Inelastic Scattering in eA and the Measurement of $R = \sigma_L/\sigma_T$

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From the perspective of a nuclear physicist:

→ Electromagnetic and weak probes are complementary for studying nucleon structure.

→ neutrino scattering is uniquely sensitive to flavor and valence structure from combining proton, neutron, ν and νbar data.

→ electron data provides important constraints on Vector form factors and structure functions, which are crucial input for modeling neutrino cross sections

Charged lepton scattering:

$$\frac{d^2\sigma^{e^\pm p}}{dxdy} = \frac{4\pi\alpha^2 s}{Q^4}\left[(1-y)F_2(x,Q^2) + y^2 x F_1(x,Q^2)\right]$$

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

Neutrino scattering:

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

R is difficult to measure in neutrino scattering and R_A for nuclear targets at low Q^2 and W is not really known.

Estimate of σ_ν uncertainty on R

(from Arie Bodek, based on quark-parton model)

With $\langle \mathcal{R} \rangle = 0.2$ and $\langle f_{\bar{q}} \rangle = 0.1725$, we obtain $\langle \sigma_{\bar{\nu}}/\sigma_\nu \rangle =$ 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 $f_{\bar{q}}$ (as shown in Table 3).

Want to know R to +- 0.025 to reduce error to 1%

source	change (error)	change in σ_ν	change in $\sigma_{\bar{\nu}}$	change in $\sigma_{\bar{\nu}}/\sigma_\nu$	
R	+0.10	-2.0%	-4.0%	-2.1%	<---- R
$f_{\bar{q}}$	+10%	-1.4%	+2.8%	+4.2$	<-----Sea antiquarks
P (K_{sea}^{axial})	+ 0.3	+1%	+2%	+1.0%	<----Axial sea
N	+3%	+3%	+3%	0	--PDF normalization quark versus gluon
Total		±4.0%	±6.1%	±4.8%	

Error in R leads to large error in the antineutrino cross sections from the inelastic part.

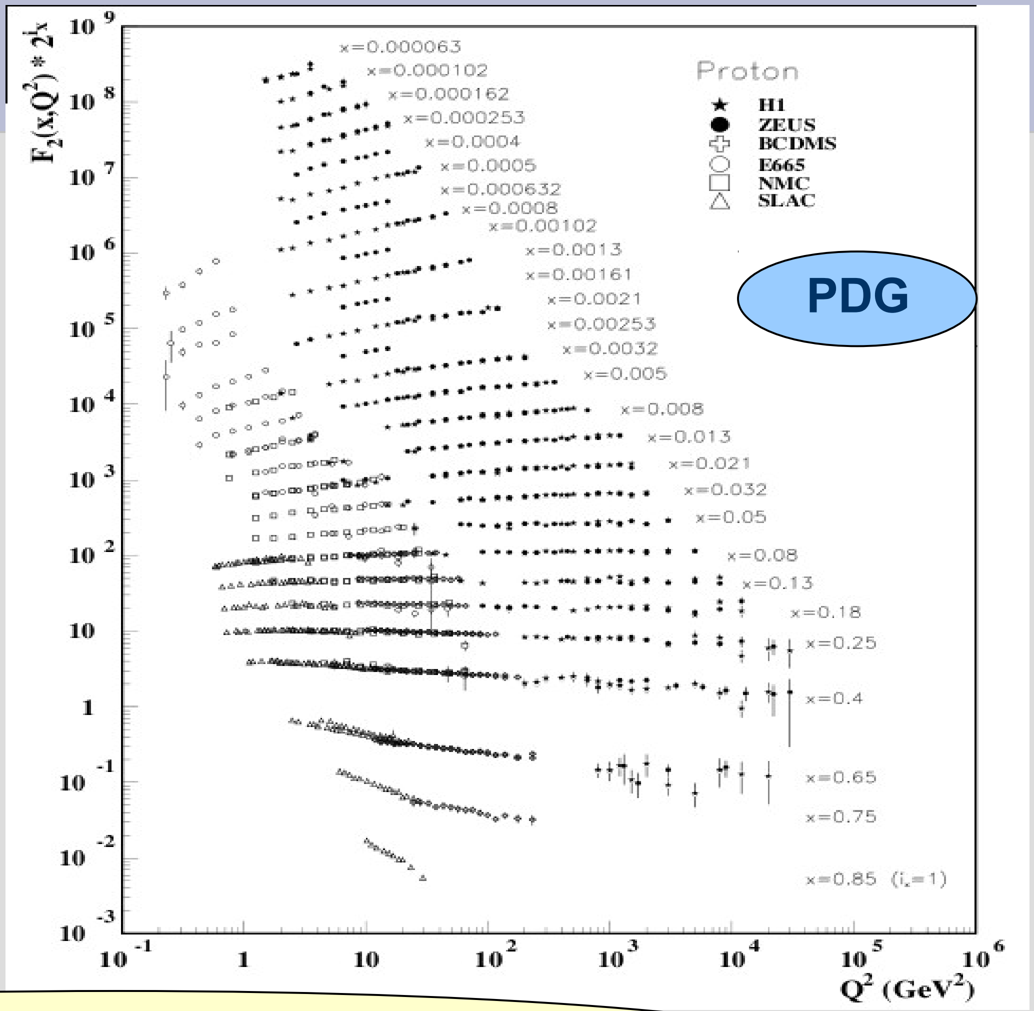
Above does not include error from EMC effect/shadowing, or axial valence. Or resonances and QE components of F2.

Measurements of Structure functions are Critical for a full understanding of QCD

→ Approximate scaling of F_2 with Q^2 provided verification of proton constituents, carrying longitudinal Momentum fraction x.

→ $R = \sigma_L/\sigma_T < 1$ provided evidence that charged constituents were spin 1/2.

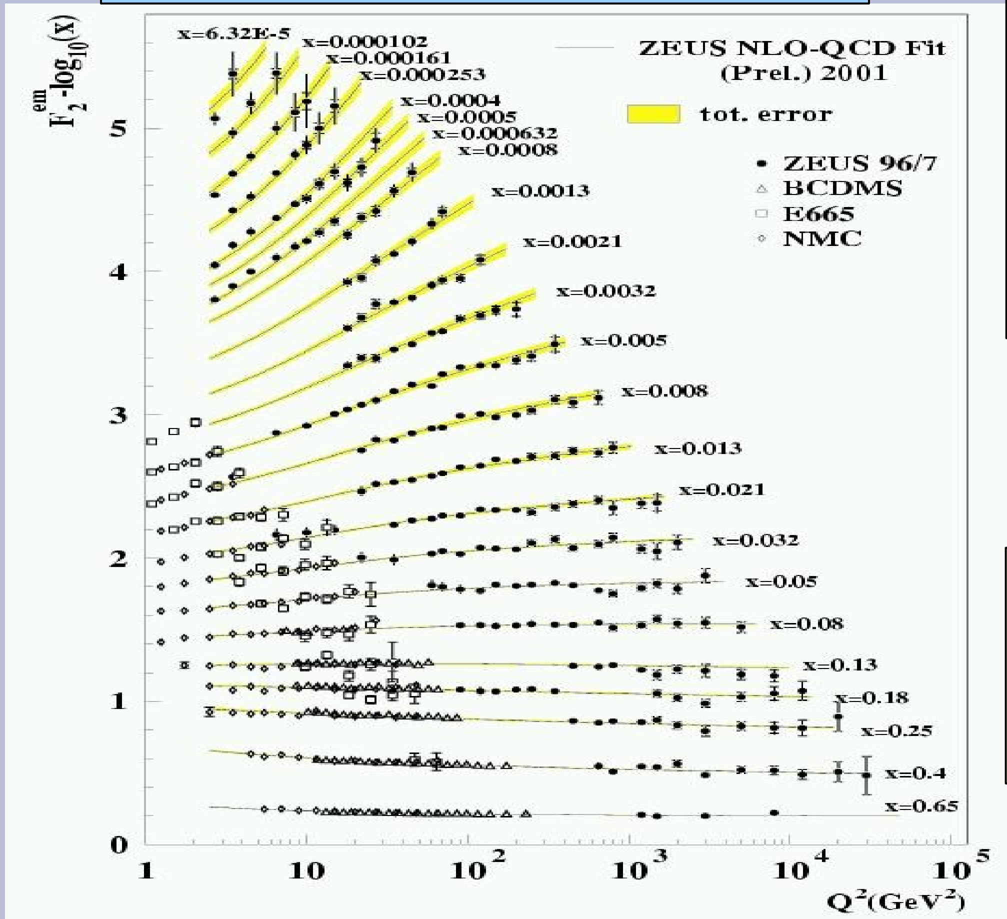
→ Scaling violations measured over orders of magnitude in x and Q^2 well described by universal set of parton distribution functions (PDFs) within pQCD.



F_L data is relatively sparse and much less precise.

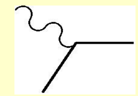
Evolution governed by perturbative QCD

Example from ZEUS NLO fit



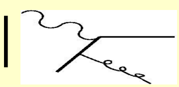
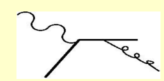
<u>Single quark scattering (LO)</u>

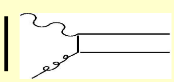
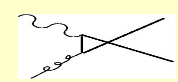
$F_2(x,Q^2) = x \Sigma\, e_q^{\;2}\, \mathbf{q}(x,Q^2)$

|  |^2

$F_L = 0 \Rightarrow F_2 = 2xF_1$, R = 0:
No transverse quark momentum

(NLO) order $\alpha_s(Q^2)$ corrections

|  +  |^2

and |  +  |^2

=> transverse momentum and F_L ,
***F_L directly sensitive to the gluon, g(x).**

$$F_L(x,Q^2) = \frac{\alpha_s(Q)}{2\pi} x^2 \int_0^1 \frac{dy}{y^3}\Big(\frac{8}{3}F_2(y,Q^2) + \sum_{i=1}^{2f} e_j^2 (y-x) g(y,Q^2)\Big) + ...$$

Scattering with longitudinal photons

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

Polarization (Relative flux of longitudinal photons)

Flux of transverse photons

Transverse cross section

Longitudinal cross section

	$\sigma_T \propto$	$\sigma_L \propto$
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)

How to separate transverse from longitudinal?

Reduced cross-section:

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

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

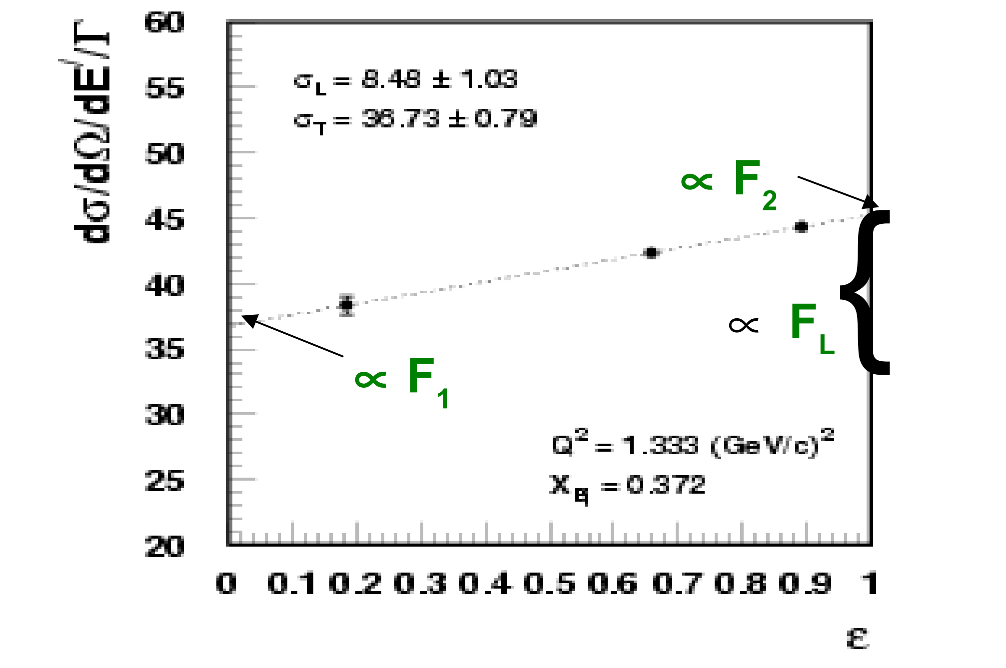
σ_L = Slope

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

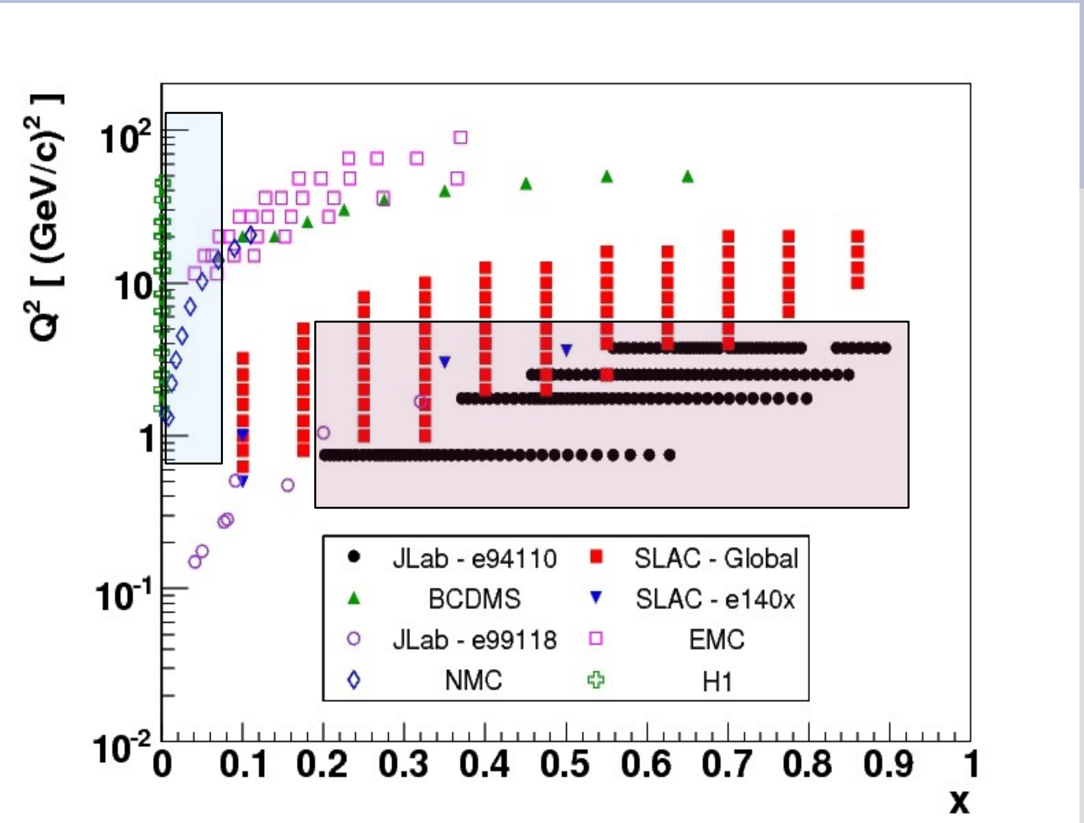


→ need 1-2% uncertainties pt-pt in ε to provide 15-20% **δR** ($\delta F_L/F_L$)

→ 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)

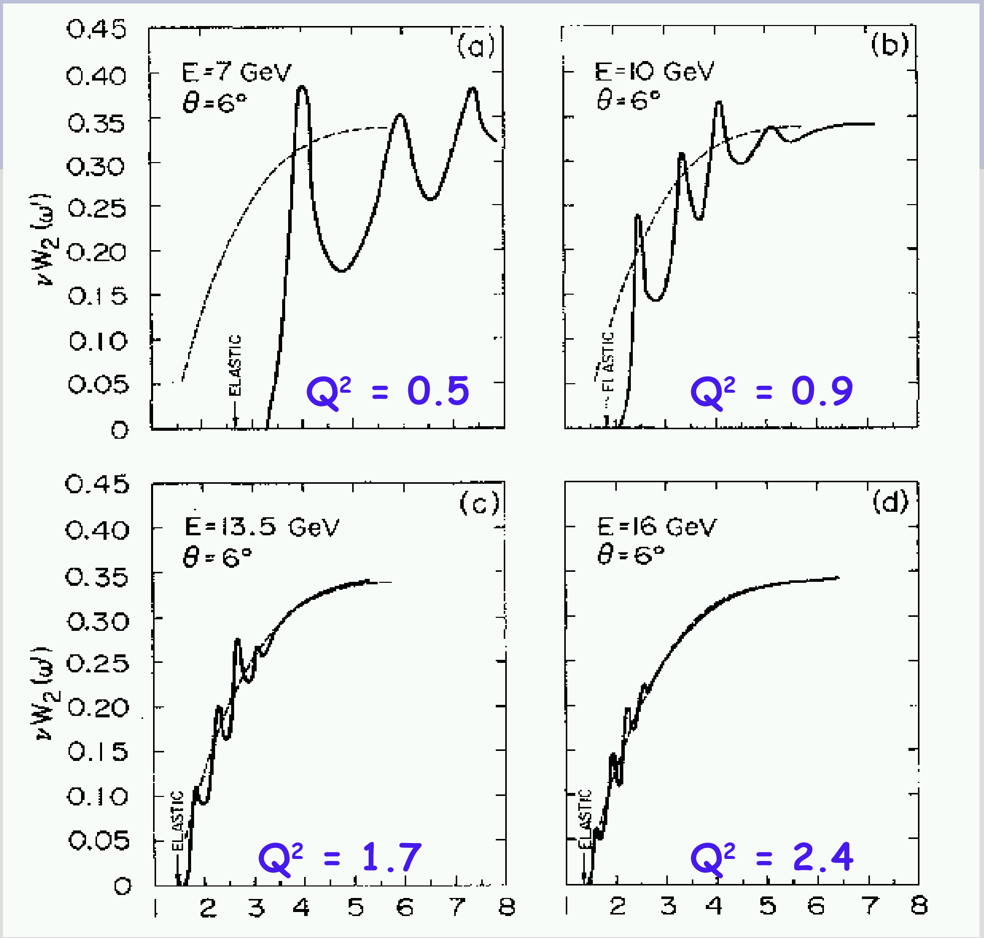
Phenomena of Quark-Hadron Duality

- First observed by Bloom and Gilman At SLAC ~1970, prior to development of QCD.

  Phys.Rev.Lett.25:1140,1970.

- Noted that resonances oscillate around a 'scaling' curve at all Q^2.

  - hadrons follow the DIS scaling behavior.



$$\omega' = 1 + W^2/Q^2$$

Novel observation that was generally left unstudied for next 30 years.
Now observed in a range of observables at JLab... eg. spin structure functions.

Lots of new L/T 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+RR	0.1 - 1.7	PRL98:14301
E00-002	p,d	DIS+RR	0.25 - 1.5	Publication in progress
E02-109	d	RR+QE	0.2 - 2.5	Finalizing analysis
E06-009	d	RR+QE	0.7 - 4.0	Publication in progress
E04-001 - I	C,Al,Fe	RR+QE	0.2 - 2.5	Finalizing analysis
E04-001 - II	C,Al,Fe	RR+QE	0.7 - 4.0	Publication in progress

Lots of results expected soon!

