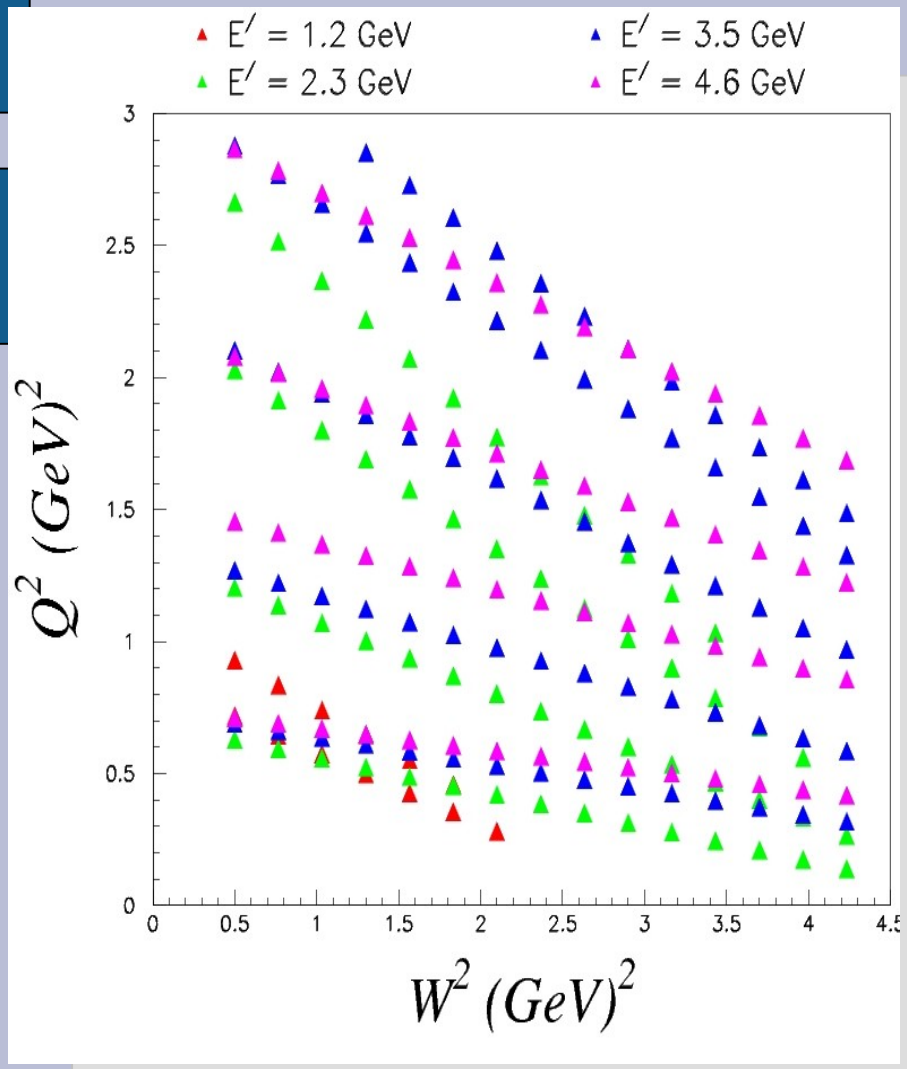


F_L, R on Deuterium and heavier targets
JLab Hall C: E02-109, E04-001, E06-009

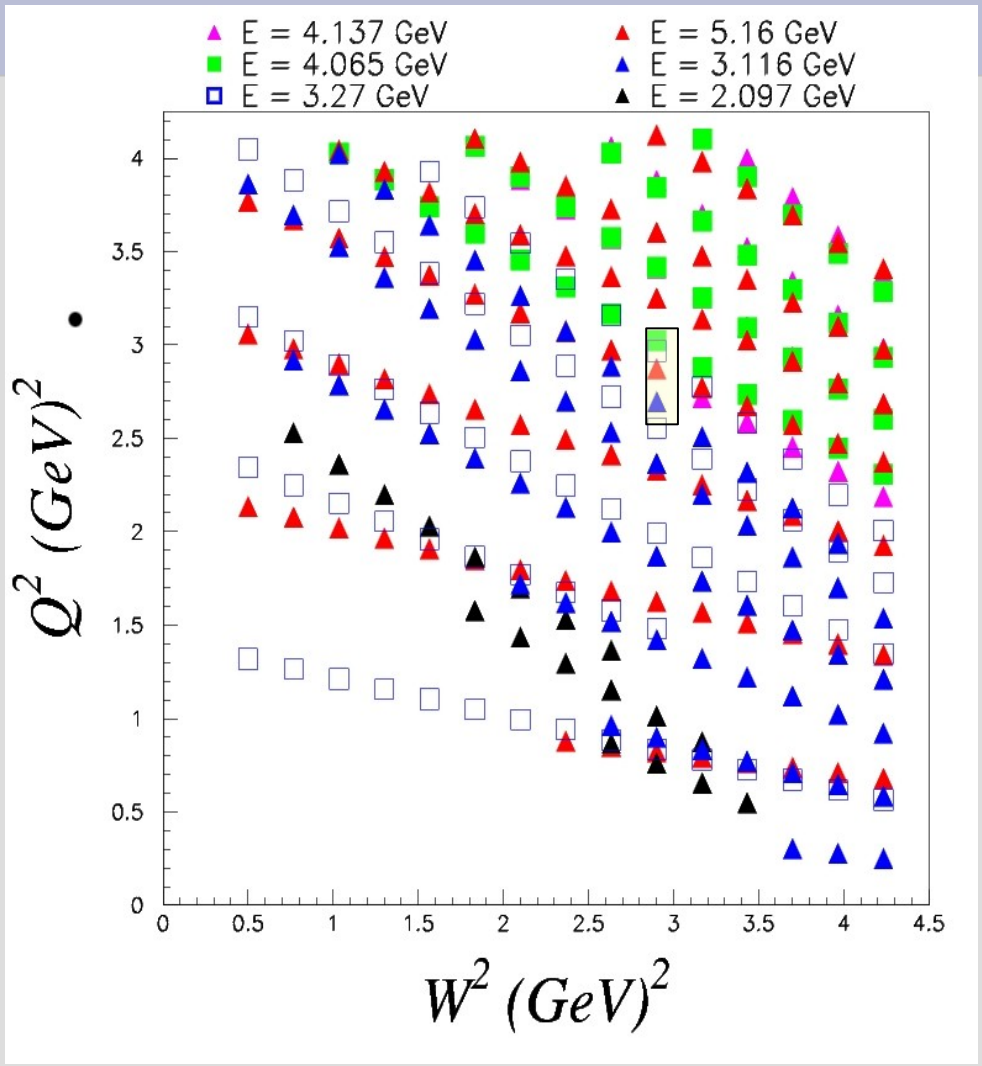
- Precision extraction separated structure functions on D, Al, C, Fe/Cu
- Search for nuclear effects in F_L, R.
- Neutron and p-n moment extractions (non-singlet / singlet).
- Allow study quark-hadron duality for neutron, nuclei separated structure function.