E94-110: proton F_L in resonance region

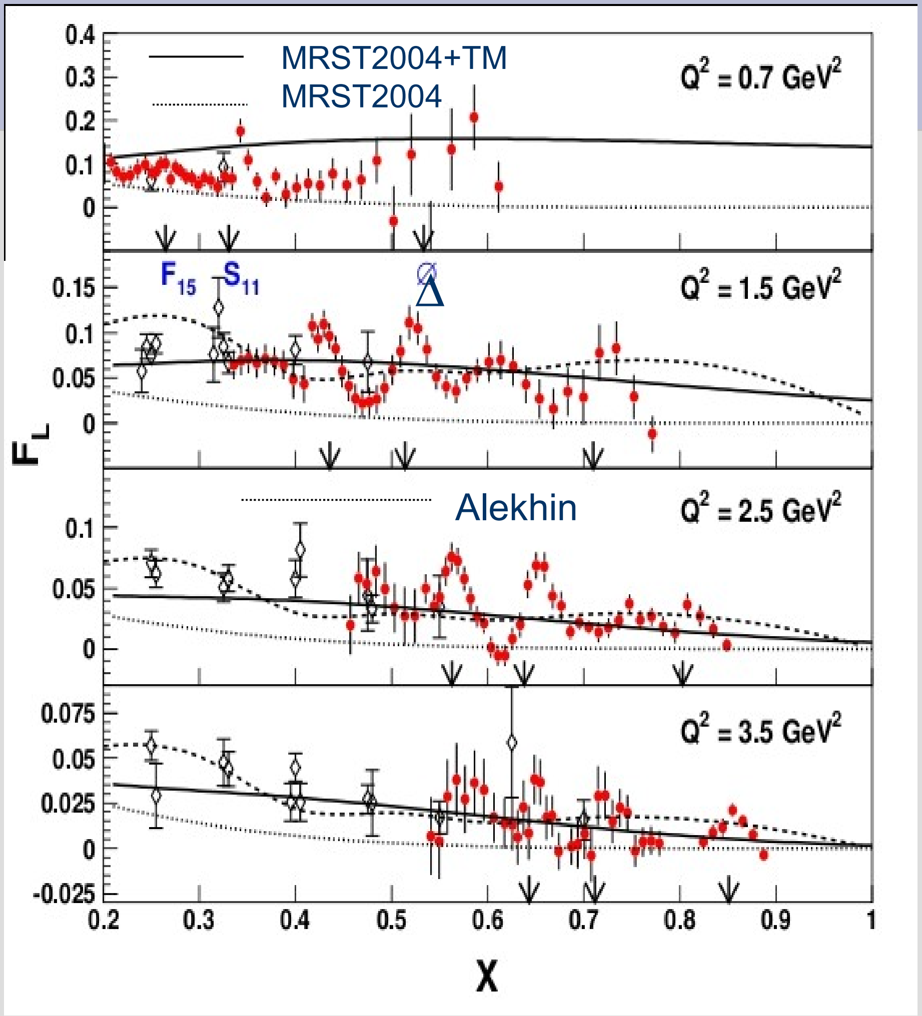
→ ~200 individual L/T separations.

→ 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.



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Measurements of the Transverse and Longitudinal Structure Functions in Electron Scattering on Nuclear Targets

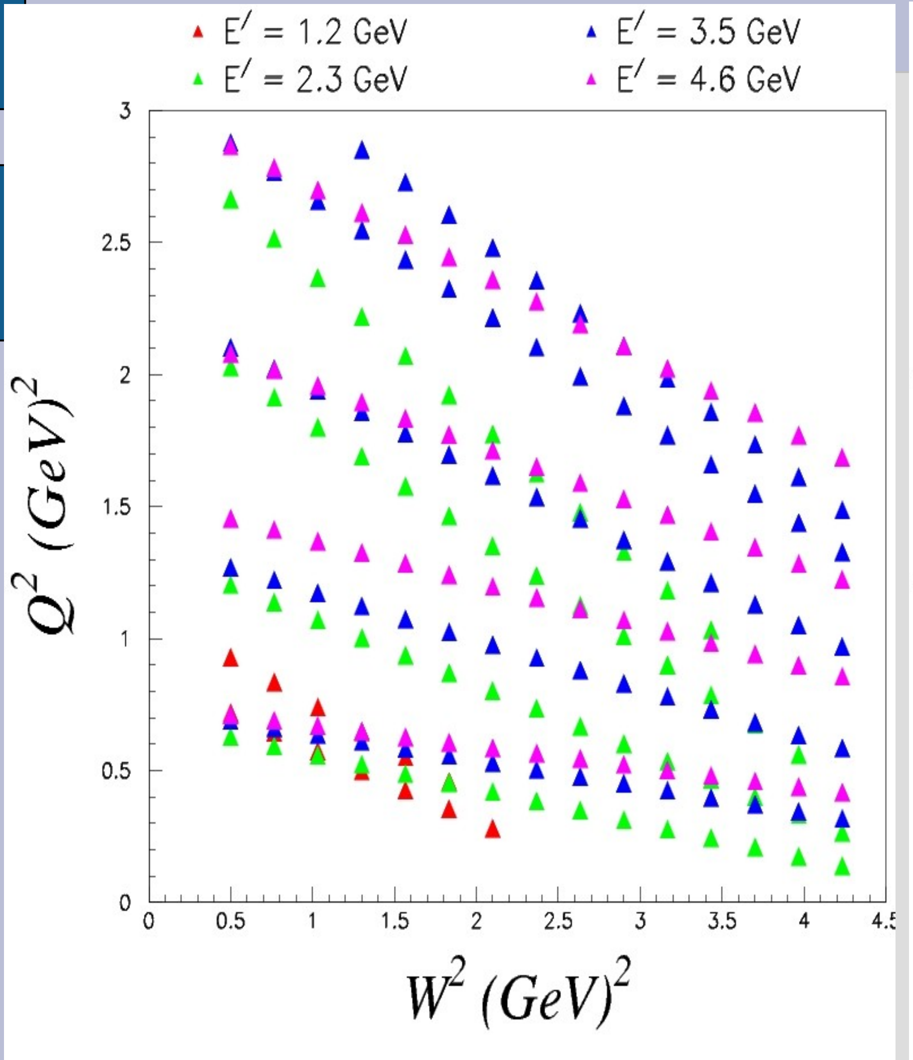
V. Mamyan,[27] A. Ahmidouch,[22] I. Albayrak,[11] J. Arrington,[1] A. Asaturyan,[31] A. Bodek,[24] P. Bosted,[29] R. Bradford,[24,1] E. Brash,[3] A. Bruell,[5] C Butuceanu,[23] M. E. Christy,[11] S. J. Coleman,[29] M. Commisso,[27] S. Connell,[9] M. M. Dalton,[27] S. Danagoulian,[22] A. Daniel,[12] D. 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. Jones,[8] N. Kalantarians,[12] A. Liyanage,[11] C. 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. 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)

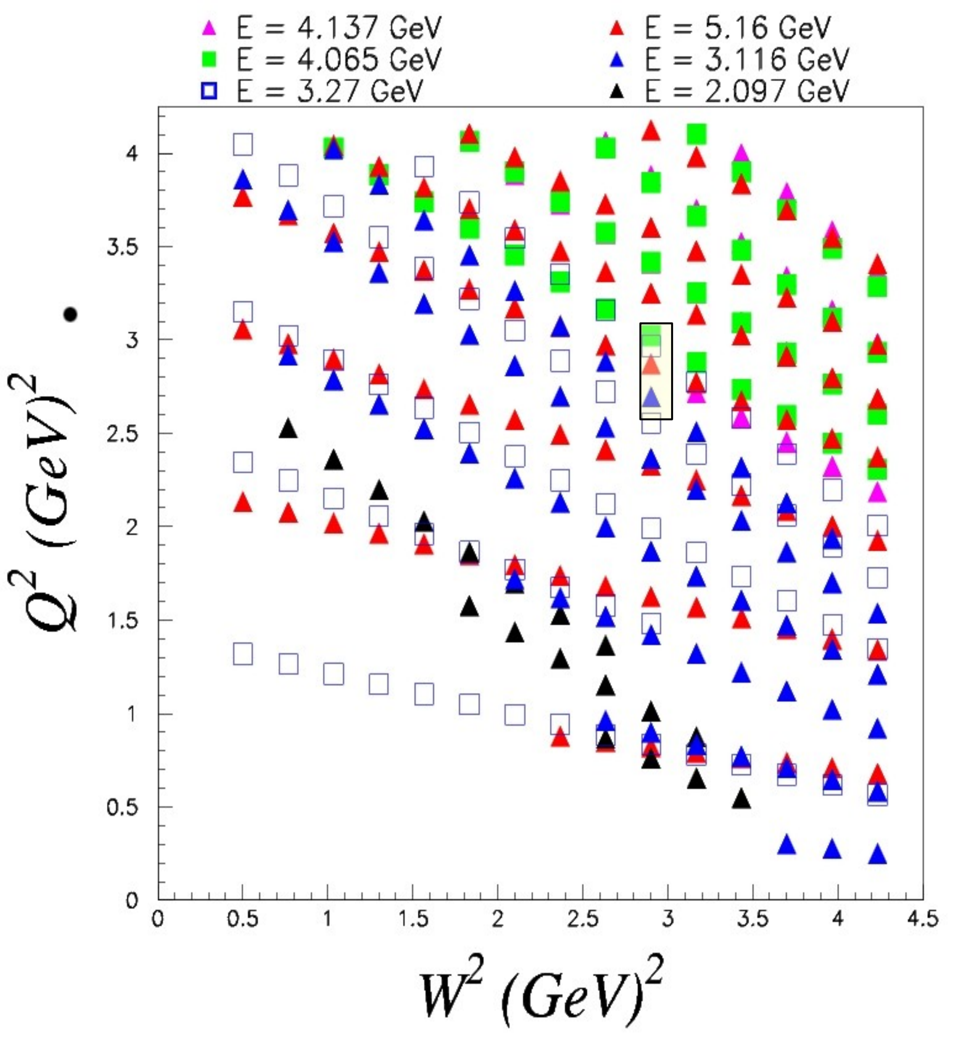
A number of neutrino physicists involved in these measurements

L/T Separations on 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)

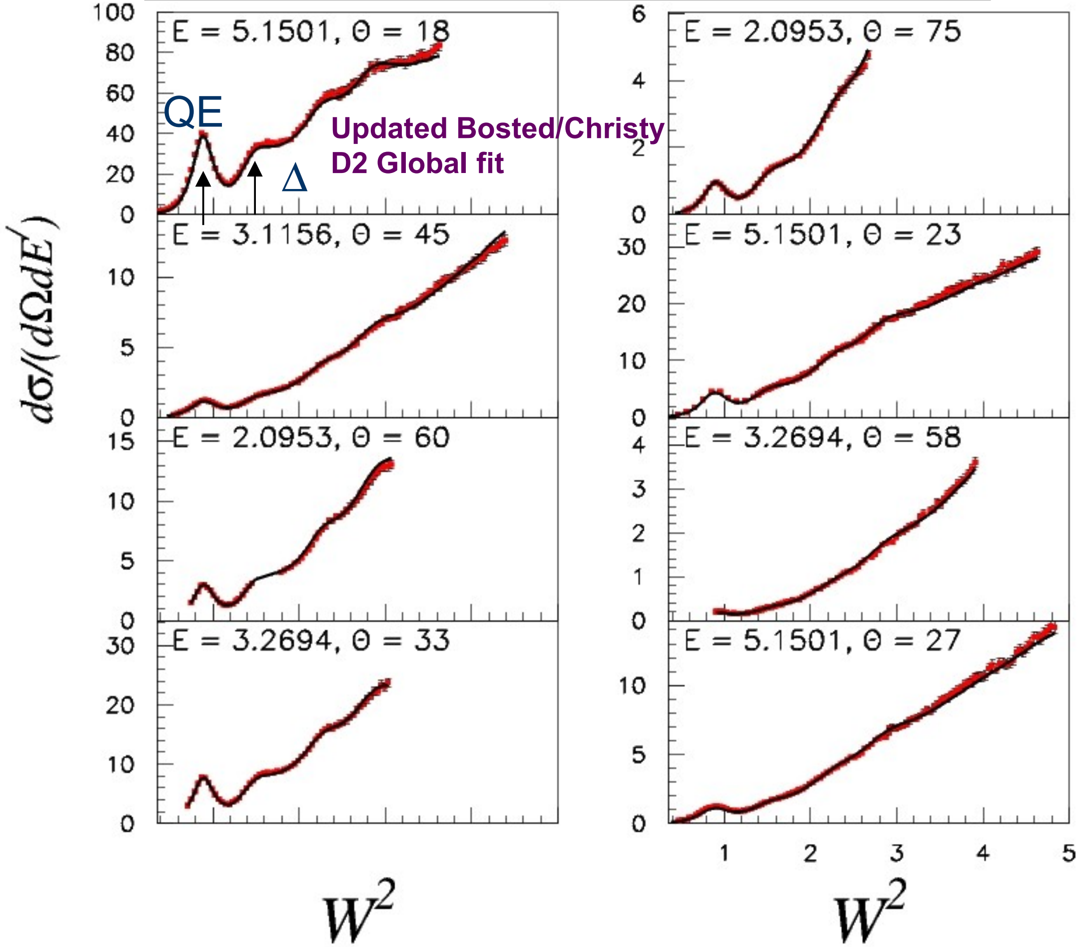
◆ Extend resonance L/T separations to deuteron.

◆ Allow study quark-hadron duality for neutron in both transverse and longitudinal structure.

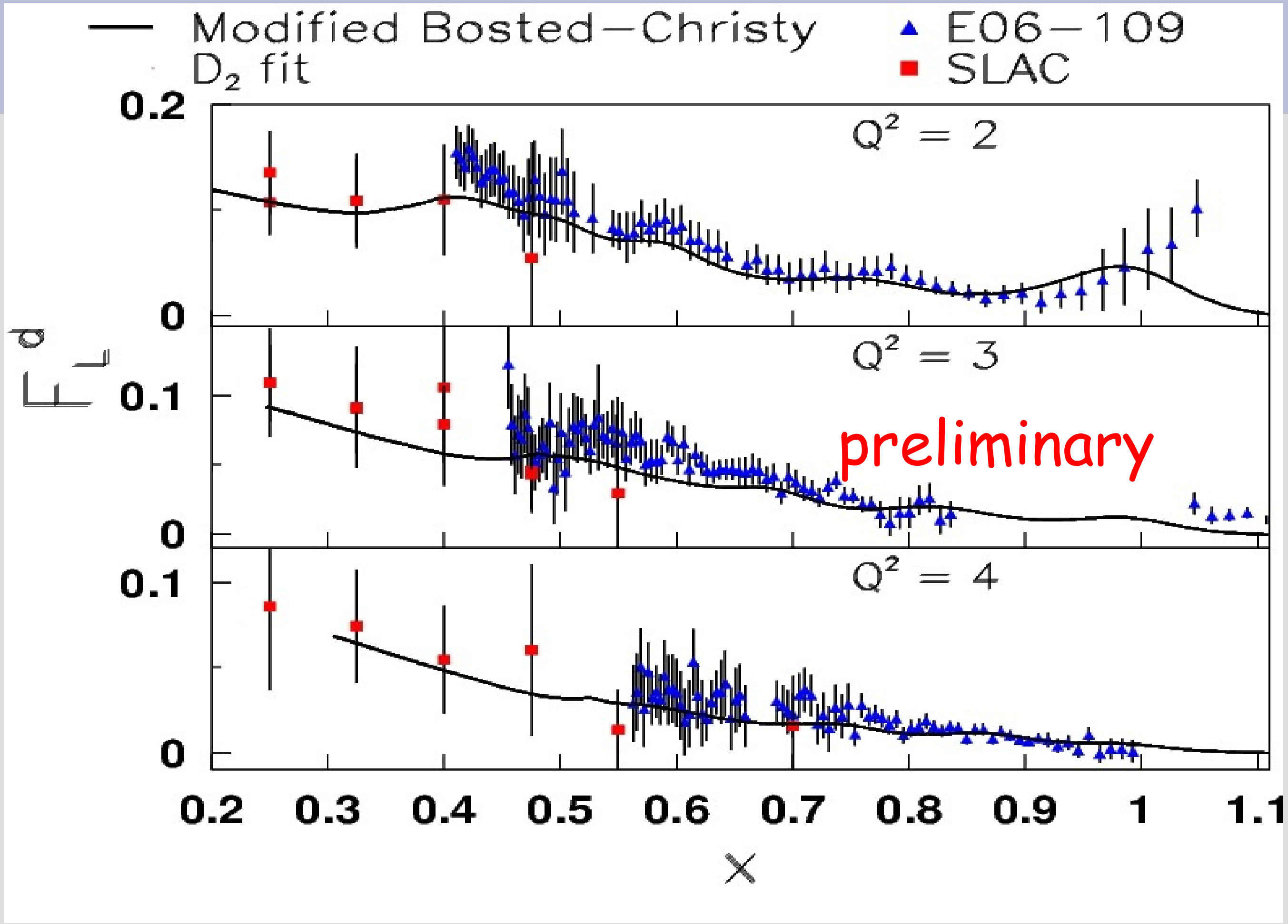
◆ Allow higher precision non-singlet moment extractions for F_2, F_1 (compare to lattice predictions at Q^2 = 4 GeV^2).

◆ Comparisons of F_L^p and F_L^d (F_l^n) and moments.

Sample E06-009 cross sections

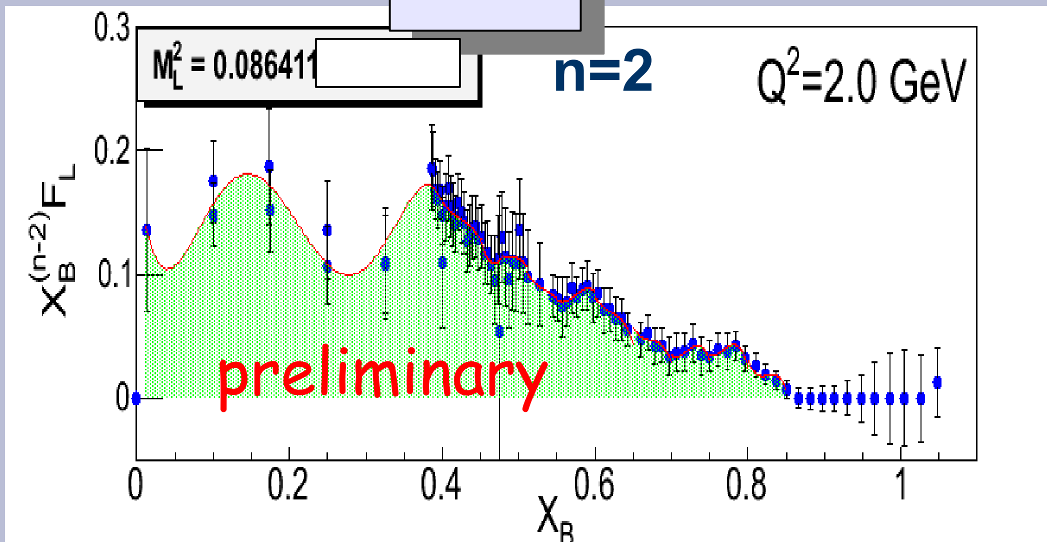


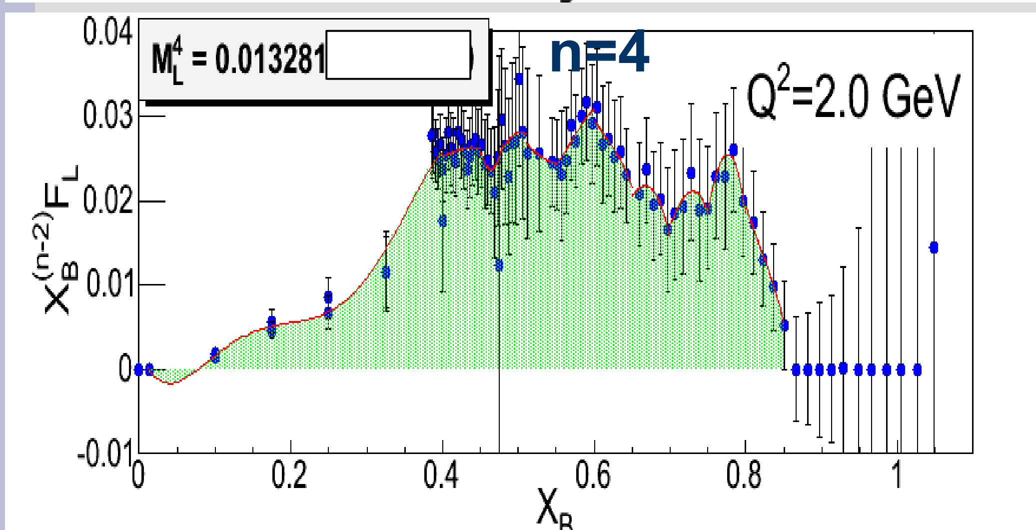
F_L^d results from E06-009



F^d_L integrand of CN moment

Q^2 = 2





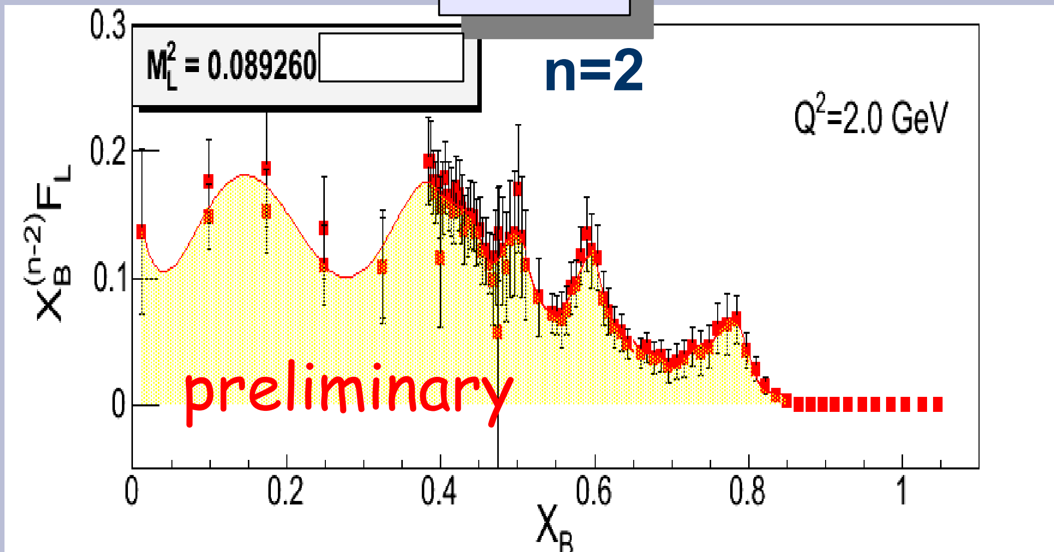
→ Subtract Quasi-elastic contribution from Hall C data using fit.