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

2005



2007

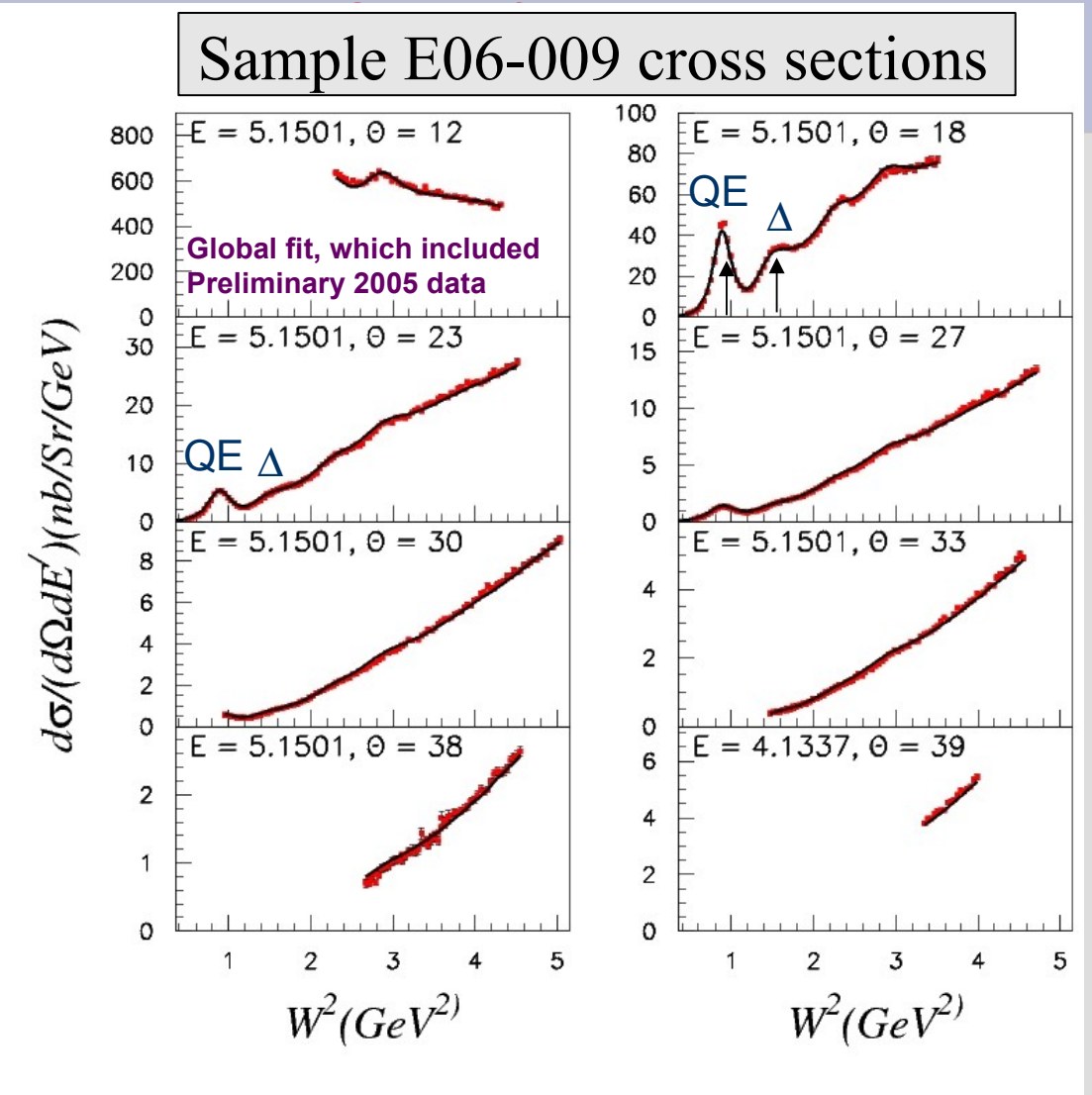


Deuteron F_L and Moments (E02-109, E06-009)

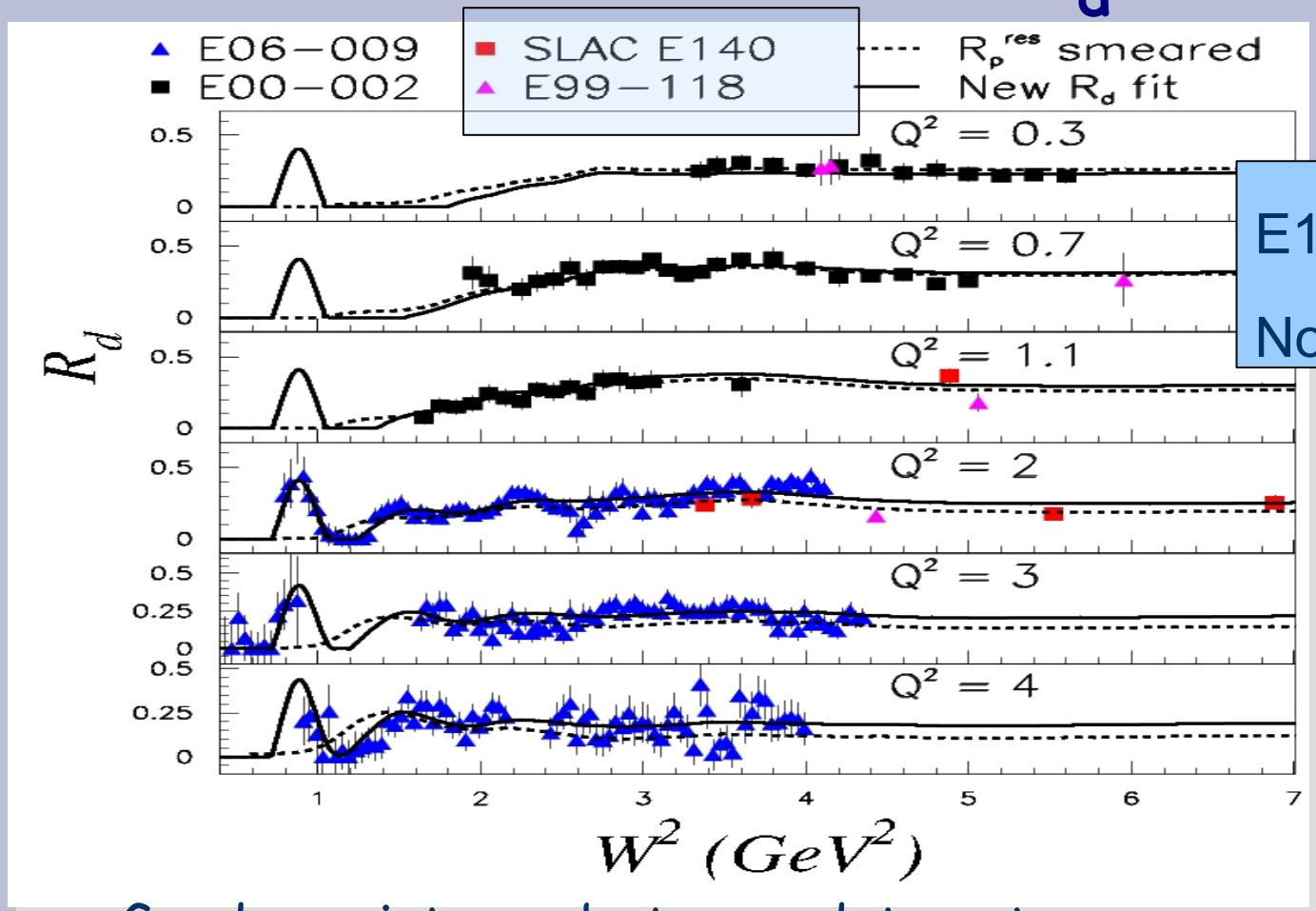
Study of deuteron F_L , and separation of singlet and non-singlet (p-n) moments – E02-109, E06-009

Dissertation of I. Albayrak (Hampton, 2011)

- Extend resonance L/T separations to deuteron.
- Allow study quark-hadron duality for neutron in both transverse and longitudinal structure.
- Allow higher precision non-singlet moment extractions for F_2,F_1 (compare to lattice predictions at Q^2 = 4 GeV^2).
- Comparisons of F_L^p and F_L^d (F_l^n) and moments.



Status of R_d



E140 and E99118

Not included in fit

→ Good consistency between data sets.