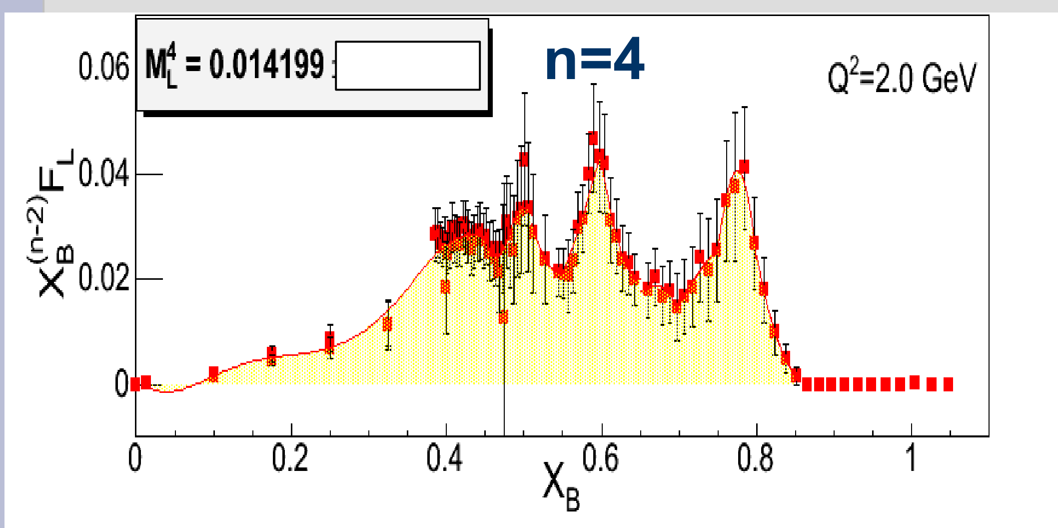
→ Include SLAC data

→ 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

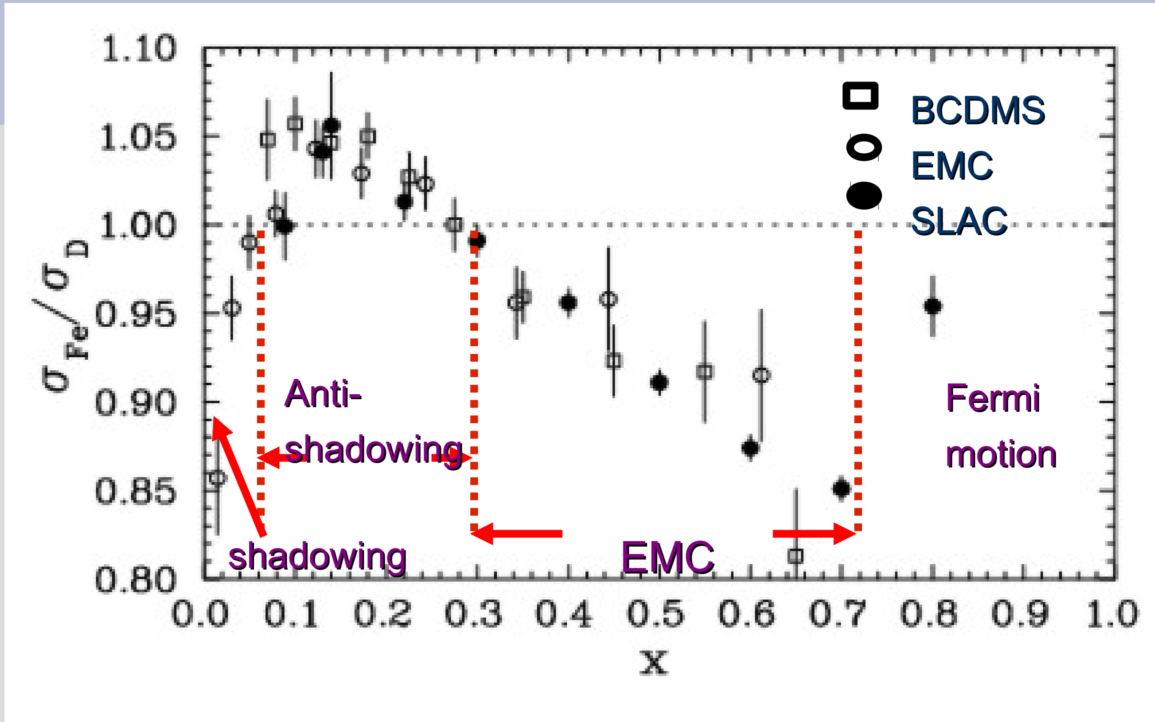
N	F_L^d	$F_L^p - F_L^n$
2:	0.089 (5)	*Coming*
4:	0.0142 (9)	*Soon!*

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

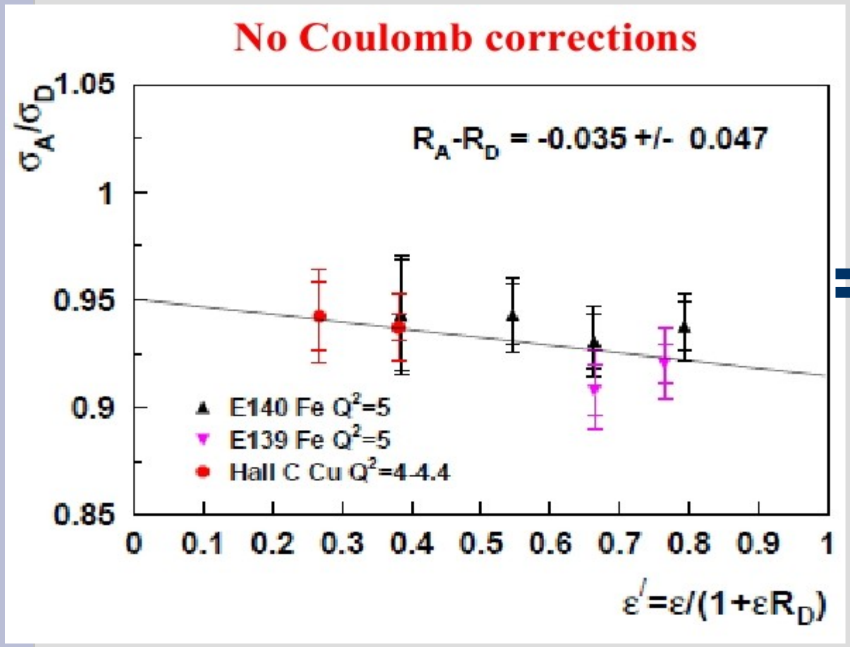
→ SLAC analysis showed *no clear evidence* for $R_A \neq R_d$ ... However

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)

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

→ **Much of systematics cancel!**



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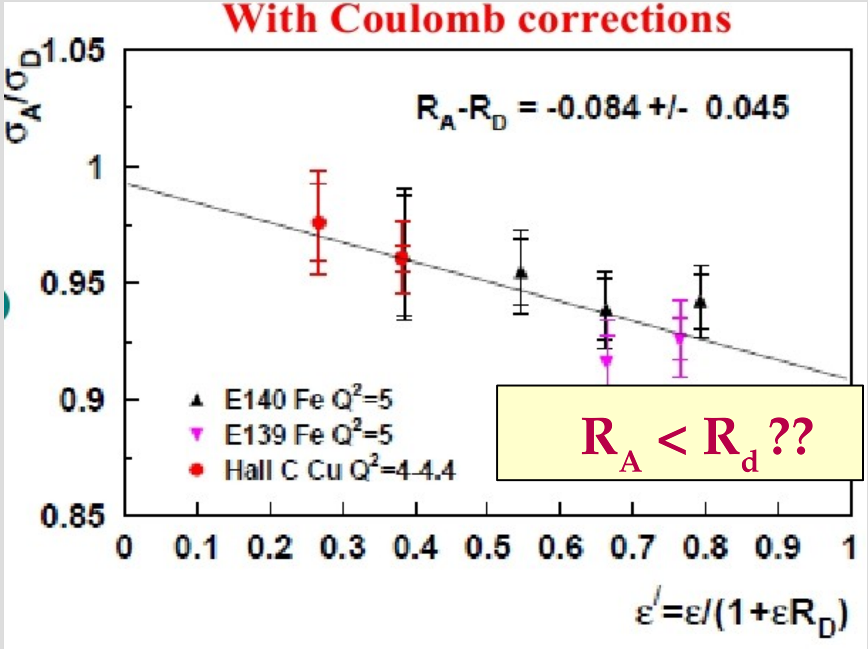
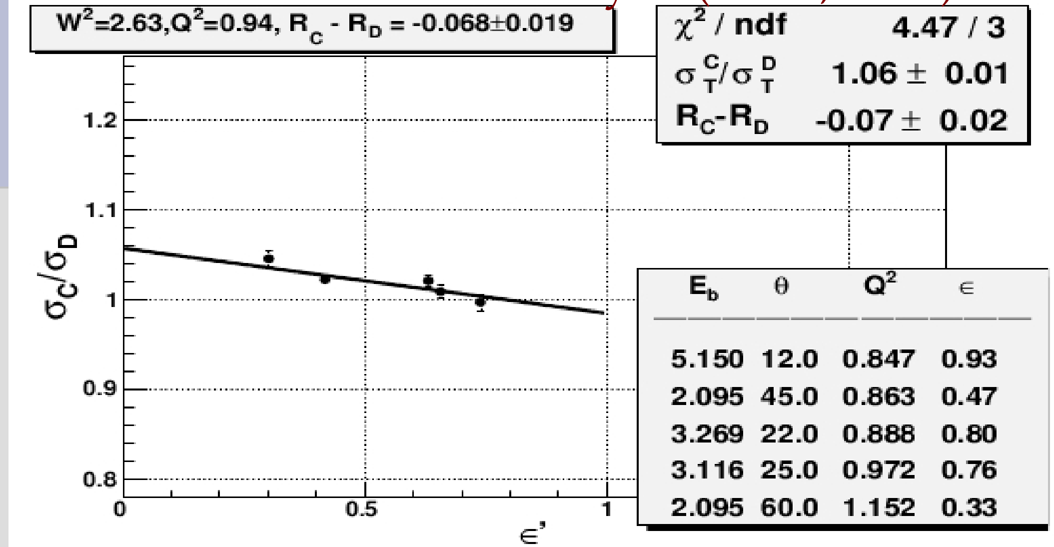
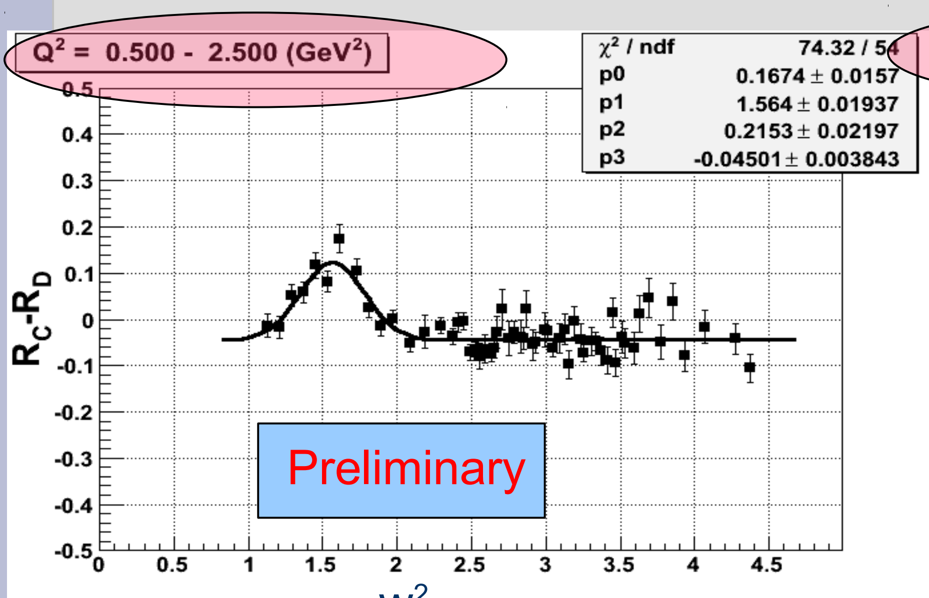
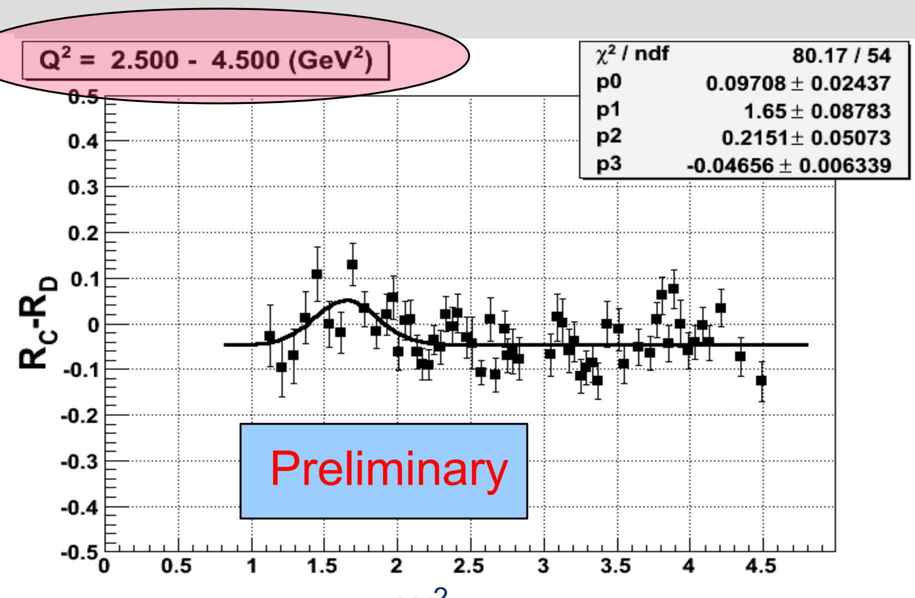


Preliminary results from JLab E06-109(D), E04-001 (A)

Dissertation of V. Mamyan (UVA, 2010)







A consistent Picture seems to be emerging...

Evidence that $R_A < R_d$ for $1 < Q^2 < 5$ and moderate to large *x*.

Further investigation forthcoming

→ Anticipate publication of R (F_L) results from 2007 data this year focusing on $2 < Q^2 < 4$.

→ Anticipate publication of full data set including 2005 low Q^2 data early 2013 for $0.25 < Q^2 < 4$.

One of the extremely useful Off-shoots of this work is global fits

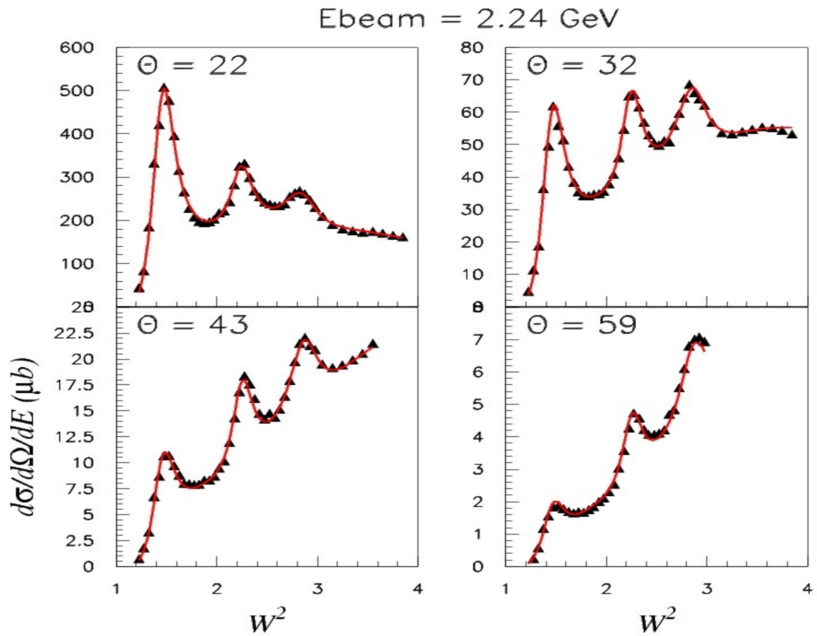
→ Global fits to cross sections / structure functions were performed For ra>diative corrections and bin-centering corrections.

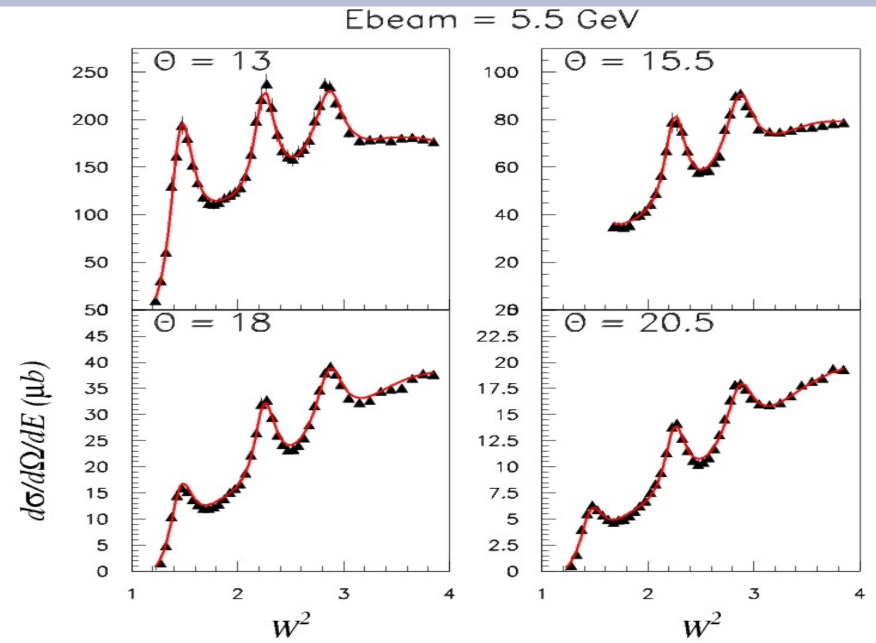
→ nucleon structure function (F1p, F2p, FLp, F1n) were determined from fits to proton and deuteron data.