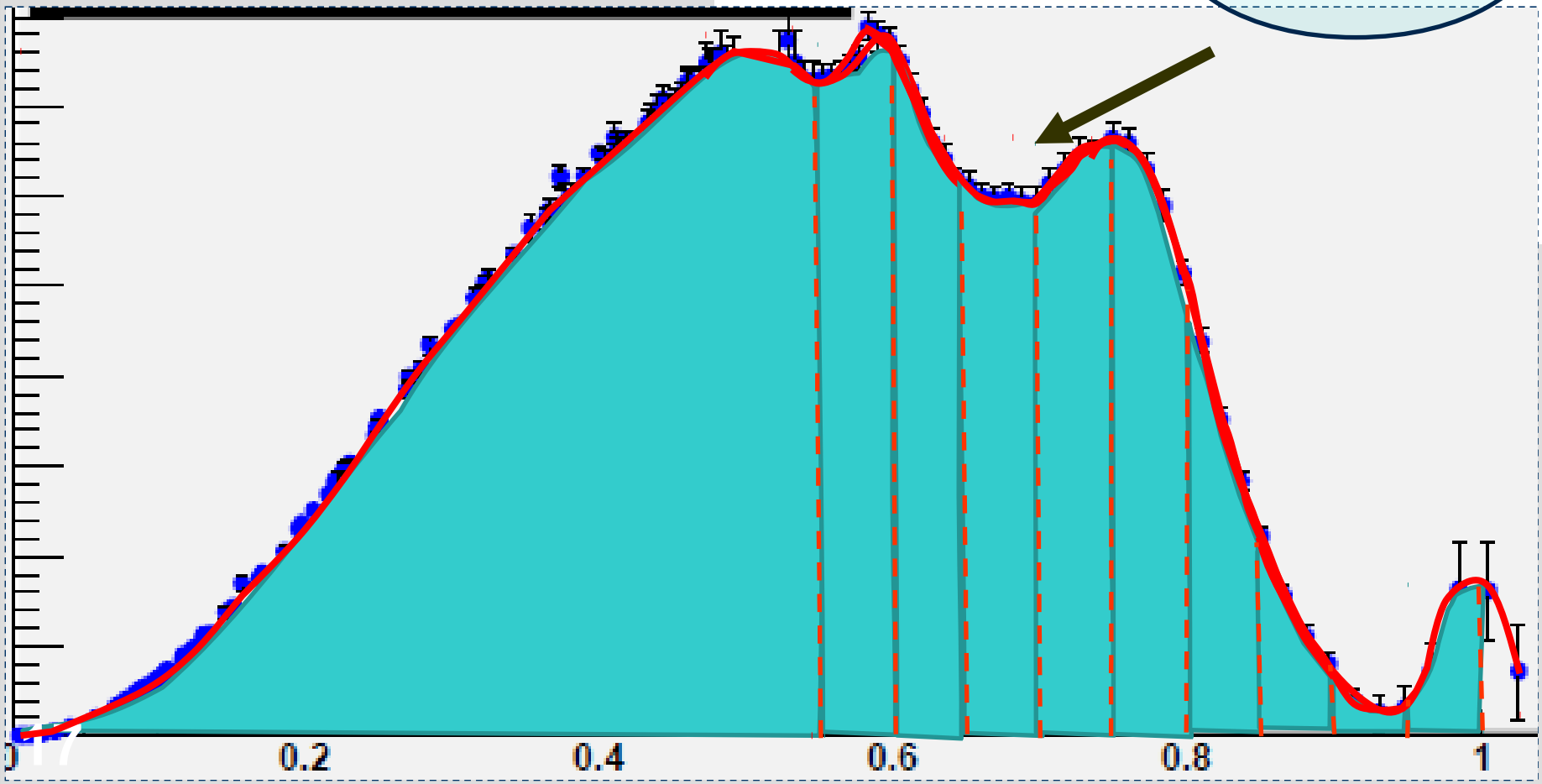
→ Low Q^2 data from 2005 data set will cover from QE to $W^2 \sim 5$

→ Still work to needed to finalize low W^2 in particular.

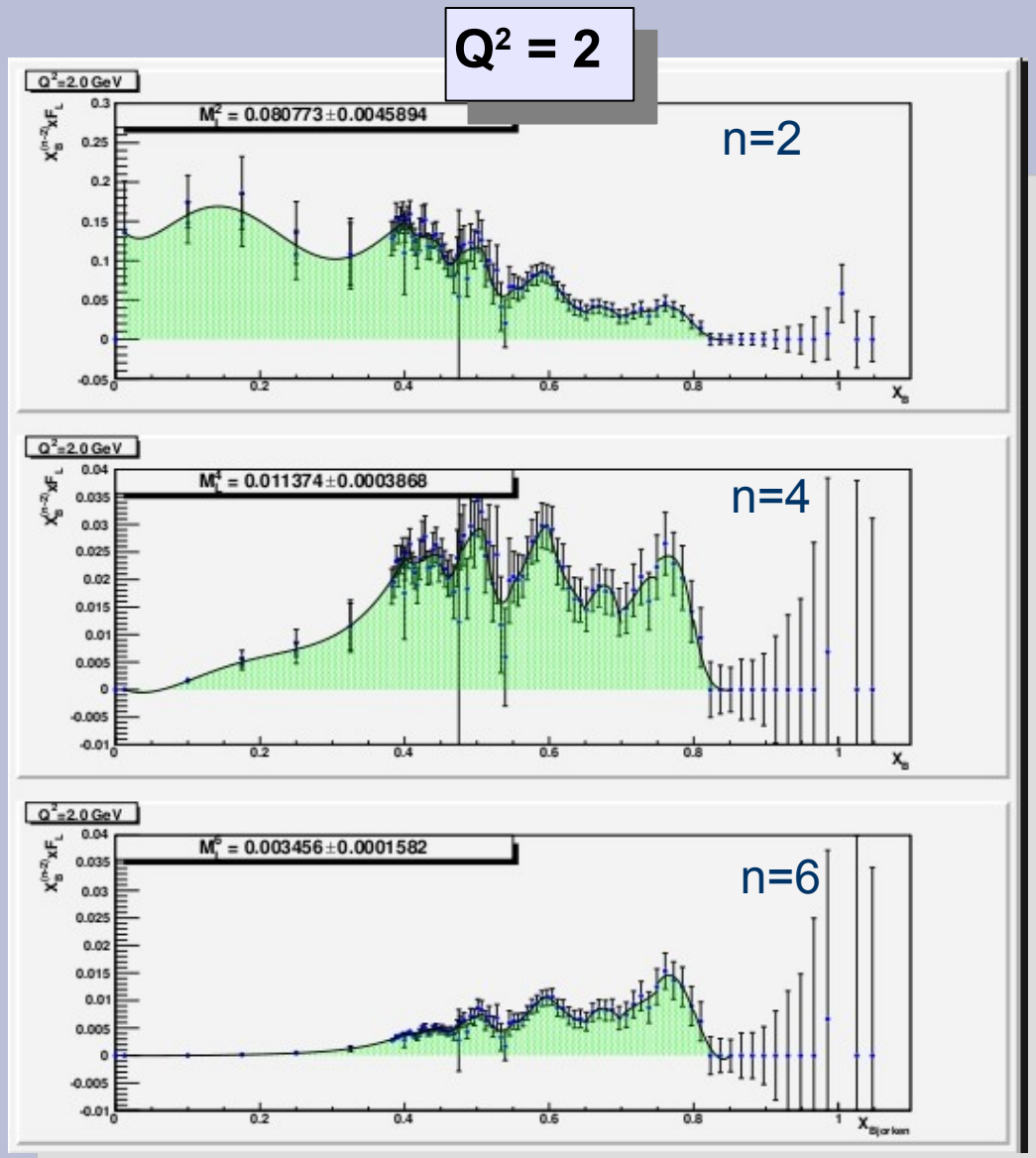
Methodology of D_2 moment determinations