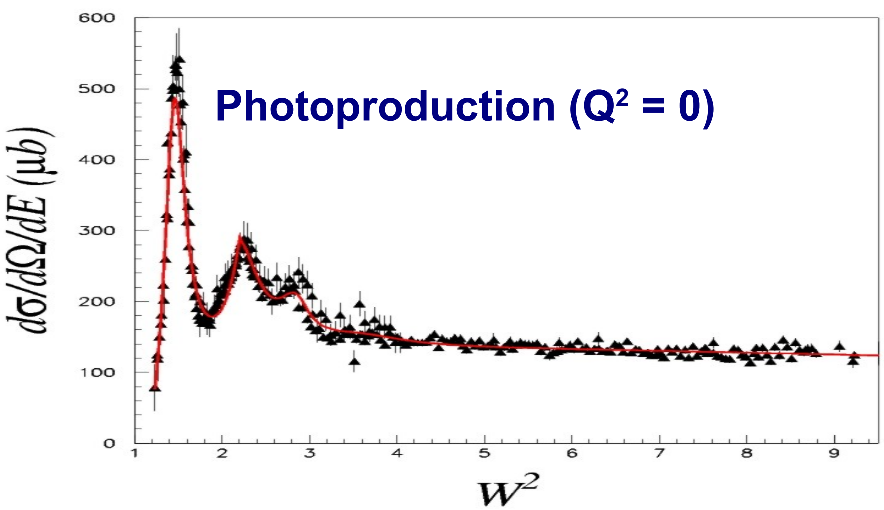
→ QE contribution determined from either sampling wf momentum Distribution (D2) or using Super-scaling formalism of Donnelly-Sick (A > 2)... See talk by M. Barbaro..

Resonance Proton fit

M.E.C. and P.E. Bosted, PRC 81,055213







Kinematic range of fit:

$0 < Q^2 < 8$ and $W < 3$

- **reproduces cross section data to ~3%**
- **Fit to both σ_T and σ_L**
- **Similar fit to deuteron (smeared n+p)**

P.E. Bosted and MEC , PRC 77, 065206

D_2 (n) fit

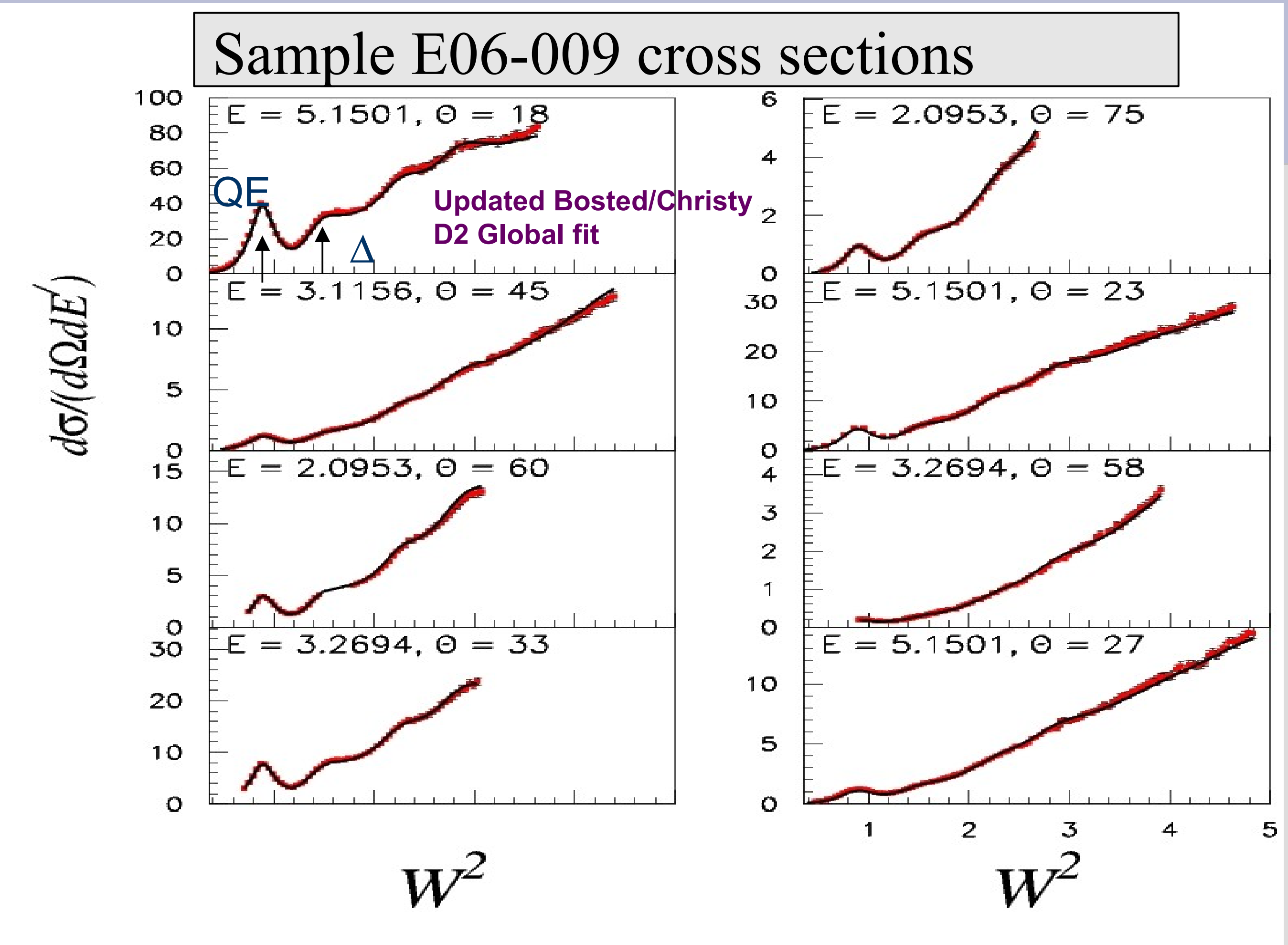
→ In published version Rd = Rp is assumed.

→ Only F1n is parameterized.

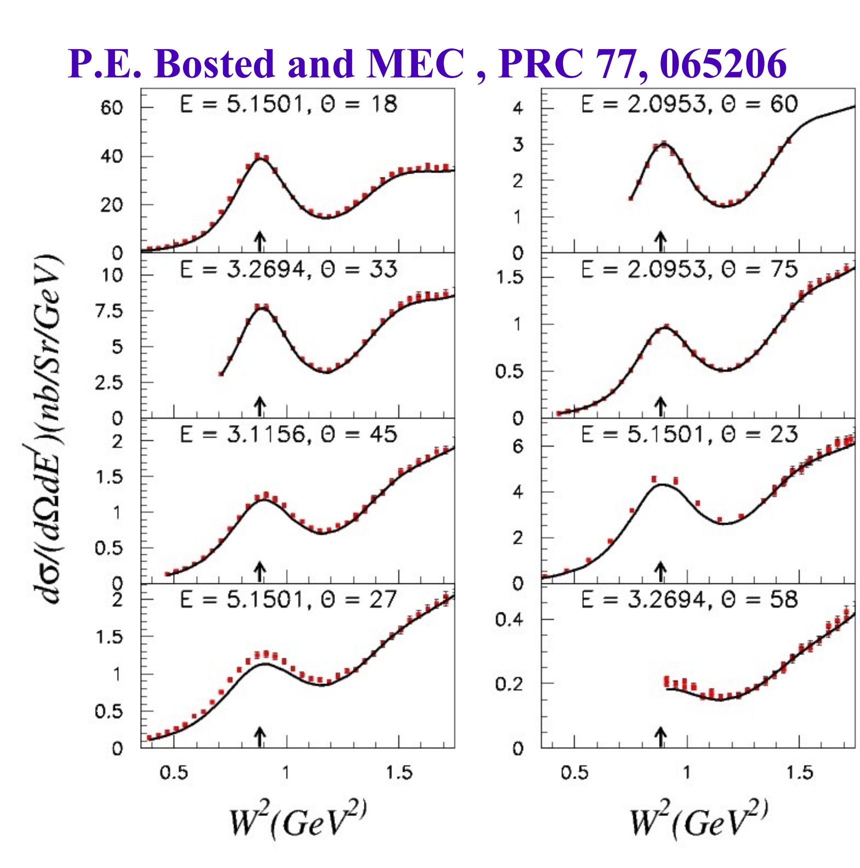
→ Both proton and neutron elastic form factors are taken from fit by P. Bosted. New fits to larger data set are now available.

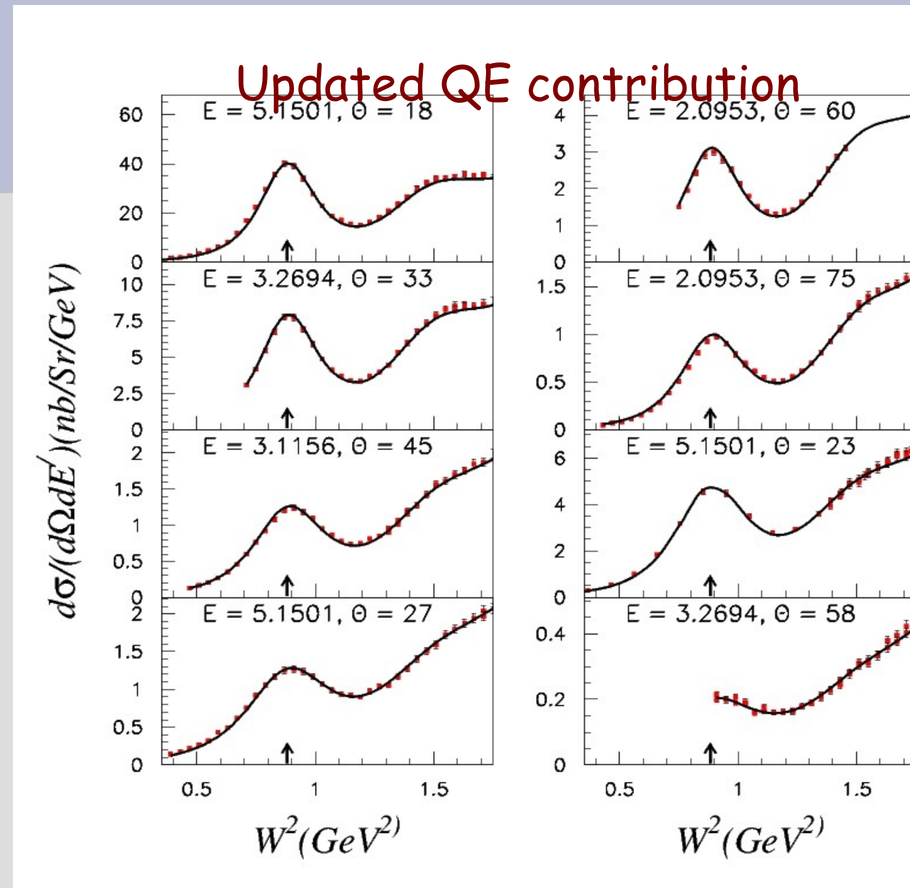
→ Smearing is done by sampling momentum distribution from Paris wf

D_2 (n) fit comparison to E06-009



D_2 (n) fit QE comparison to E06-009





→ Replaced QE smearing with convolution model of W. Melnitchouk.
→ Will study with different potentials & off-shell effects, including BONUS n
→ Replaced p,n form factors with modern parameterizations including new GMN data from CLAS. (biggest contribution to difference)

A>2 fit

→ For QE use superscaling formalism of Sick, Donnelly, Maieron (nucl--th/0109032)

$$\frac{d^2\sigma}{d\Omega d\omega}\frac{1}{\sigma_{Mott}}\epsilon\left(\frac{q}{Q}\right)^4 = \epsilon R_L(q,\omega) + \frac{1}{2}\left(\frac{q}{Q}\right)^2 R_T(q,\omega)$$

$$f_{L,T} \equiv k_F \frac{R_{L,T}}{G_{L,T}}$$

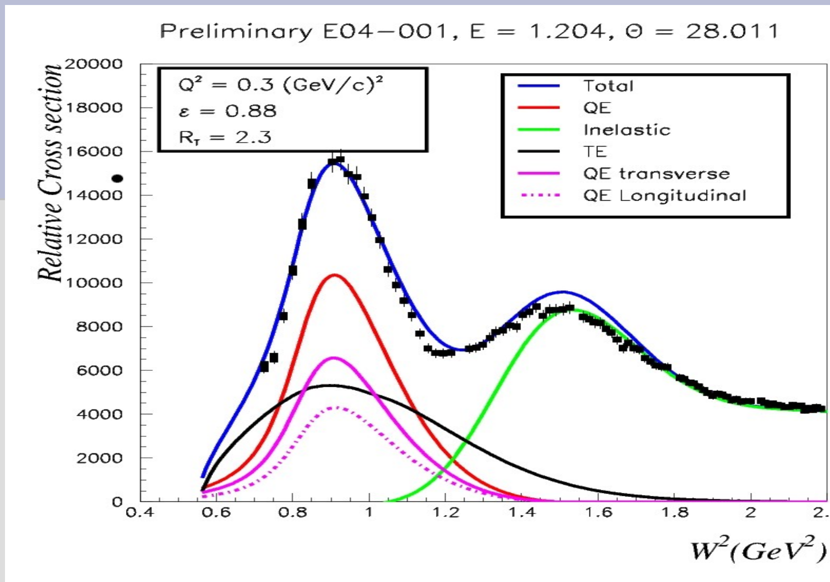
→ Developed by Peter Bosted and tuned by Vahe Mamyan for E04-001.

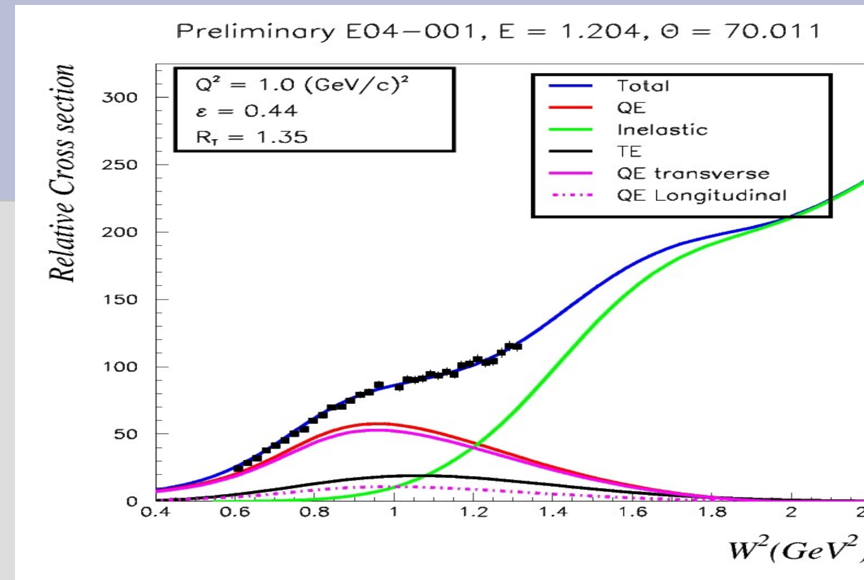
→ uses nucleon fits by by Bosted and Christy as input and Fermi smears for nuclear targets using FG.

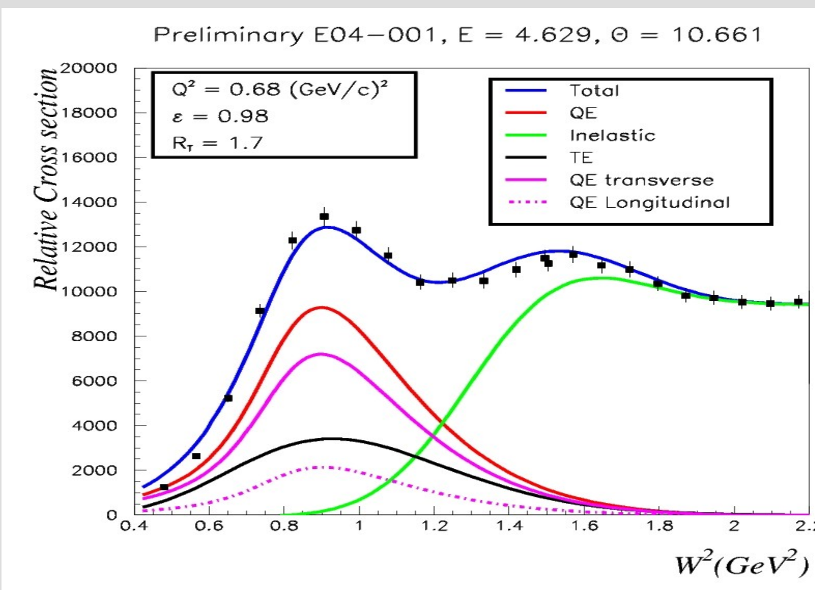
→ nuclear modifications to inelastic structure functions are determined from fit parameters.

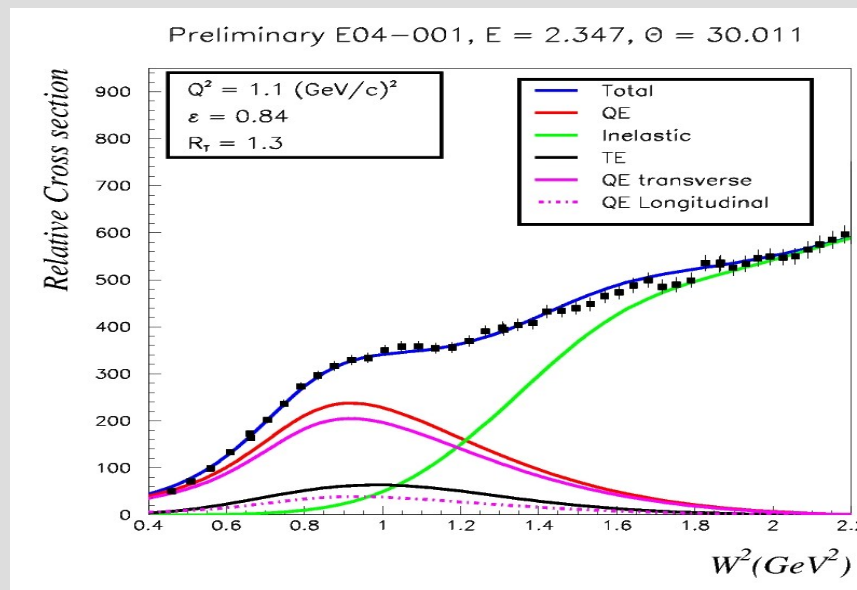
→ Uses existing world data.

Comparison to selected E04-001 data









Bosted-Mamyan fit

Extracting Transverse enhancement at Q^2>0.3 GeV2

$$\mathcal{R}_T = \frac{QE_{transverse} + TE}{QE_{transverse}}$$

In order to fit the data on nuclear targets we find that a ***<u>TE component is needed</u>***.

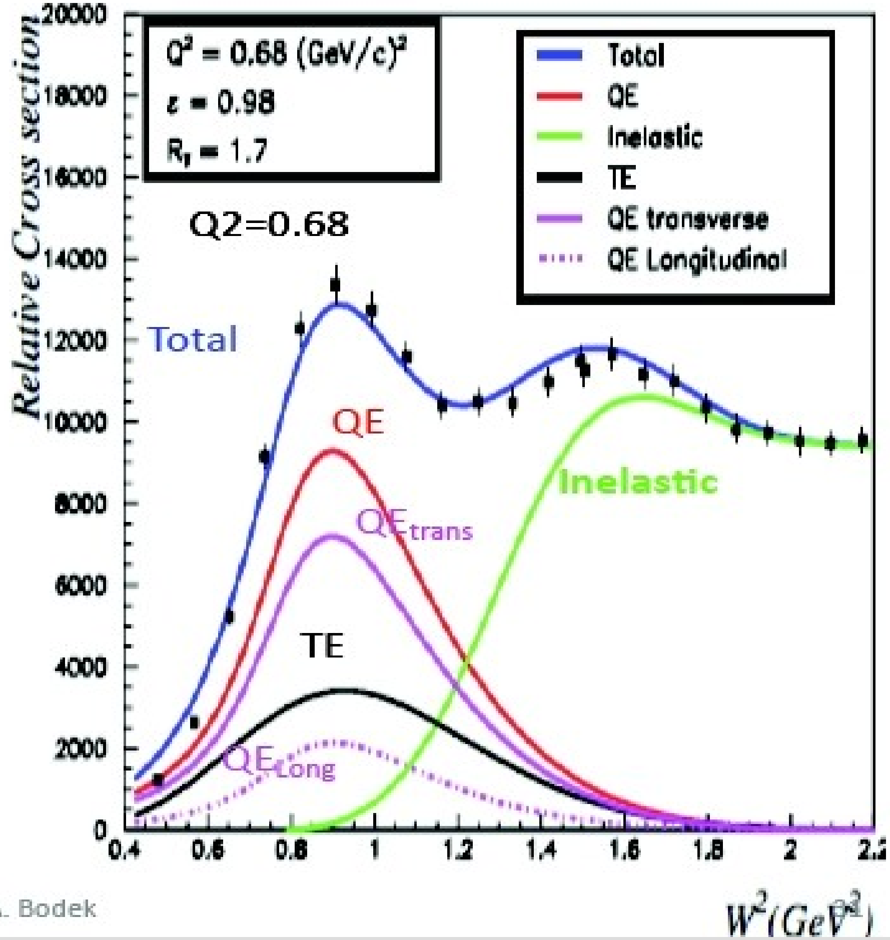
We take the TE component from the fit, Integrate up to $W^2 = 1.5$, and extract $R_T(Q^2) = (QE_{trans} + TE)/QE_{trans}$

Assign a conservative systematic error to R_T (since some of the transverse excess may be produced with final state pions)

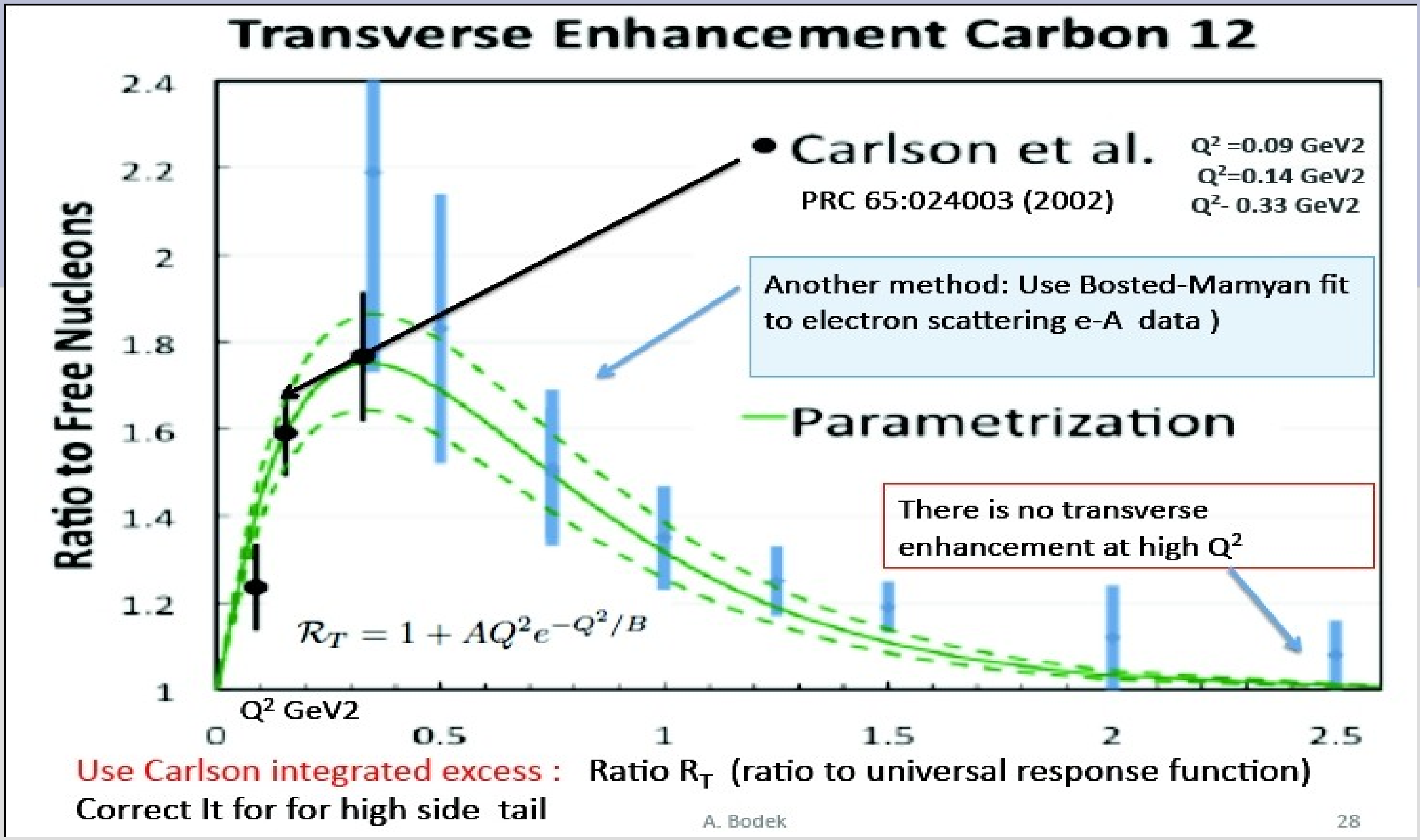
(In future we plan to improve it with updated L-T separated data from E04-001)

Primary purpose of this preliminary fit was as input to radiative corrections.

A spinoff of the fit is the TE component versus Q2



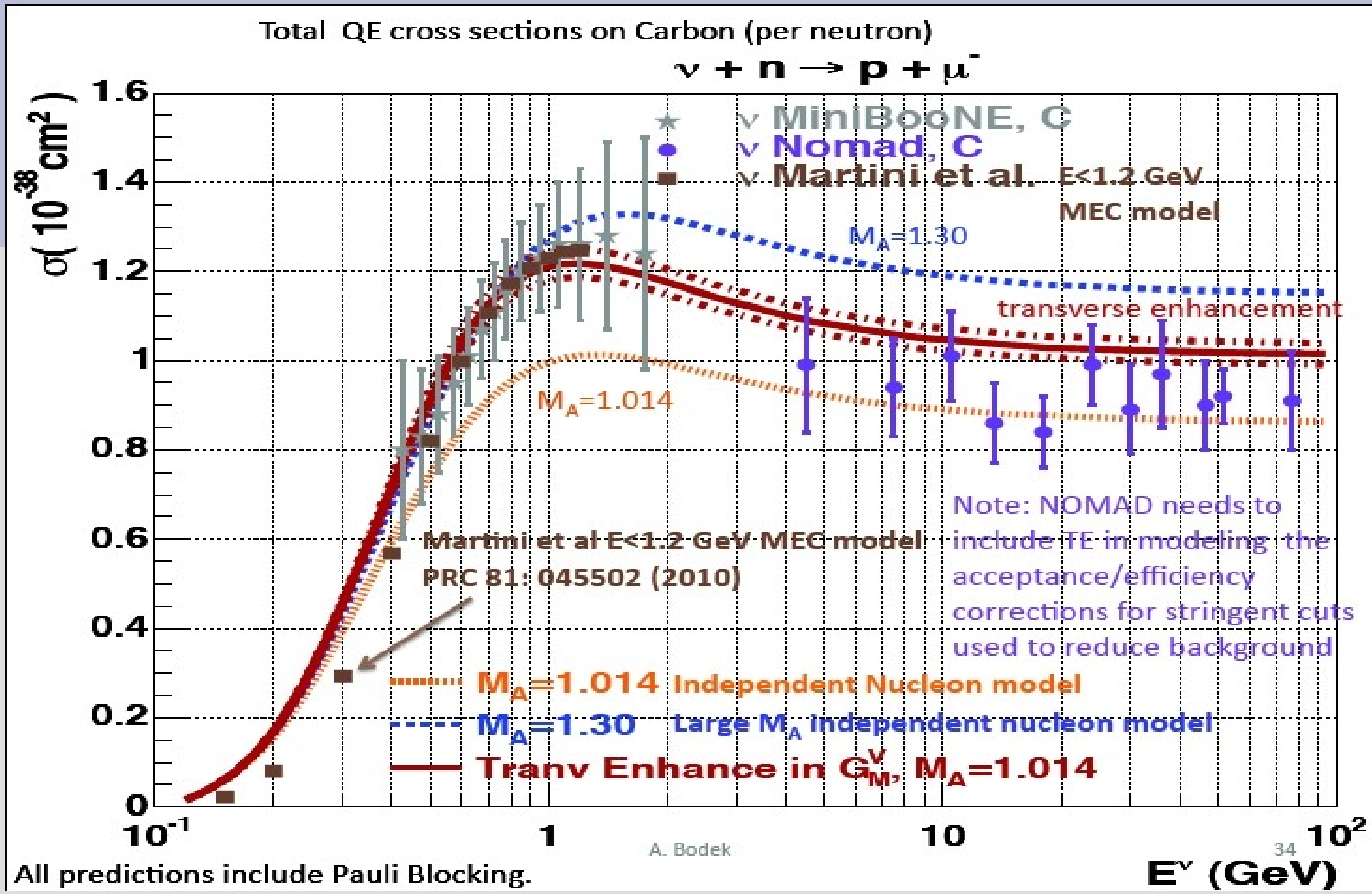
A. Bodek



→ Include TE in vector form factors => predict neutrino cross section

$$G_{Mp}^{nuclear}(Q^2) = G_{Mp}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}$$
$$G_{Mn}^{nuclear}(Q^2) = G_{Mn}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}.$$

A. Bodek, H. Budd, M.E.C., Eur.Phys.J.C71:1726,2011 (arXiv:1106.0340)



→ TE resolves most of tension between high and low E_ν data.

→ Enhancement is relative to independent nucleon FG, whether Underlying physics is MEC or not.

Summary

→ Lots of new JLab results for F_L and R for nucleons and nuclei with publications coming very soon.

→ Fits available which describe the data to few % on average

→ Plenty of physics studies coming in the future

Stay tuned....

And Thank You!

Backup Slides

but additional contributions at finite Q^2, e.g.

Kinematic 'Target Mass' Corrections':

Fractional nucleon momentum carried by the struck quark away from Bjorken limit

$$\xi = 2x/(1+r)$$

With

$$r = 1 + \nu^2/Q^2 = \sqrt{1 + \frac{4M^2x^2}{Q^2}}$$

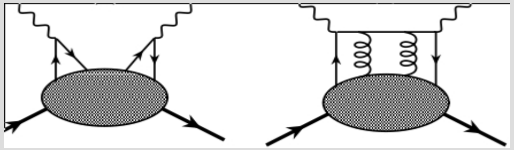
$$F_2^{TM}(x,Q^2) = \frac{x^2}{r^3}\frac{F_2^{(0)}(\xi,Q^2)}{\xi^2} + 6\frac{M^2}{Q^2}\frac{x^3}{r^4}\int_\xi^1 dx' \frac{F_2^{(0)}(x',Q^2)}{x'^2} + 12\frac{M^4}{Q^4}\frac{x^4}{r^5}\int_\xi^1 dx' \int_{x'}^1 dx'' \frac{F_2^{(0)}(x'',Q^2)}{x''^2}$$

What experiments measure **'Massless' limit described by PDFs**

Geogi, Politzer / Barbieri, et.al, '76

Higher Twist contributions (H-T):

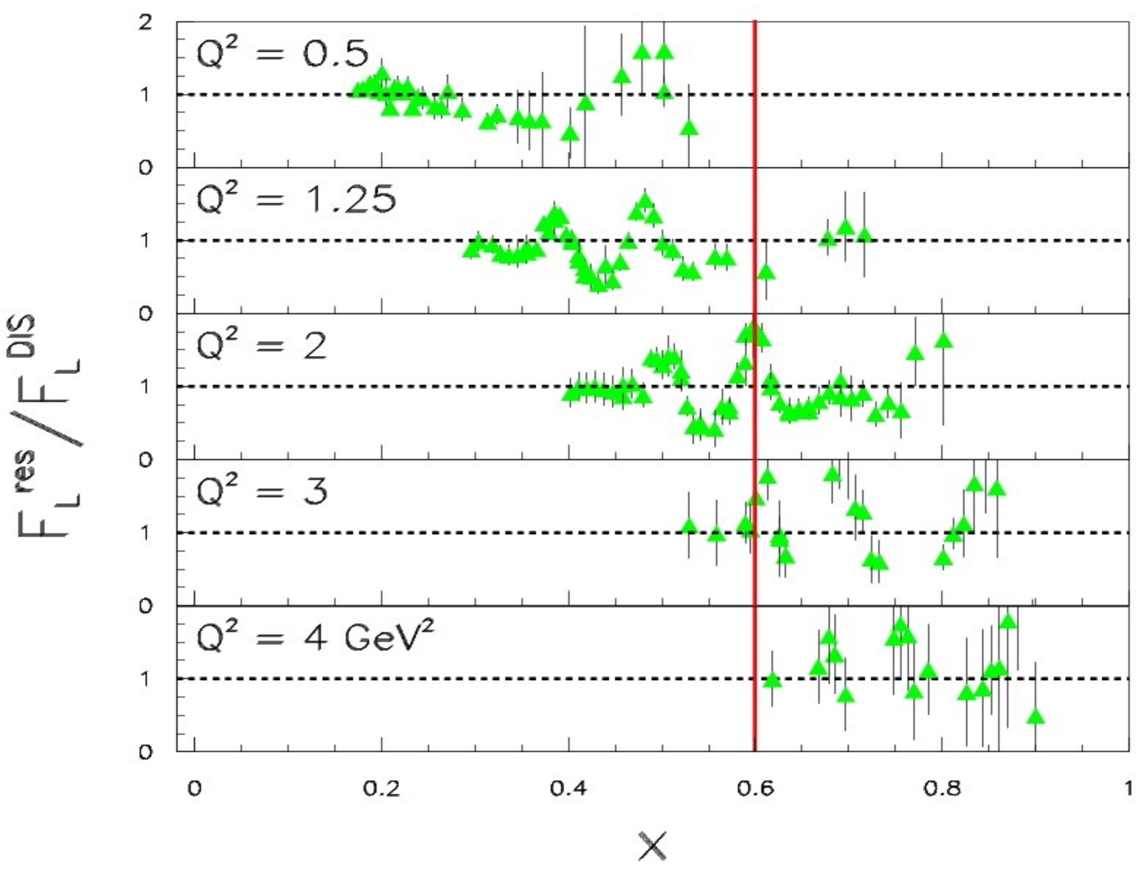
Quark-Quark correlations: eg. gluon exchange between struck and spectator quarks.



Suppressed as powers of $1/Q^2$

Q-H duality: comparisons to empirical DIS fits

- F_2ALLM fit to F_2 H.Abramowicz and A.Levy, et.all., hep-ph/9712415
- R_{1998} to $R = \sigma_L / \sigma_T$ K. Abe et.al Phys.Lett.B452:194-200,1999



Observations

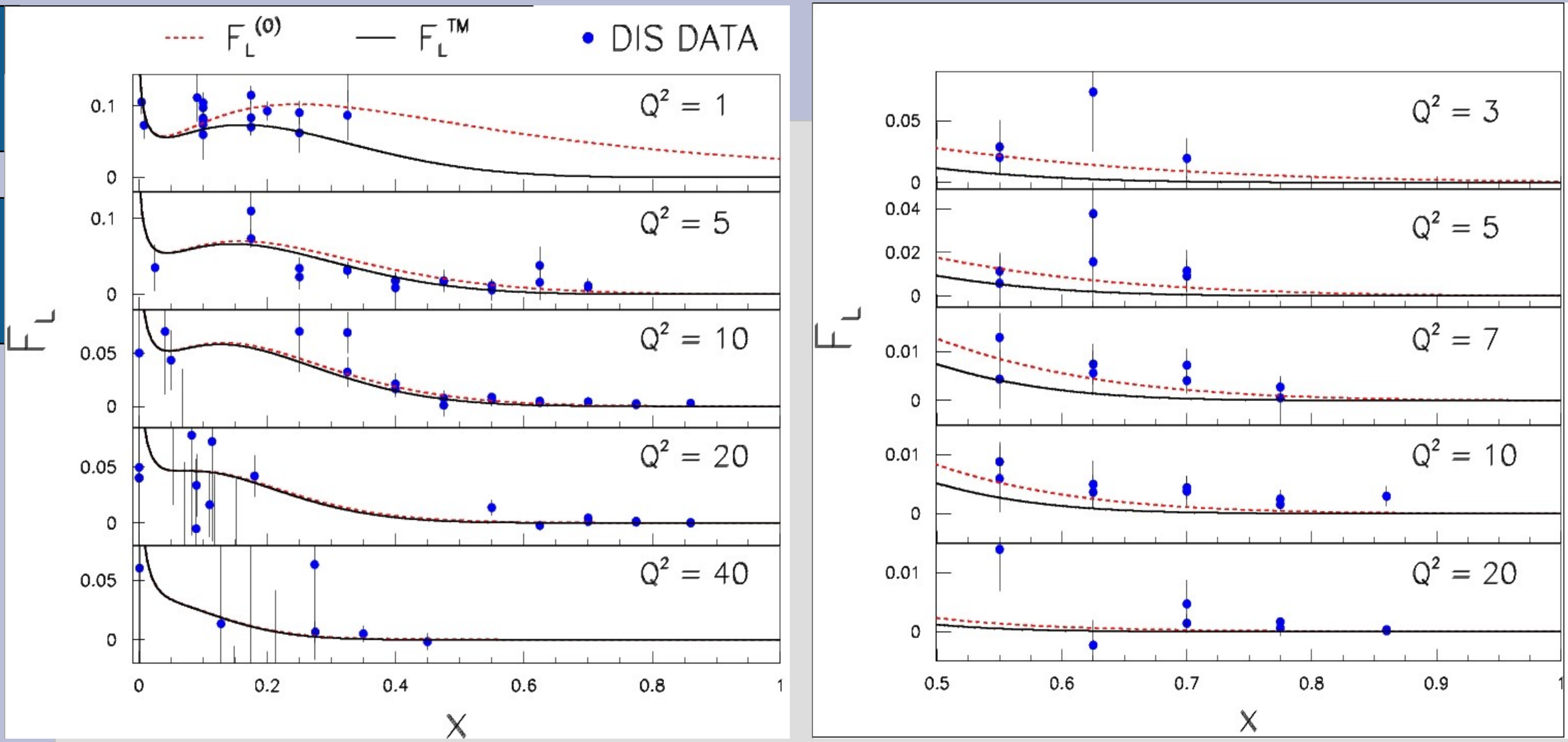
As Q^2 increases, different resonance peak and valleys pass through x=0.6

=> Averaging over a range in Q^2 at fixed x effectively averages out the variations due to the resonance contribution to the structure function.

Can we use this to provide DIS-like data?