From I. Albayrak

$$M_n^{2,L}(Q^2) \equiv \int_0^1 dx x^{n-2} F_{2,L}(x, Q^2)$$



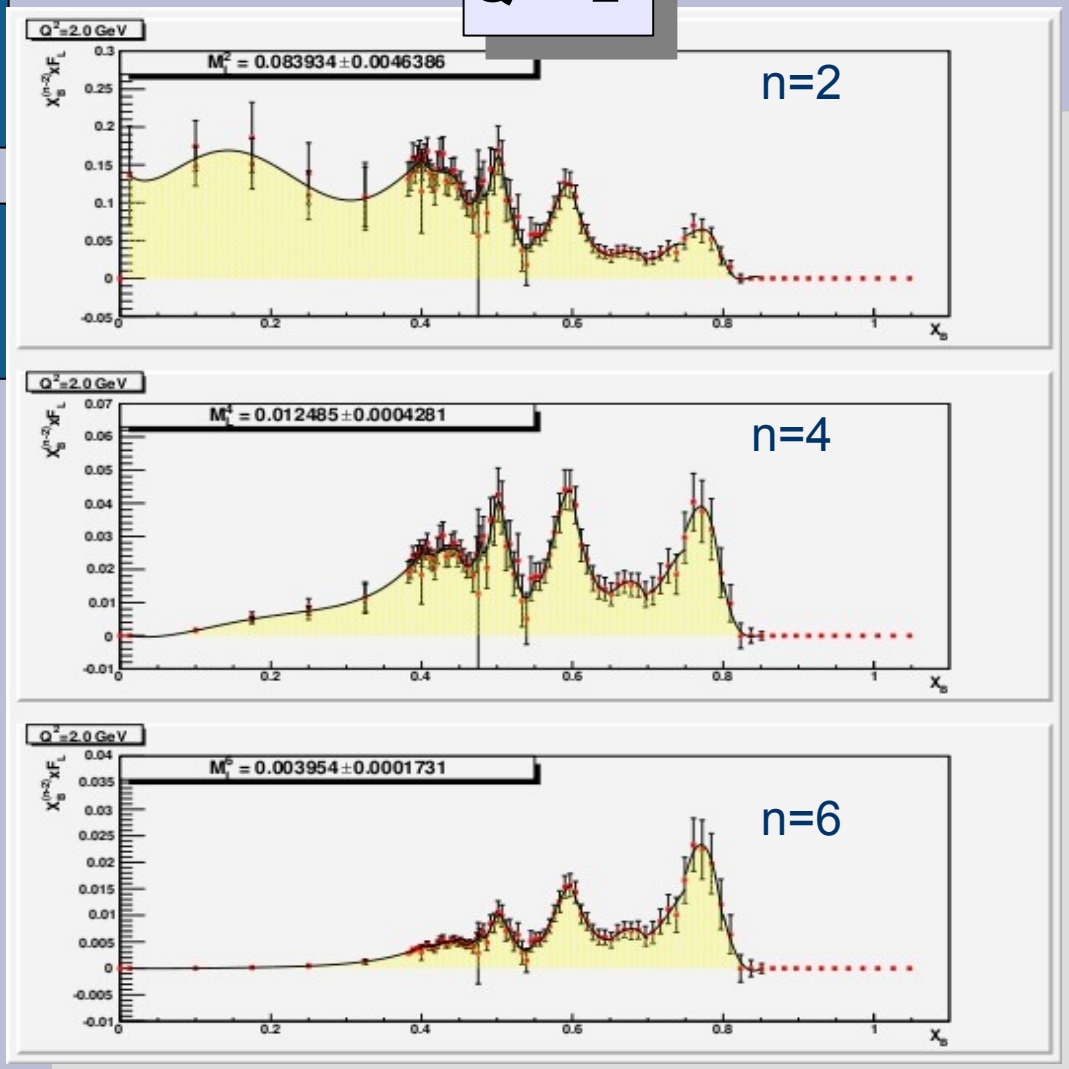
F_L^d integrand of CN moment



- → Subtract Quasi-elastic contribution from Hall C data using fit.
- → Include SLAC data
- → Next, correct for Fermi smearing.

Fermi Corrected F_L^d integrand

$Q^2 = 2$



Fermi corrected using Bosted-Christy fit to inclusive e-d cross section.

- assumes R_d = smeared R_p

Preliminary Results

N	F_L^d	$F_L^p - F_L^n$
2:	0.084 (5)	*Coming*
4:	0.0125 (4)	*Soon!*
6:	0.0395 (2)	

→ Finalized results will

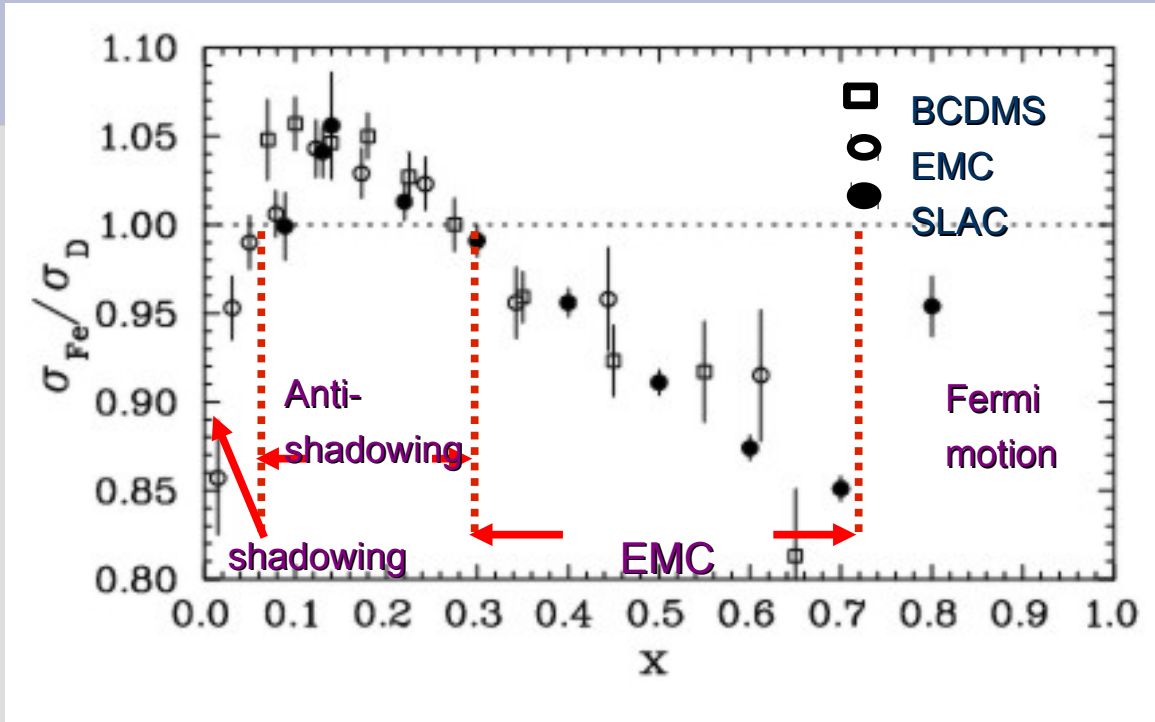
1. utilize new R_d fit
2. alternate smearing corrections

F_L (R) in Nuclei

*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 !

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

Highest precision data on R_A comes from SLAC E139/E140

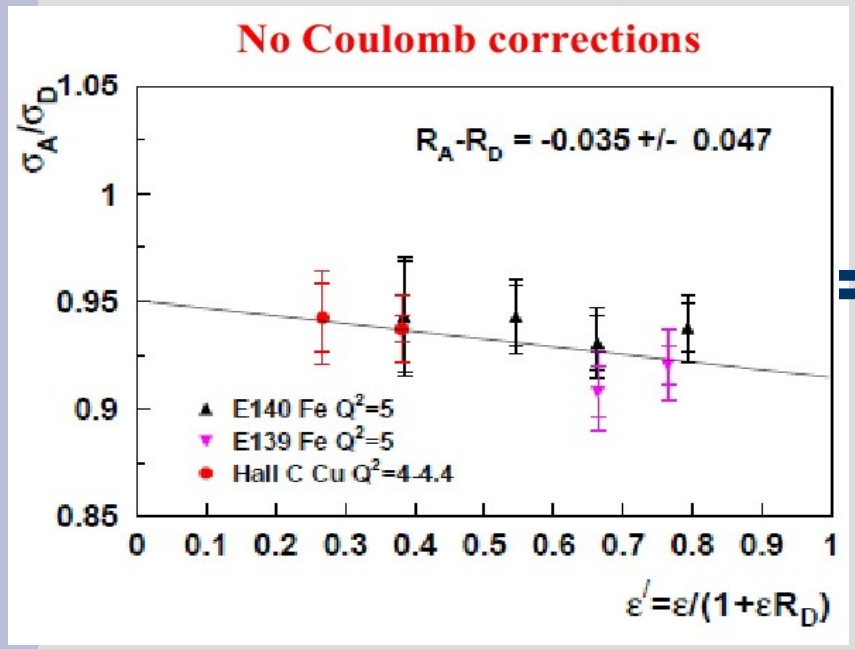
→ SLAC analysis showed *no clear evidence* for $R_A \neq R_d$ ... However