F_L^p results from TMC unfolding procedure

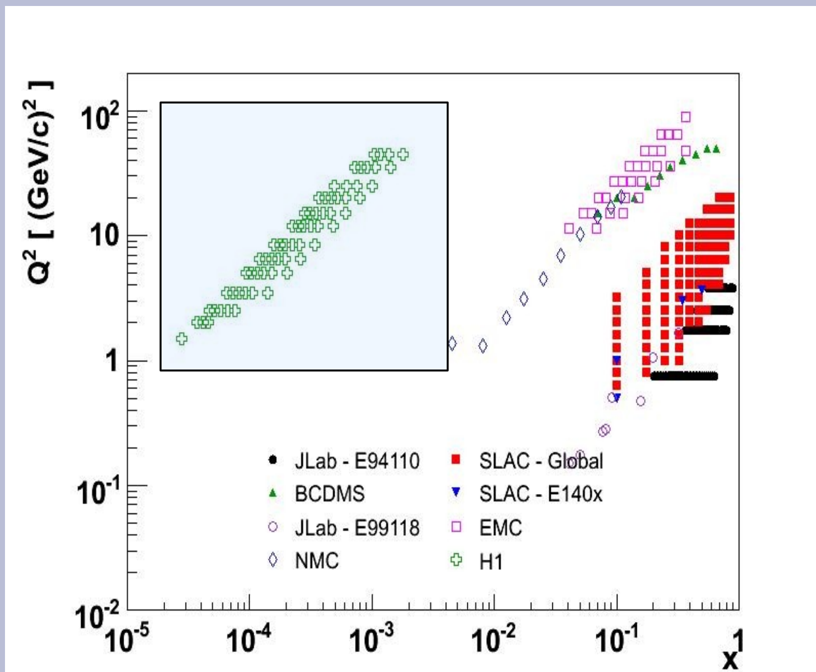
(MEC, J. Blumlein, H. Bottcher – in preparation)

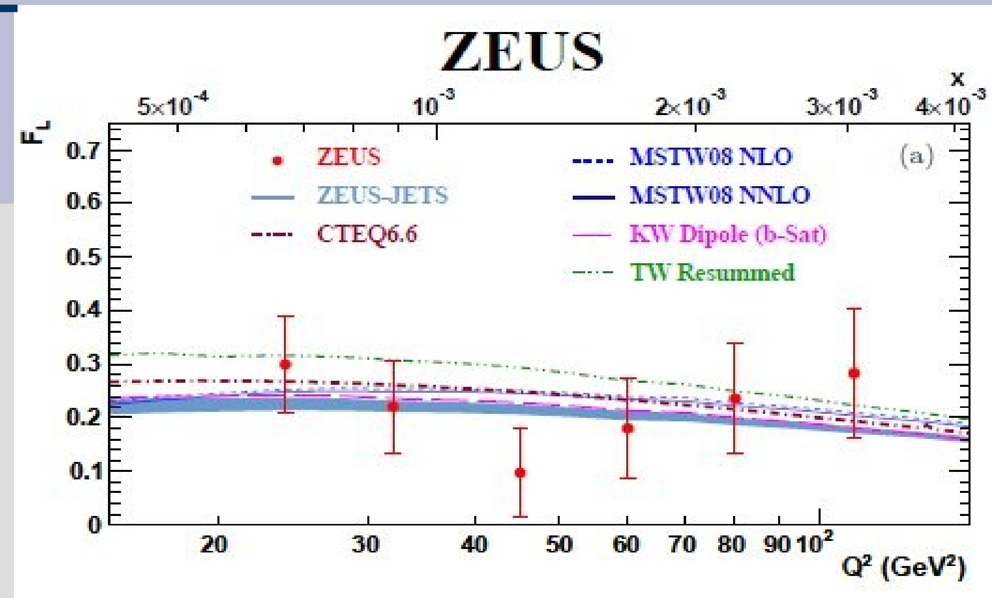


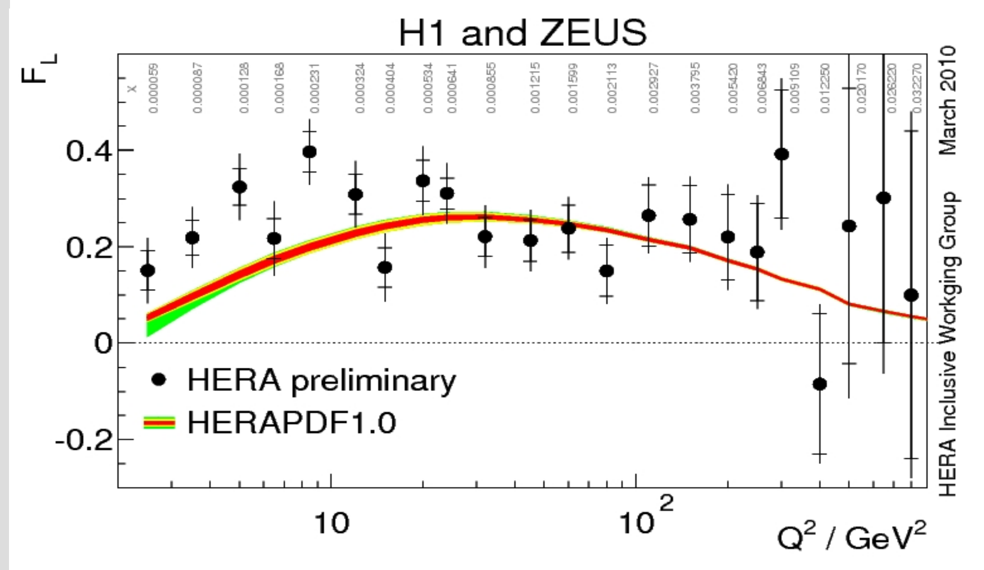
Use to → test pQCD evolution of extracted $F_{L,2}^{(o)}$

→ Further duality studies using as 'scaling' curve

New HERA F_L data at low x



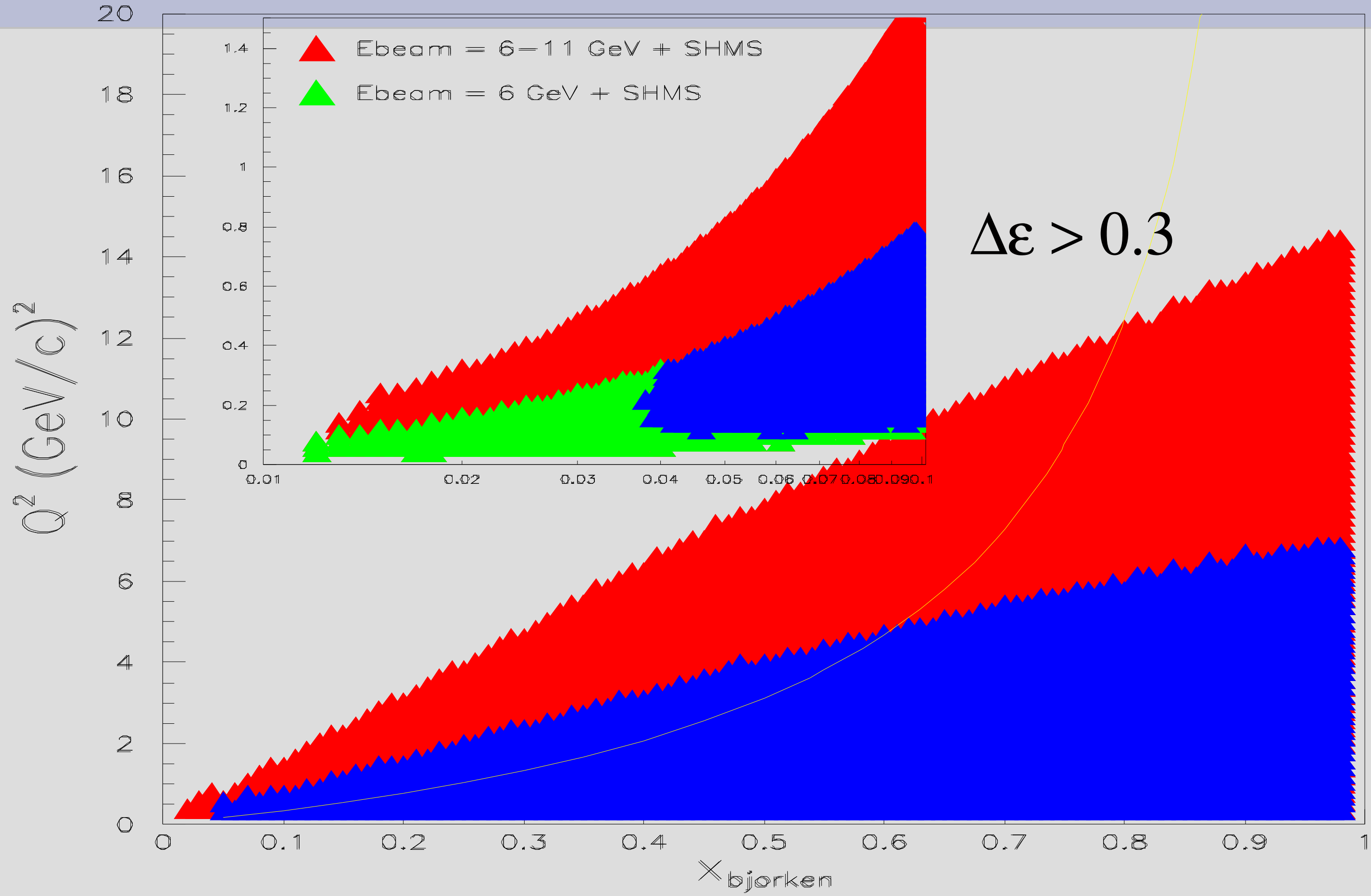




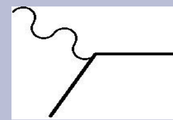
→ Lowering of beam energy during Last years of HERA allowed L/T separations to be performed by both H1 and ZEUS.

→ provides important constraint on g(x).

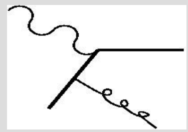
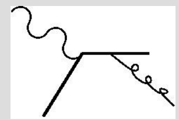
Can significantly increase Q^2 Accessible for F_L at 11 GeV JLab

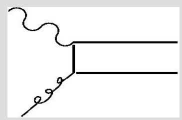
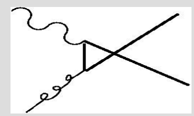


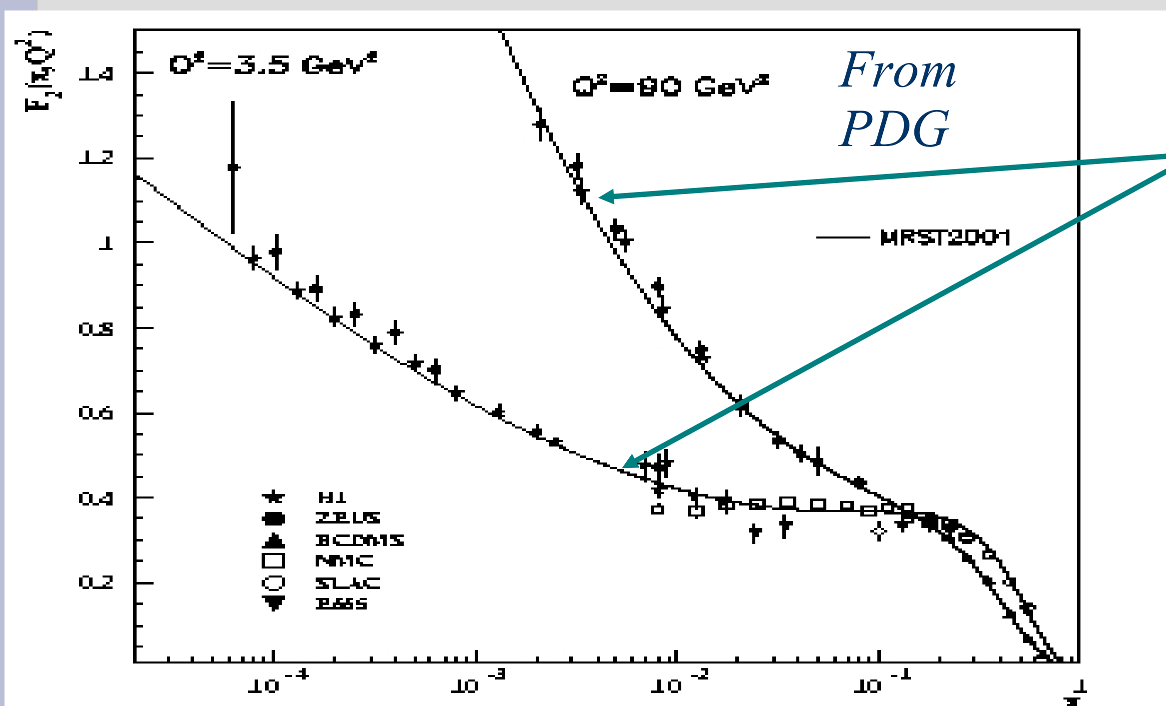
F_2 Structure Function allows study of *pQCD*

$F_2(x) = x \int e_q^{\,2}\, \mathbf{q}(x)\ :\ x \left|\right.$  $\left.\right|^2$ (*parton model prediction of x scaling*)

Order $\alpha_s(Q^2)$ corrections look like:

(1) + ( ) : $x \left|\right.$  +  $\left.\right|^2$ $\alpha_s(Q^2)\log(Q^2/m^2)$ $\mathbf{q}(y)\, P_{qq}(x/y)$

(2) + ( ) : $x \left|\right.$  +  $\left.\right|^2$ $\alpha_s(Q^2)\log(Q^2/m^2)$ $\mathbf{g}(y)\, P_{qg}(x/y)$



Sea quarks mix with glue!

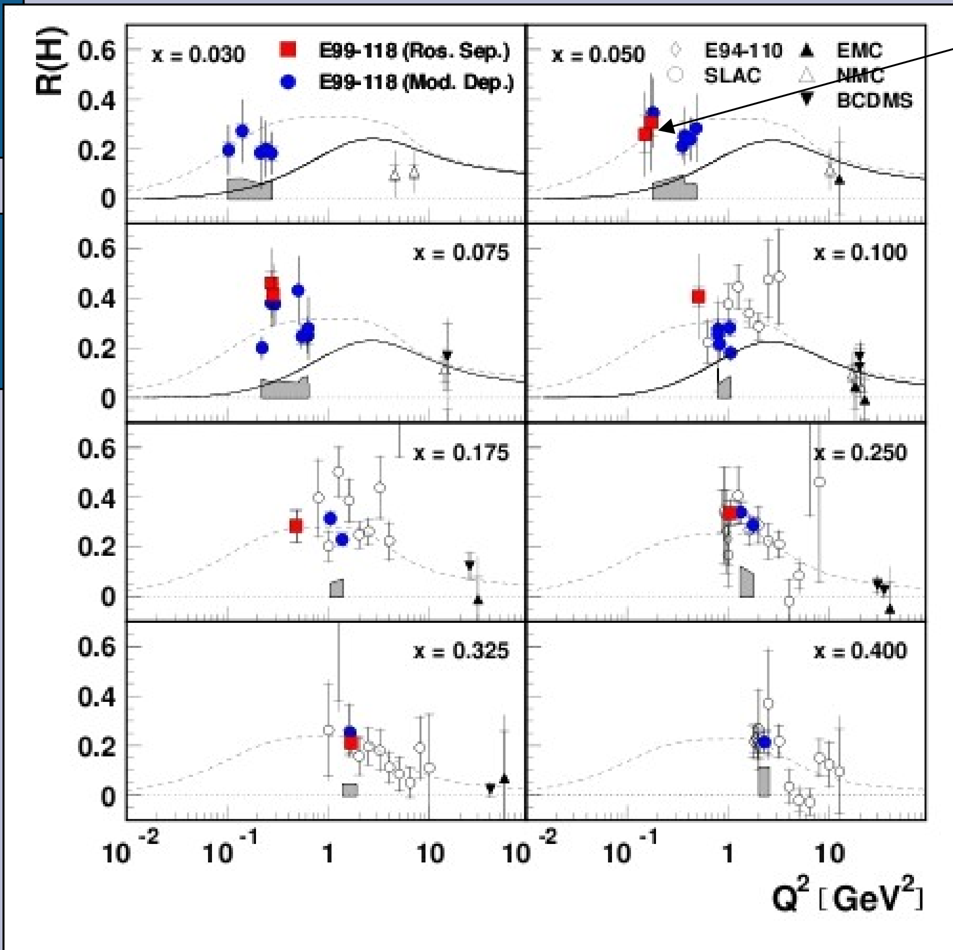
pQCD evolution given by logarithmic scaling violations from (1) and (2)!

(1) introduces transverse quark momentum

(2) Sensitive to the gluon density $g(x)$

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

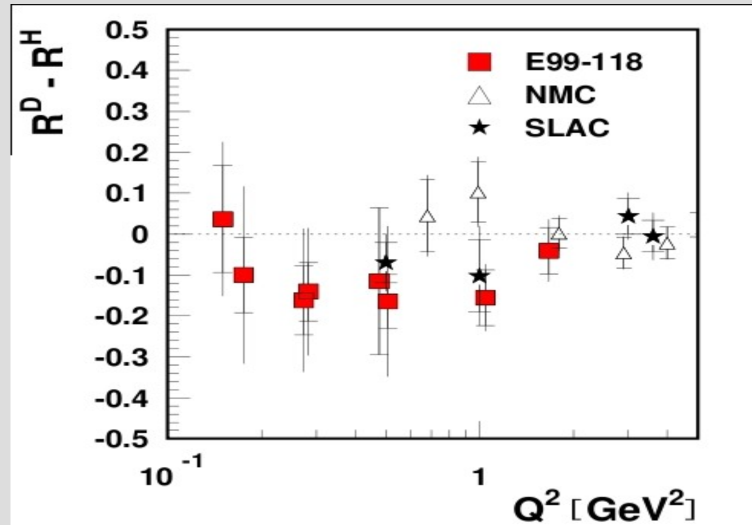
E99-118



From current conservation

R → Q² for **Q² → 0**

But this behavior is not yet observed.



For first time, intriguing hint that

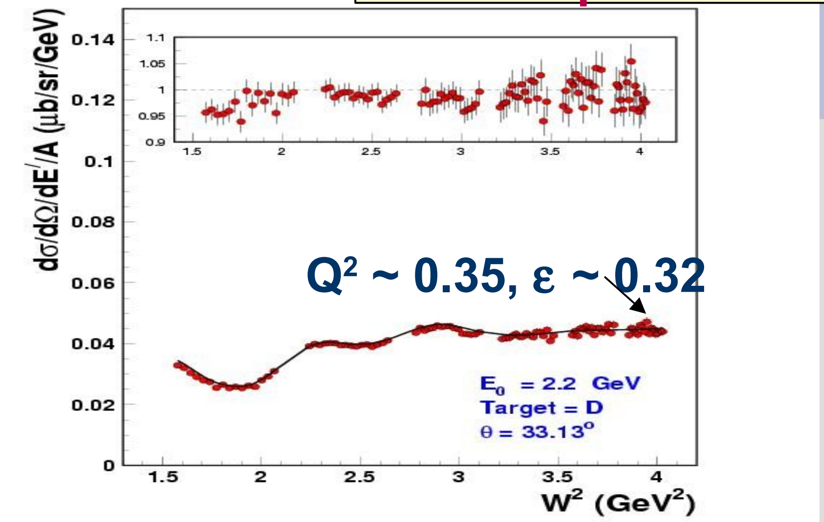
$R_d < R_p$

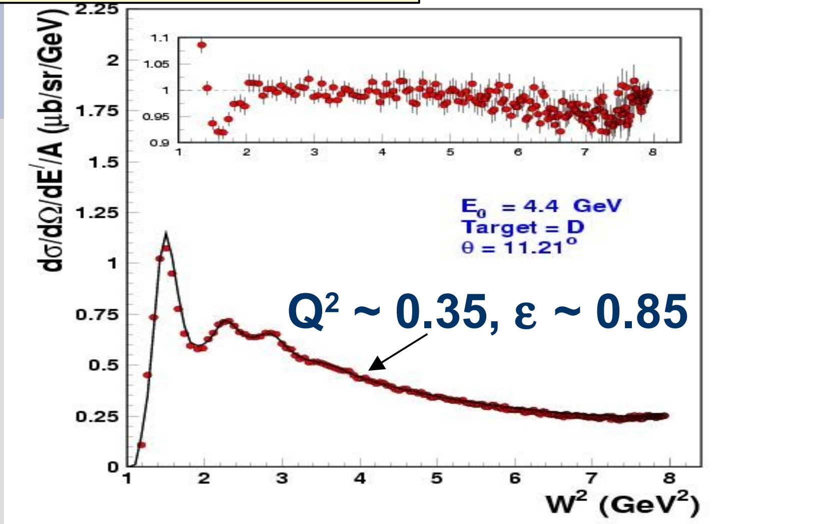
Difference in neutron?