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

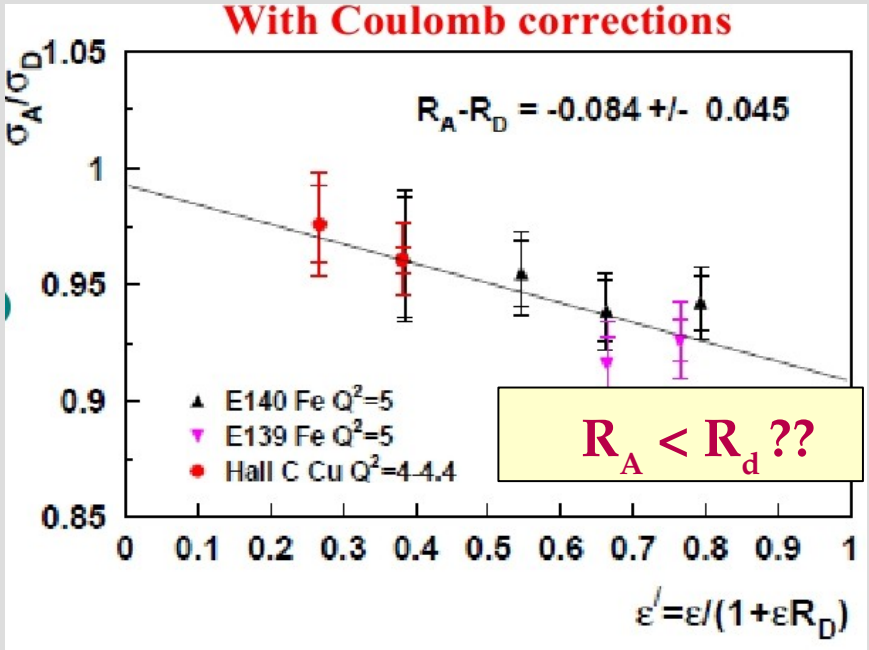
Following Dasu *et.al* *Analysis of SLAC* (PRD.49.5641)

$$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_A^T}{\sigma_D^T}\left(1 + r \cdot \varepsilon'\right) \qquad r = R_A - R_d, \quad \varepsilon' = \varepsilon/(1+\varepsilon R_d)$$

→ **Much of systematics cancel!**

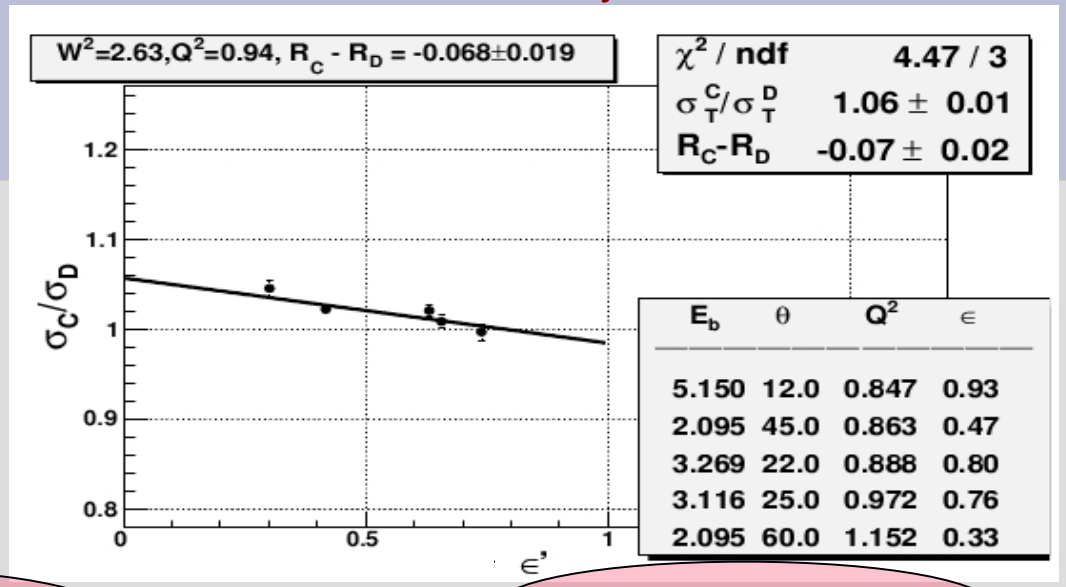


=>

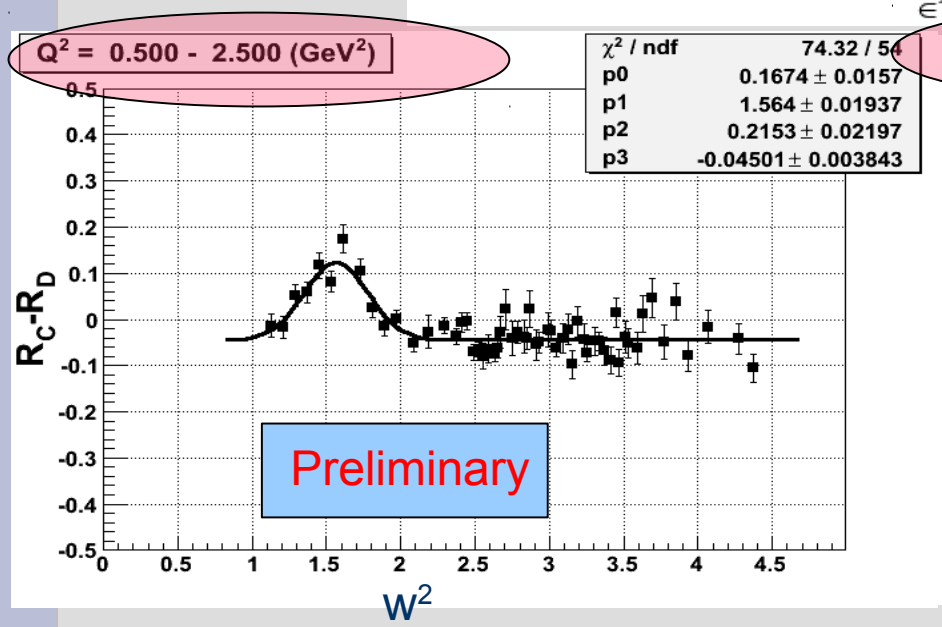


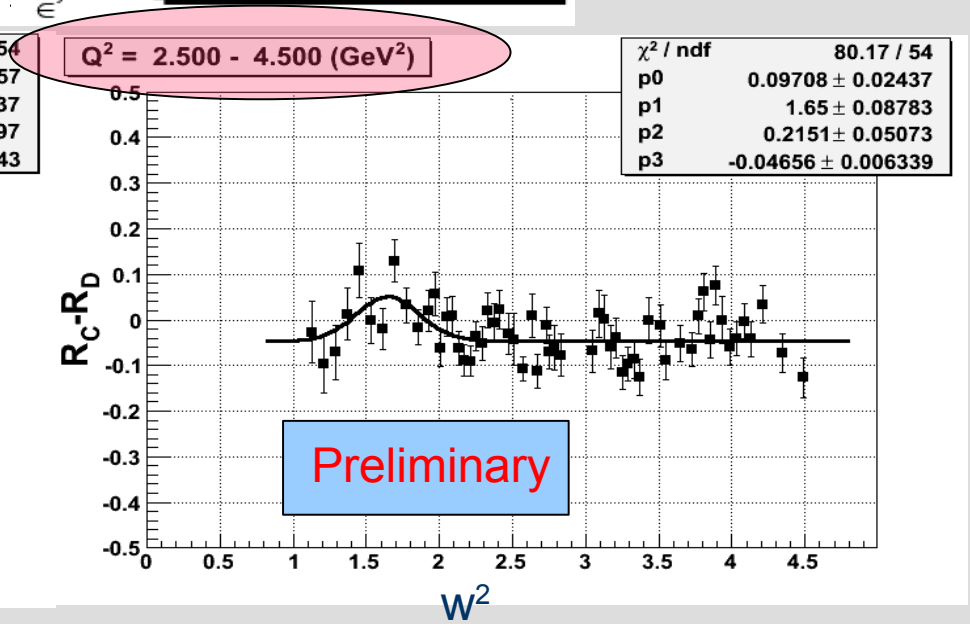
Preliminary results from JLab E06-109(D), E04-001 (A)

Dissertation of V. Mamyan (UVA, 2010)



E_b	θ	Q^2	ϵ
5.150	12.0	0.847	0.93
2.095	45.0	0.863	0.47
3.269	22.0	0.888	0.80
3.116	25.0	0.972	0.76
2.095	60.0	1.152	0.33





A consistent Picture seems to be emerging...

→ **Evidence that $R_A < R_d$ for $1.5 < Q^2 < 5$ and moderate to large *x*.**

Additional low Q^2 data from *2005* data set will allow for precision determination of Q^2 dependence down to Q^2 ~0.3

→ Plan to finish analysis of this data set in first half of this year

Knowledge of vector form factors and Structure functions are important input For neutrino cross section modeling.

This is needed for improving precision of Neutrino oscillation parameters.

… see next talk by Arie Bodek

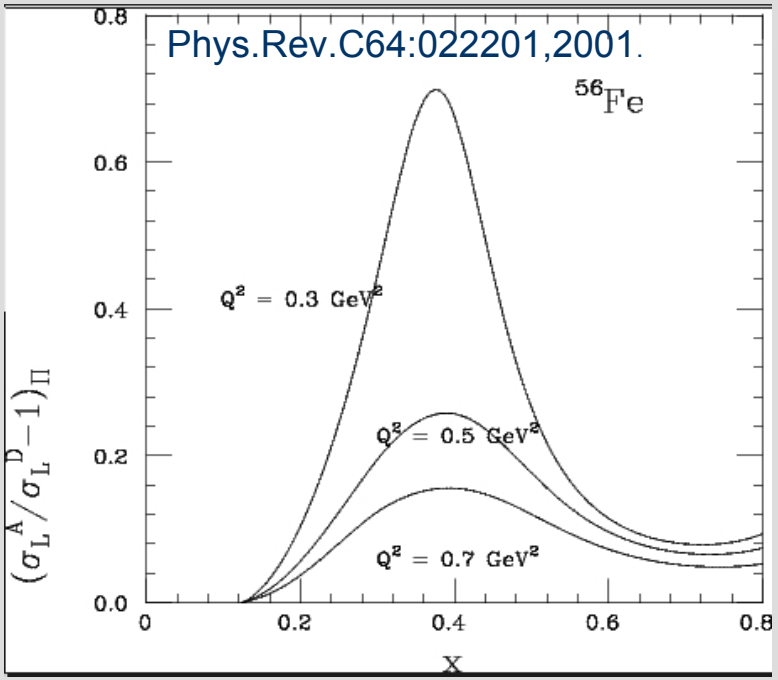
Lot's more F_L data to be finalized

including deuteron,

as well as C, Al, Fe, and Cu targets to study nuclear dependence of F_L / R (E04-001).

Look for enhancement of σ_L^A / σ_L^d
→ signature of nuclear pions as suggested by G. Miller

Stay tuned....



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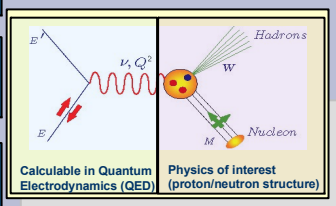

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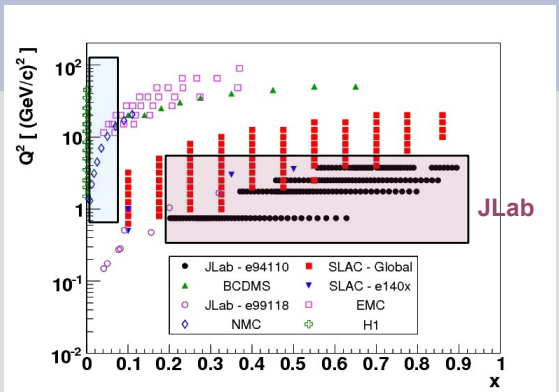

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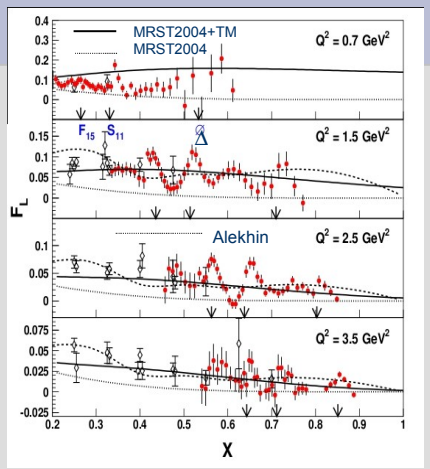

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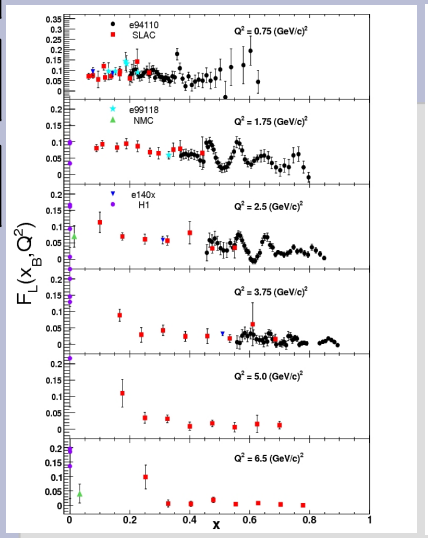

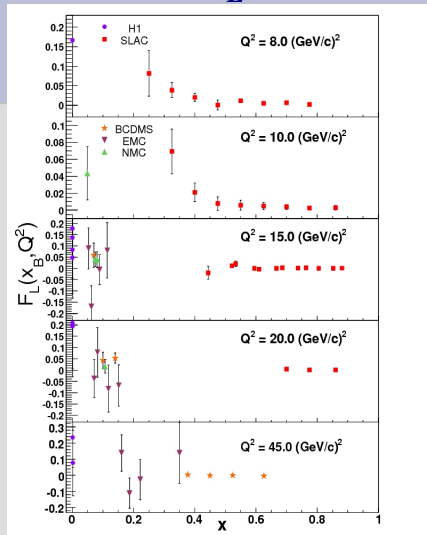

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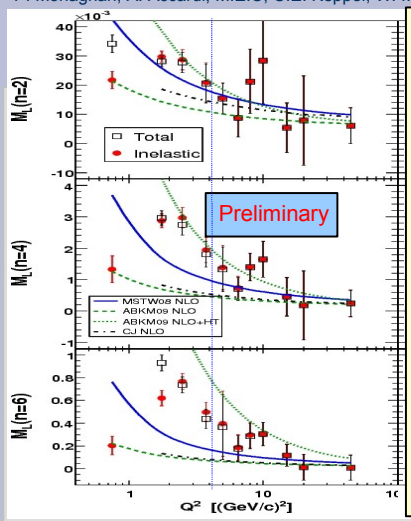