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

E00-002 Results

Sample deuteron cross sections

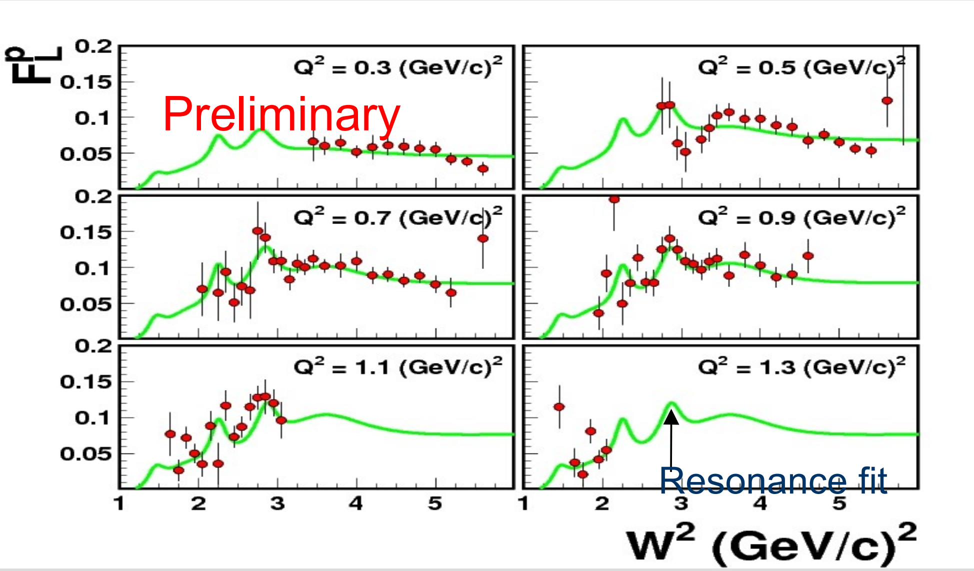




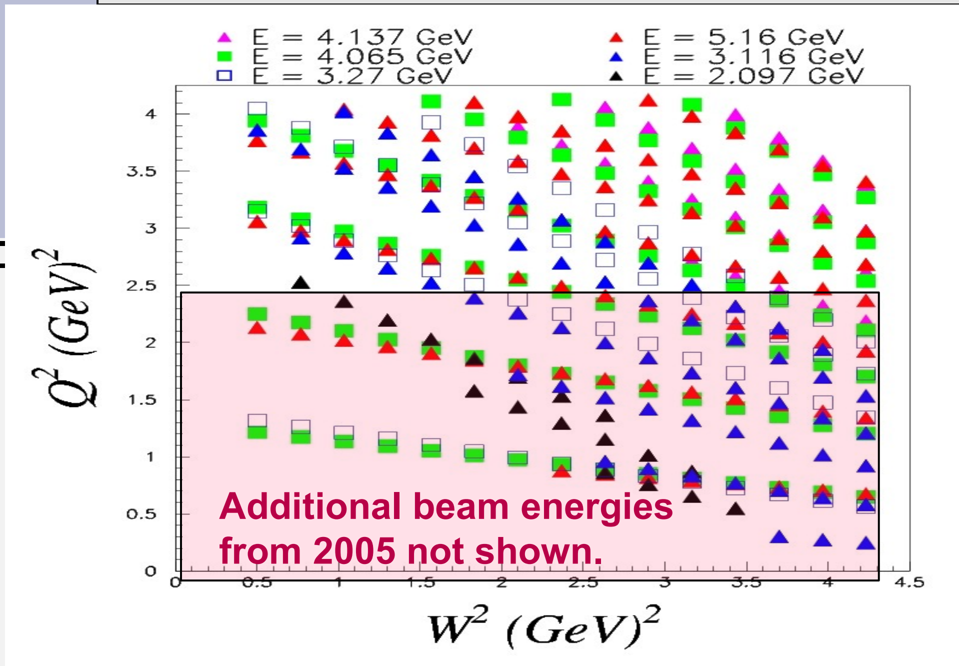
Preliminary results for F_L^p

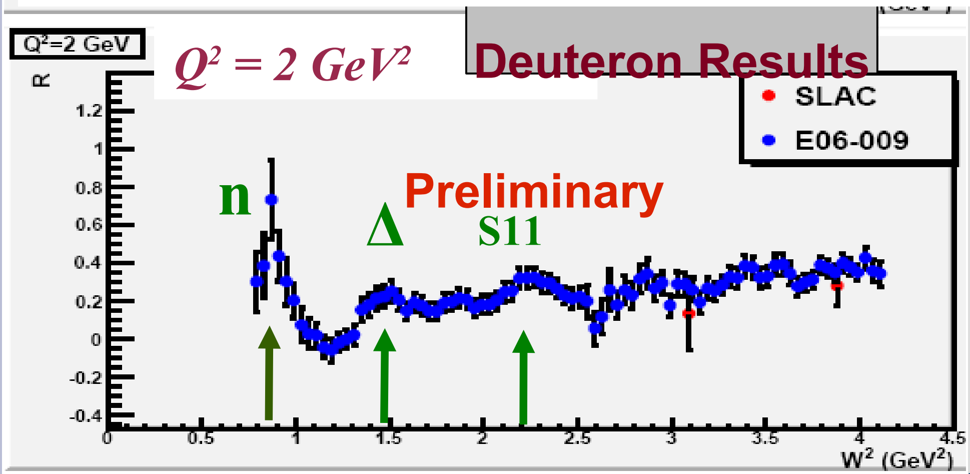
Consistent with resonance global fit.

Results for deuteron and R_d-R_p coming soon.



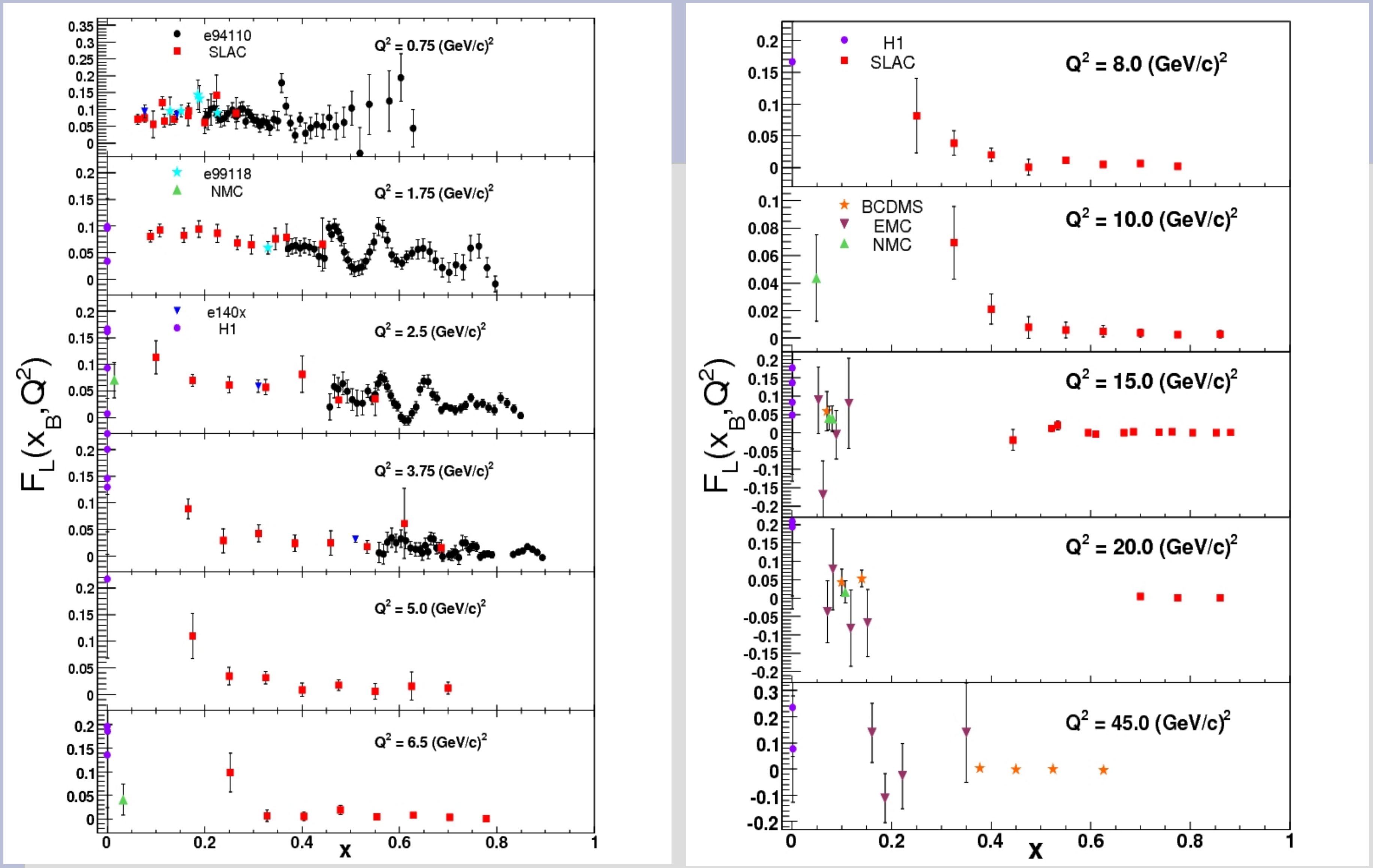
F_L, R on Deuterium and heavier targets
JLab Hall C: E02-109, E04-001, E06-009





- 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.

Global status of the Proton F_L data



Unfolding TM Contributions from data

In the OPE

$$F_2^{TM}(x,Q^2) = \frac{x^2}{r^3}\frac{F_2^{(0)}(\xi,Q^2)}{\xi^2} + 6\frac{M^2}{Q^2}\frac{x^3}{r^4}\int_\xi^1 dx' \frac{F_2^{(0)}(x',Q^2)}{x'^2} + 12\frac{M^4}{Q^4}\frac{x^4}{r^5}\int_\xi^1 dx' \int_{x'}^1 dx'' \frac{F_2^{(0)}(x'',Q^2)}{x''^2}$$

$$F_1^{TM}(x,Q^2) = \frac{x}{r}\frac{F_1^{(0)}(\xi,Q^2)}{\xi} + \frac{M^2}{Q^2}\frac{x^2}{r^2}\int_\xi^1 dx' \frac{F_2^{(0)}(x',Q^2)}{x'^2} + \frac{2M^4}{Q^4}\frac{x^3}{r^3}\int_\xi^1 dx' \int_{x'}^1 dx'' \frac{F_2^{(0)}(x'',Q^2)}{x''^2}$$

$$2xF_1^{TM} = \frac{F_2^{TM} - F_L^{TM}}{r^2}$$

$$2xF_1^{(0)} = F_2^{(0)} - F_L^{(0)}$$

$$r = 1 + \nu^2/Q^2 = \sqrt{1 + \frac{4M^2x^2}{Q^2}}$$

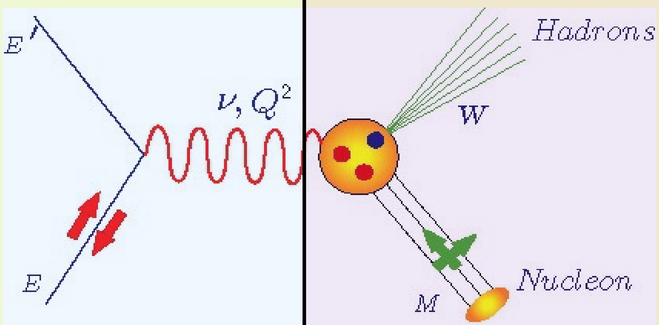
$$\xi = 2x/(1+r)$$

Parameterize $F_{2,L}^{M=0}$ (x,Q^2) and fit $F^{TM}{}_{2,L}$(*x*,Q^2) to world data set => determine TMCs directly from data.

- ***Not* a perturbative expansion**
- ***Assume that higher twist operators obey same formalism.***

*Proton charged lepton data on F_2 and F_L fit for **$0.3 < Q^2 < 250$** and **$x > 1x10^{-4}$***

Scattering of virtual photons from nucleons



Calculable in Quantum Electrodynamics (QED)

Physics of interest (proton/neutron structure)

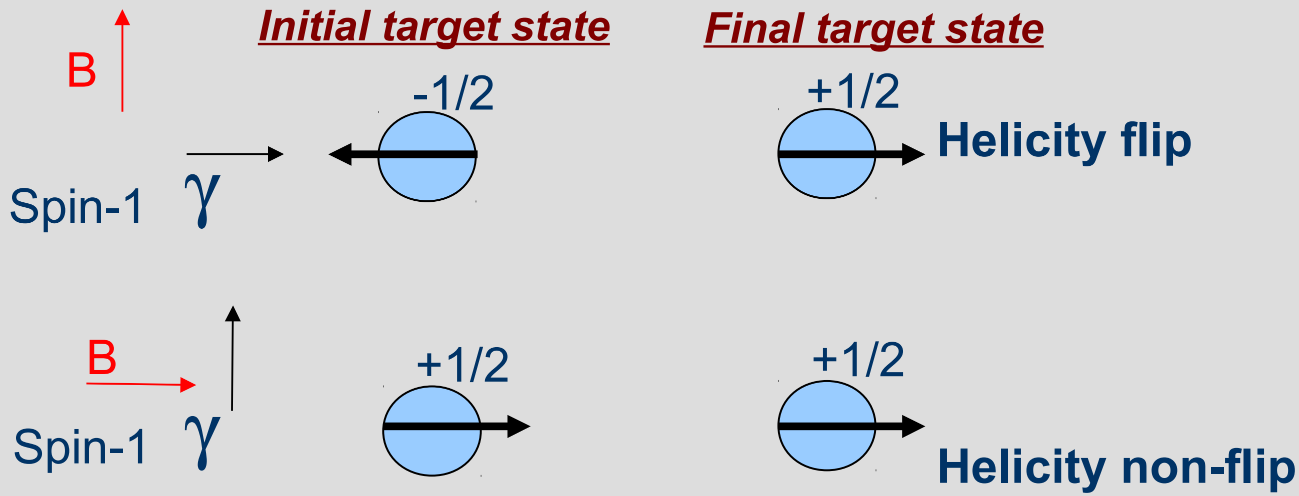
→ Virtual photon scatters from nucleon or from constituents.

→ Exchanged photon can have helicity (0,+/-1) corresponding to **B**-field (longitudinal, transverse)

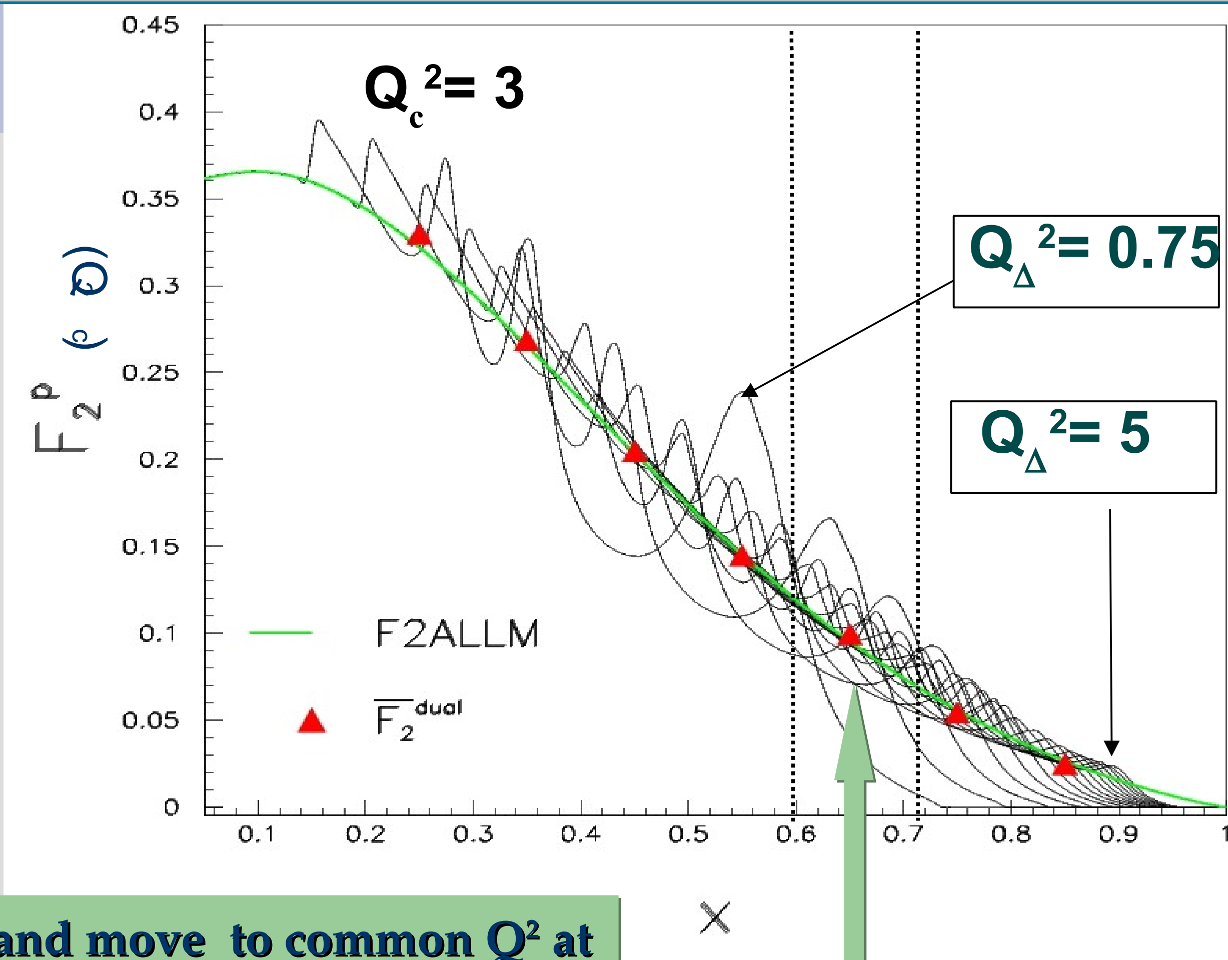
Initial target state ***Final target state***

Transverse Photon exchange (helicity -1 or +1)

Longitudinal Photon exchange (helicity 0)



Duality Averaging Procedure for proton F_2



Averaging over bite in Q^2 effectively averages over resonances.

Can use fit to do averaging and correct with data where available.

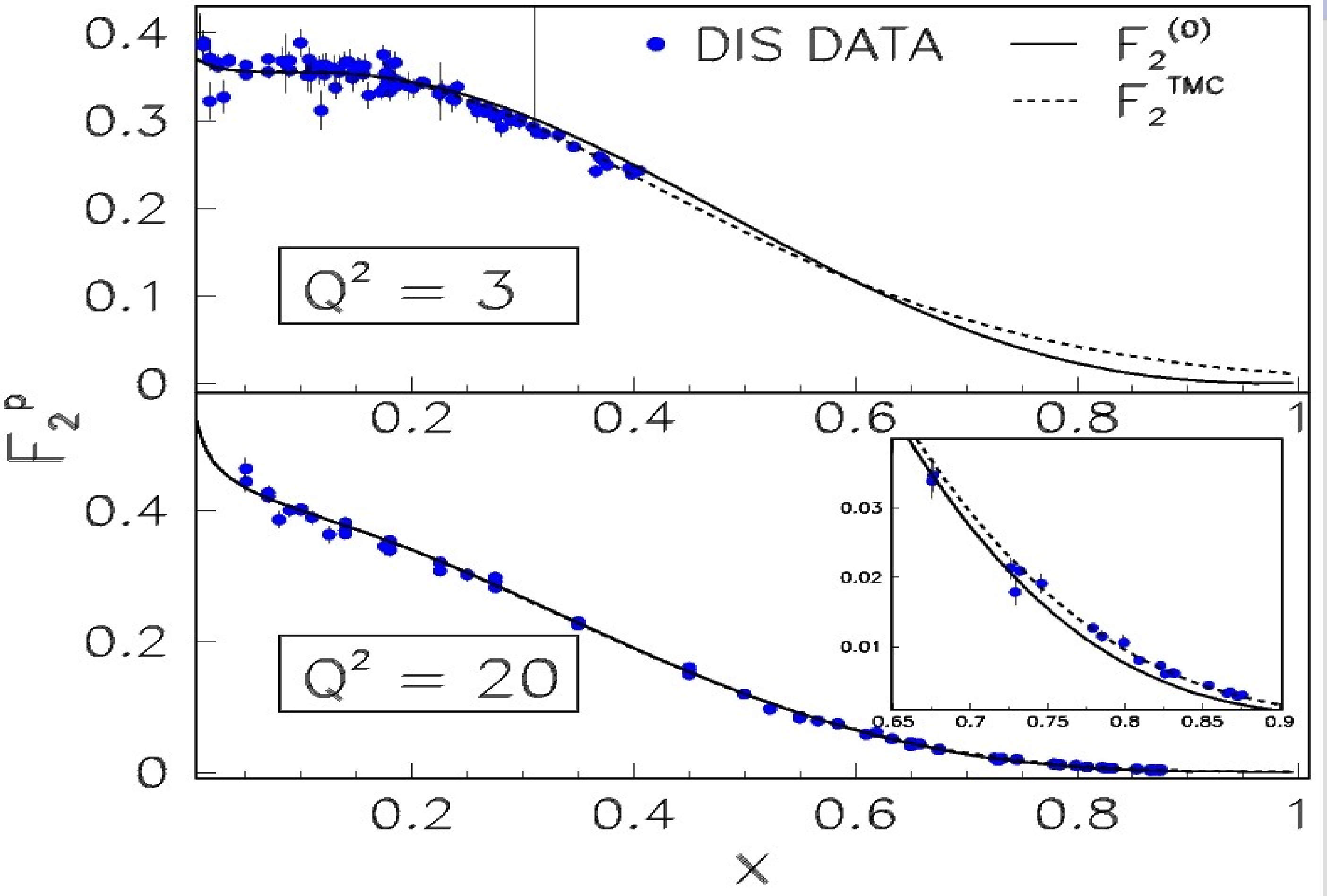
For F_2 resonance average is very close to DIS fit!