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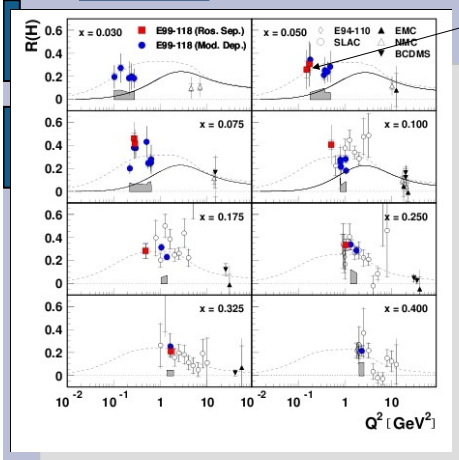

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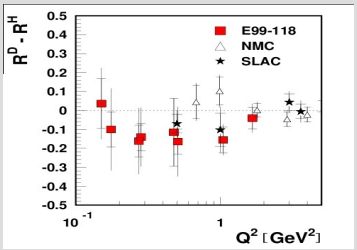

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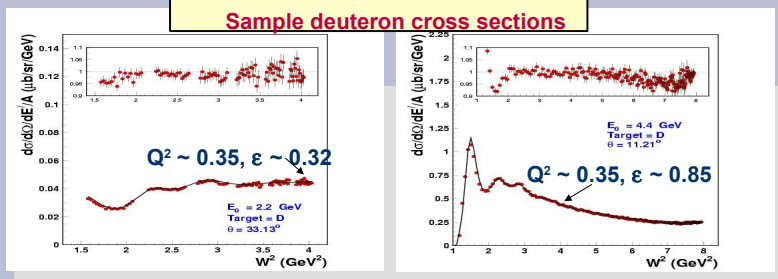
E00-002 Results (in preparation)

Sample deuteron cross sections

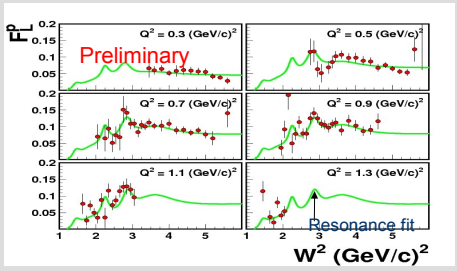


Preliminary results for F_L^p

Consistent with resonance global fit.

Results for deuteron shown in later slides

R_d-R_p coming soon.

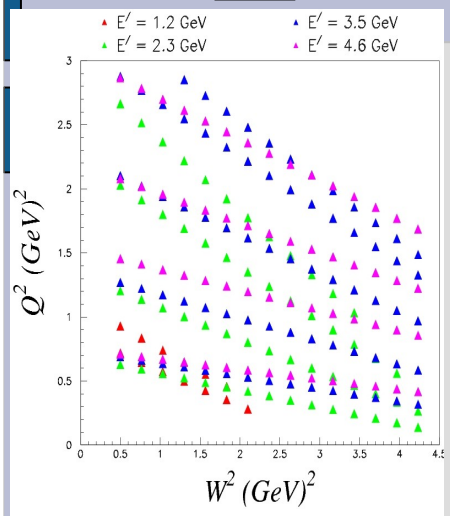


F_L, R on Deuterium and heavier targets
JLab Hall C: E02-109, E04-001, E06-009

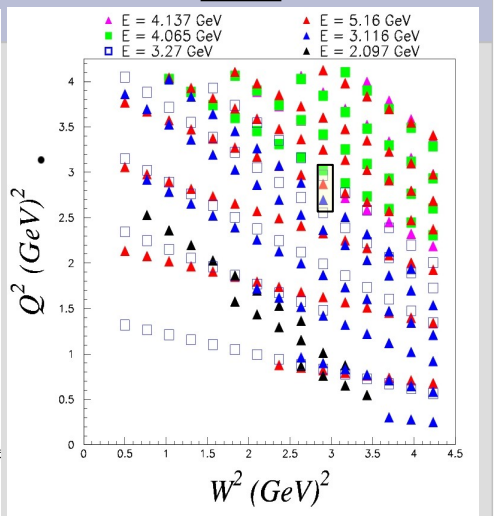
- Precision extraction separated structure functions on D, Al, C, Fe/Cu
- Search for nuclear effects in F_L, R.
- Neutron and p-n moment extractions (non-singlet / singlet).
- Allow study quark-hadron duality for neutron, nuclei separated structure function.

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

2005



2007

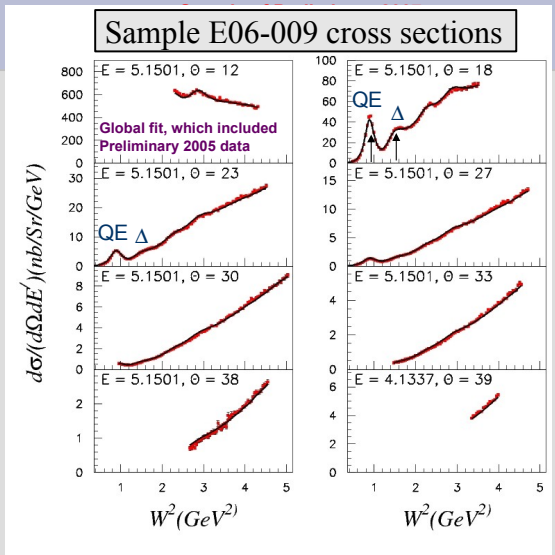


Deuteron F_L and Moments (E02-109, E06-009)

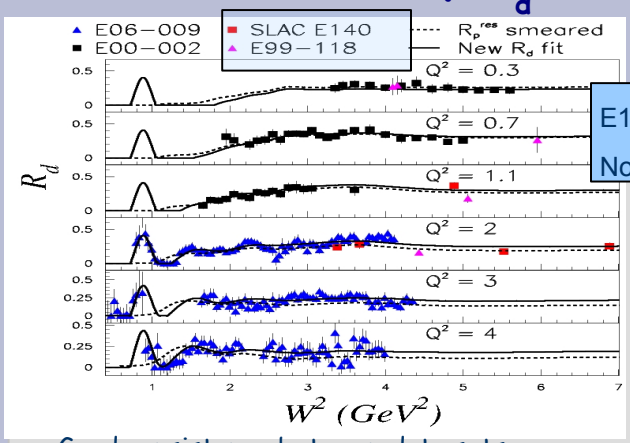
Study of deuteron F_L , and separation of singlet and non-singlet (p-n) moments – E02-109, E06-009

Dissertation of I. Albayrak (Hampton, 2011)

- Extend resonance L/T separations to deuteron.
- Allow study quark-hadron duality for neutron in both transverse and longitudinal structure.
- Allow higher precision non-singlet moment extractions for F_2, F_1 (compare to lattice predictions at $Q^2 = 4$ GeV^2).
- Comparisons of F_L^p and F_L^d (F_1^n) and moments.



Status of R_d



E140 and E99118

Not included in fit

→ Good consistency between data sets.

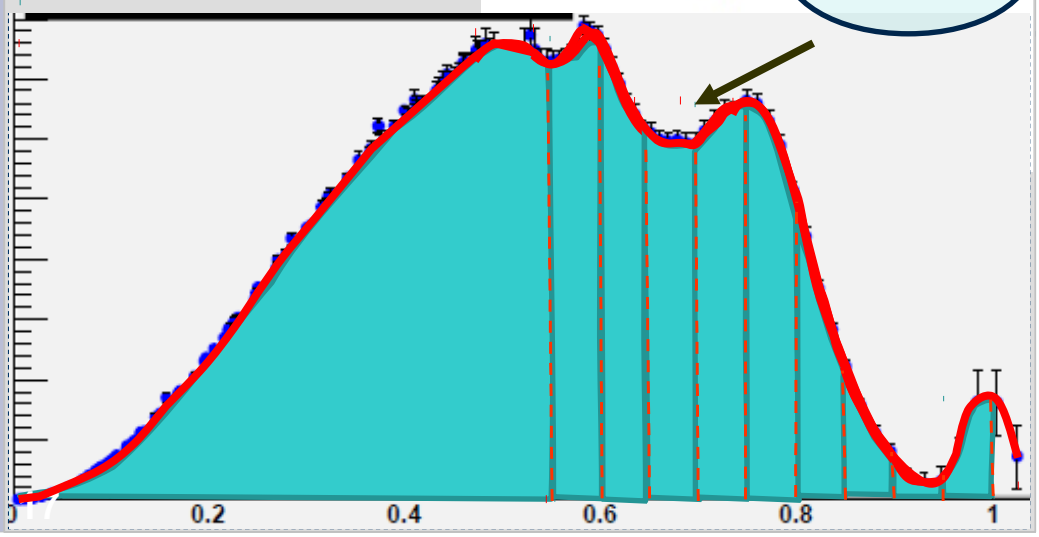
→ Low Q^2 data from 2005 data set will cover from QE to $W^2 \sim 5$

→ Still work to needed to finalize low W^2 in particular.

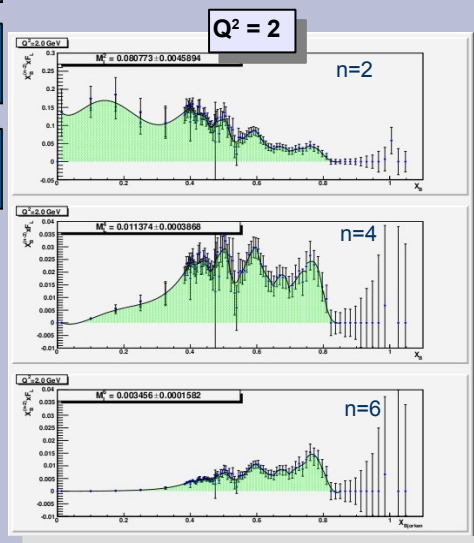
Methodology of D_2 moment determinations

From I. Albayrak

$$M_n^{2,L}(Q^2) \equiv \int_0^1 dx\, x^{n-2} F_{2,L}(x, Q^2)$$

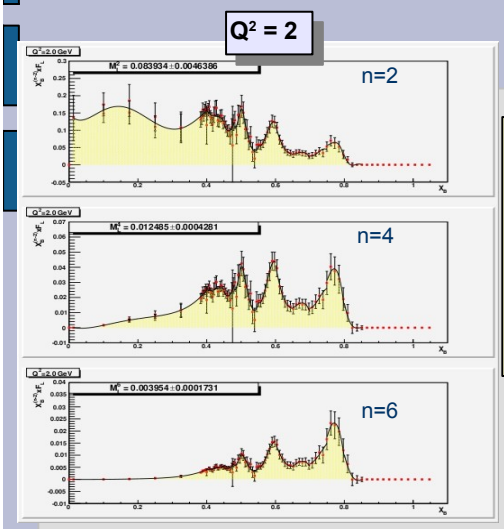


F_L^d integrand of CN moment



- → Subtract Quasi-elastic contribution from Hall C data using fit.
- → Include SLAC data
- → Next, correct for Fermi smearing.

Fermi Corrected F_L^d integrand



Fermi corrected using Bosted-Christy fit to inclusive e-d cross section.

- assumes R_d = smeared R_p

Preliminary Results

N	F_L^d	$F_L^p - F_L^n$
2:	0.084 (5)	*Coming*
4:	0.0125 (4)	*Soon!*
6:	0.0395 (2)	

→ Finalized results will

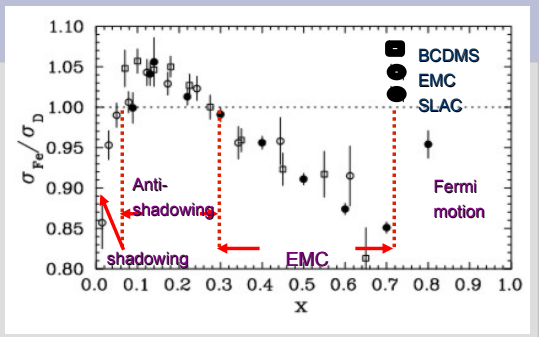
1. utilize new R_d fit
2. alternate smearing corrections

F_L (R) in Nuclei

*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 !

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

Highest precision data on R_A comes from SLAC E139/E140

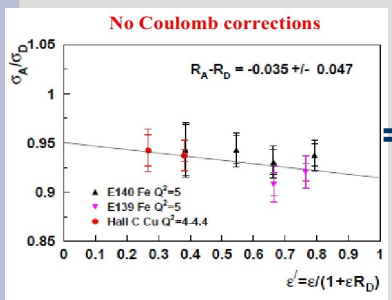
→ SLAC analysis showed *no clear evidence* for $R_A \neq R_d$ ... However

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

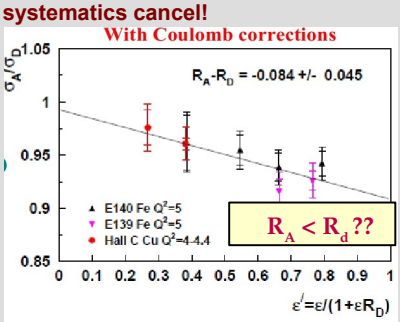
Following Dasu *et.al* *Analysis of SLAC* (PRD.49.5641)

$$\frac{\sigma_A}{\sigma_D} = \frac{\sigma_A^T}{\sigma_D^T}\left(1 + r \cdot \varepsilon'\right) \qquad r = R_A - R_d, \quad \varepsilon' = \varepsilon/(1+\varepsilon R_d)$$

→ **Much of systematics cancel!**

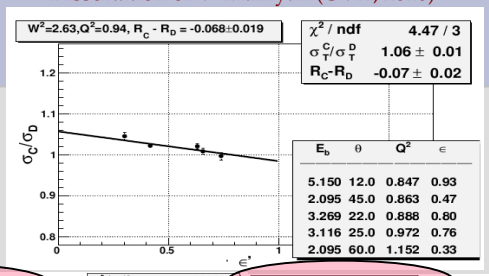


=>

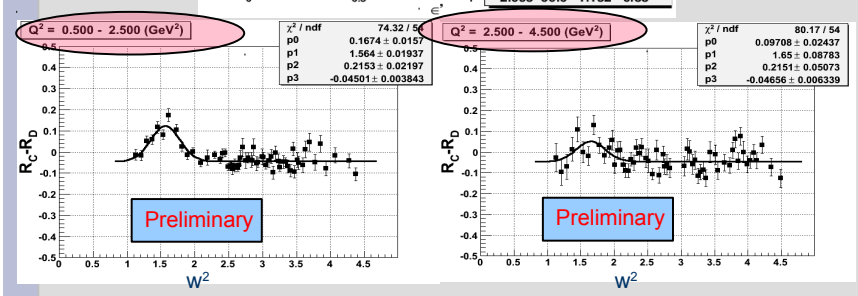


Preliminary results from JLab E06-109(D), E04-001 (A)

Dissertation of V. Mamyan (UVA, 2010)



E_b	θ	Q^2	ε
5.150	12.0	0.847	0.93
2.095	45.0	0.863	0.47
3.269	22.0	0.888	0.80
3.116	25.0	0.972	0.76
2.095	60.0	1.152	0.33



A consistent Picture seems to be emerging...

→ **Evidence that $R_A < R_d$ for $1.5 < Q^2 < 5$ and moderate to large *x*.**

Additional low Q^2 data from *2005* data set will allow for precision determination of Q^2 dependence down to Q^2 ~0.3

→ Plan to finish analysis of this data set in first half of this year

Knowledge of vector form factors and Structure functions are important input For neutrino cross section modeling.

This is needed for improving precision of Neutrino oscillation parameters.

… see next talk by Arie Bodek

Lot's more F_L data to be finalized

including deuteron,

as well as C, Al, Fe, and Cu targets to study nuclear dependence of F_L / R (E04-001).

Look for enhancement of σ_L^A / σ_L^d
→ signature of nuclear pions as suggested by G. Miller

Stay tuned....