Fix x and move to common Q^2 at using Q^2 dependence of DIS fits. (Can iterate to get new fit)

Then average fit/data over this x bin

=> 'DIS-like' data

F_2 fit results



Are the CN moments of data what should be compared to pQCD?

In pQCD

$$M_2^{(n)}(Q^2) = \int dx\, x^{n-2} F_2^{(0)}(x)$$

This is not true for finite M^2/Q^2 due to TMCs. However, *Nachtmann (1973)* found a way to project out the massless limit contribution via

$$\begin{aligned} M_L^{(n)}(Q^2) &= \int_0^1 dx\, \frac{\xi^{n+1}}{x^3} \{F_L(x,Q^2) \\ &+ \frac{4M^2x^2}{Q^2} \frac{(n+1)\xi/x - 2(n+2)}{(n+2)(n+3)} F_2(x,Q^2)\} \end{aligned} \qquad (1)$$

→ Here F_2, F_L are the *experimental* structure functions.

→ Nachtmann moment effectively removes the TM contributions.

How do we determine the Proton F_L Nachtmann Moments?

- Bin data in fine x bins over ($0.01 < x < 1$).

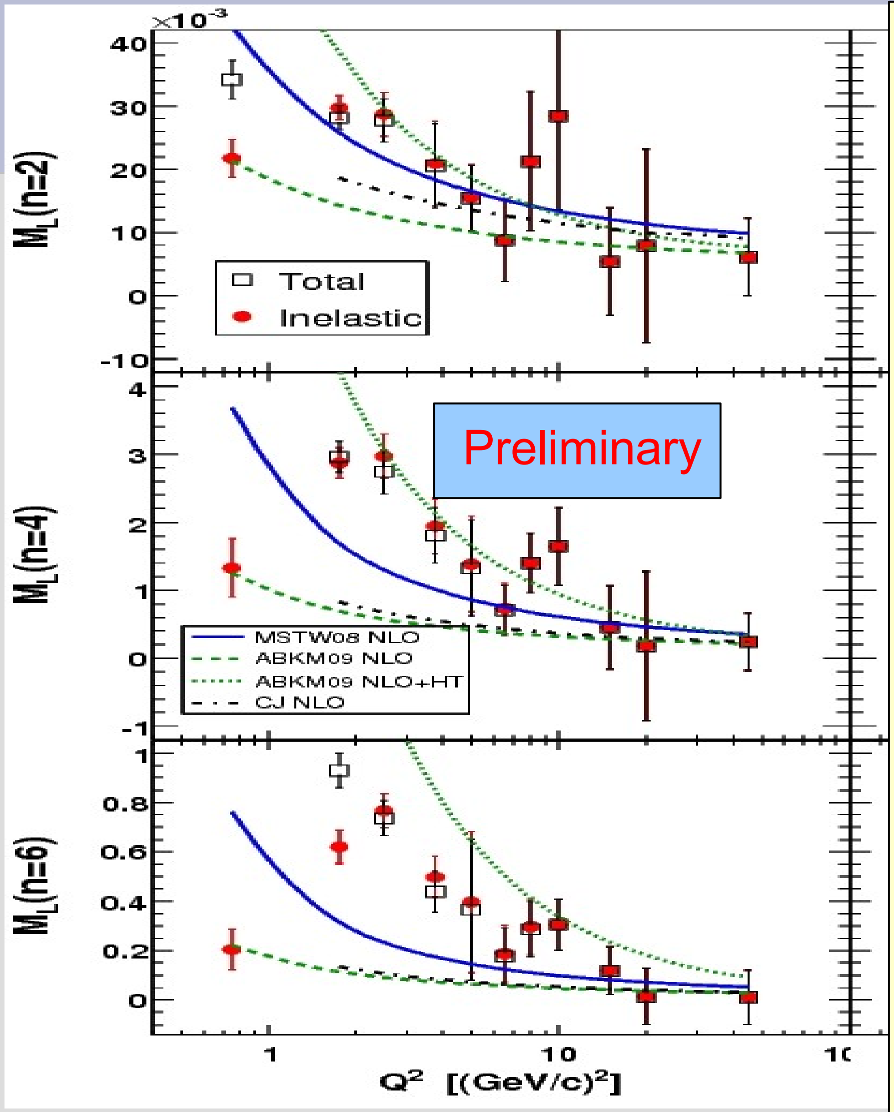
- Utilize resonance and DIS fits to interpolate between data points, where necessary.

- Determine uncertainties in moments from uncorrelated uncertainties by generating 1000 'pseudo' data sets with individual F_L values randomly sampled within uncorrelated uncertainties.
  → produces set of 1000 moment values with uncorrelated uncertainty given width of distribution.

* Nachtmann F_L moment requires F_2 moments be determined.

Results for Proton F_L Nachtmann Moments

P. Monaghan, A. Accardi, M.E.C, C.E. Keppel, W. Melnitchouk, L. Zhu



→ 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.

→ Different PDF NLO results are similar at $Q^2 > 20$, but are significantly different at Low Q^2.

→ Note that only ABKM includes H-T terms in fit. Contribution partially absorbed in MRST gluon?

→ Differences in higher moments likely due to underestimated Gluon strength at high x and/or H-T contributions.

Cornwall-Norton Moments of F_L

Moments of the Structure Function

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

  $$M_n^{1}(Q^2) \equiv \int_0^1 dx \; x^{n-1} \, F_1(x,Q^2).$$

If n = 2 → Bloom-Gilman duality integral!

(integral of DIS or resonance curve is the same)

Operator Product Expansion

$M_n(Q^2) = \Sigma \; (nM_0^2/ Q^2)^{k-1} B_{nk}(Q^2)$ K=1 term is twist-2, eg *free* partons

higher twist pQCD

→ Duality is described in the Operator Product Expansion *as higher twist effects being small or cancelling* - **DeRujula, Georgi, Politzer (1977)**

→ The determination of structure function moments allow us to study the transition of QCD from asymptotic to confinement scales..

From the perspective of a nuclear physicist:

→ Electromagnetic and weak probes are complementary for studying nucleon structure.

→ neutrino scattering is uniquely sensitive to flavor and valence structure from combining proton, neutron, ν and νbar data.

→ electron data provides important constraints on Vector form factors and structure functions, which are crucial input for modeling neutrino cross sections

Charged lepton scattering:

$$\frac{d^2\sigma^{e^\pm p}}{dxdy} = \frac{4\pi\alpha^2 s}{Q^4}\left[(1-y)F_2(x,Q^2) + y^2 x F_1(x,Q^2)\right]$$

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

Neutrino scattering:

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

R is difficult to measure in neutrino scattering and R_A for nuclear targets at low Q^2 and W is not really known.

Estimate of σ_ν uncertainty on R

(from Arie Bodek, based on quark-parton model)

With $\langle \mathcal{R} \rangle = 0.2$ and $\langle f_{\bar{q}} \rangle = 0.1725$, we obtain $\langle \sigma_{\bar{\nu}}/\sigma_\nu \rangle = 0.487$, 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 $f_{\bar{q}}$ (as shown in Table 3).

Want to know R to +- 0.025 to reduce error to 1%

source	change (error)	change in σ_ν	change in $\sigma_{\bar{\nu}}$	change in $\sigma_{\bar{\nu}}/\sigma_\nu$	
R	+0.10	-2.0%	-4.0%	-2.1%	<---- R
$f_{\bar{q}}$	+10%	-1.4%	+2.8%	+4.2$	<-----Sea antiquarks
P (K^{axial}_{sea})	+ 0.3	+1%	+2%	+1.0%	<----Axial sea
N	+3%	+3%	+3%	0	--PDF normalization quark versus gluon
Total		±4.0%	±6.1%	±4.8%	

Error in R leads to large error in the antineutrino cross sections from the inelastic part.

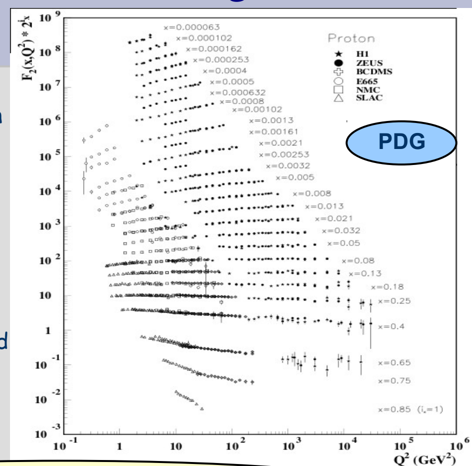
Above does not include error from EMC effect/shadowing, or axial valence. Or resonances and QE components of F2.

Measurements of Structure functions are Critical for a full understanding of QCD

→ Approximate scaling of F_2 with Q^2 provided verification of proton constituents, carrying longitudinal Momentum fraction x.

→ $R = \sigma_L/\sigma_T < 1$ provided evidence that charged constituents were spin 1/2.

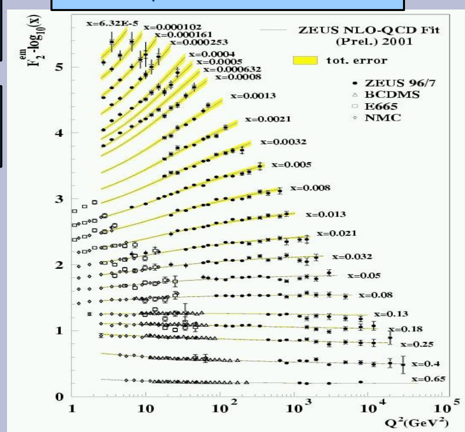
→ Scaling violations measured over orders of magnitude in x and Q^2 well described by universal set of parton distribution functions (PDFs) within pQCD.



F_L data is relatively sparse and much less precise.

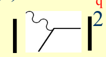
Evolution governed by perturbative QCD

Example from ZEUS NLO fit



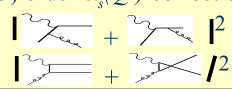
Single quark scattering (LO)

$F_2(x,Q^2) = x\,\Sigma\, e_q^{\,2}\,\mathbf{q}(x,Q^2)$



$F_L = 0 \Rightarrow F_2 = 2xF_1$, $R = 0$:
No transverse quark momentum

(NLO) order $\alpha_s(Q^2)$ corrections



=> transverse momentum and F_L ,
$^*F_L$ directly sensitive to the gluon, g(x).

$$F_L(x,Q^2) = \frac{\alpha_s(Q)}{2\pi} x^2 \int_0^1 \frac{dy}{y^3}\Big(\frac{8}{3}F_2(y,Q^2) + \sum_{i=1}^{2f} e_i^2 (y-x) g(y,Q^2)\Big) + \ldots$$

Scattering with longitudinal photons

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 (Γ)

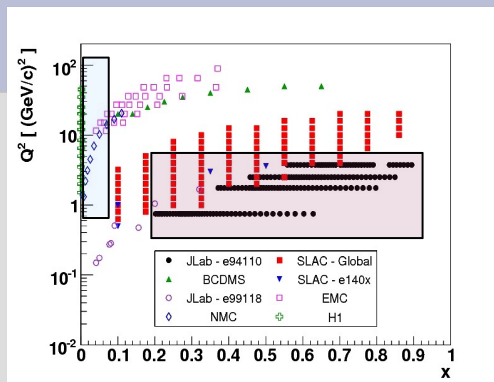
Transverse cross section (σ_T)

Longitudinal cross section (σ_L)

	$\sigma_T \propto$	$\sigma_L \propto$
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)

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)

Lots of new L/T 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+RR	0.1 - 1.7	PRL98:14301
E00-002	p,d	DIS+RR	0.25 - 1.5	Publication in progress
E02-109	d	RR+QE	0.2 - 2.5	Finalizing analysis
E06-009	d	RR+QE	0.7 - 4.0	Publication in progress
E04-001 - I	C,Al,Fe	RR+QE	0.2 - 2.5	Finalizing analysis
E04-001 - II	C,Al,Fe	RR+QE	0.7 - 4.0	Publication in progress

Lots of results expected soon!

E94-110: proton F_L in resonance region

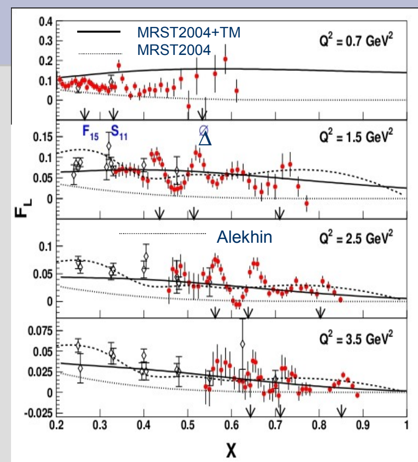
→ ~200 individual L/T separations.

→ 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.



"

Measurements of the Transverse and Longitudinal Structure Functions in Electron Scattering on Nuclear Targets

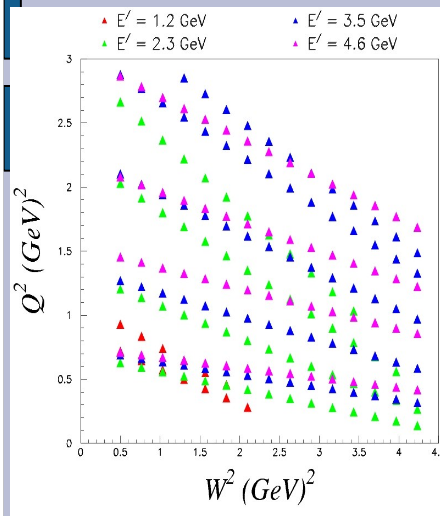
V. Mamyan,[21] A. Ahmidouch,[22] I. Albayrak,[11] J. Arrington,[1] A. Asaturyan,[31] A. Bodek,[24] P. Bosted,[29] R. Bradford,[24,1] E. Brash,[3] A. Bruell,[5] C Butuceanu,[23] M. E. Christy,[11] S. J. Coleman,[29] M. Commisso,[27] S. Connell,[9] M. M. Dalton,[27] S. Danagoulian,[22] A. Daniel,[12] D. 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. Jones,[8] N. Kalantarians,[12] A. Liyanage,[11] C. 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. 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)

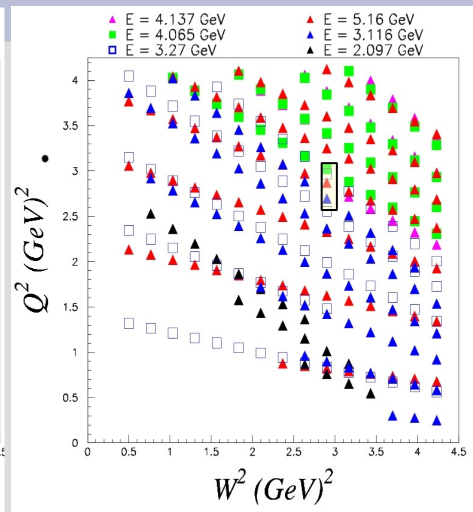
A number of neutrino physicists involved in these measurements

L/T Separations on d, C, Al, Cu, Fe

2005



2007



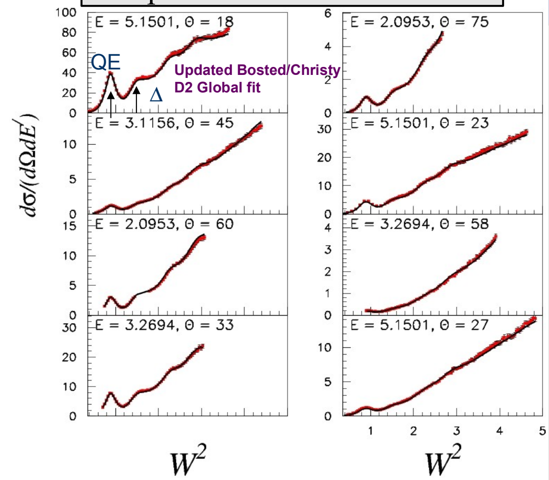
Deuteron F_L and Moments (E02-109, E06-009)

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

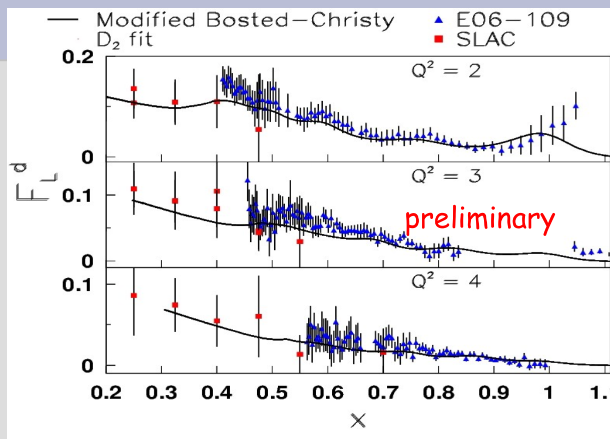
Dissertation of I. Albayrak (Hampton, 2011)

- 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.

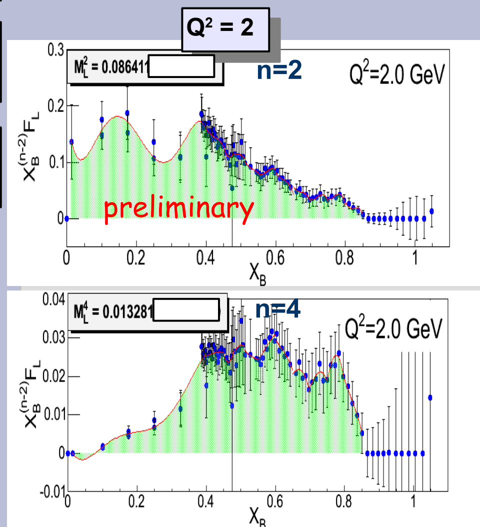
Sample E06-009 cross sections



F_L^d results from E06-009



F^d_L integrand of CN moment



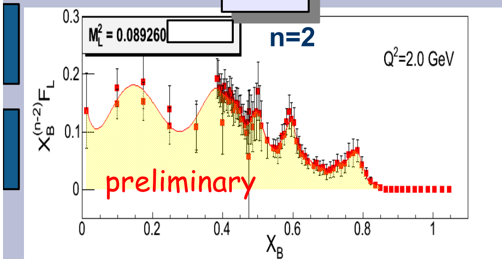
→ Subtract Quasi-elastic contribution from Hall C data using fit.

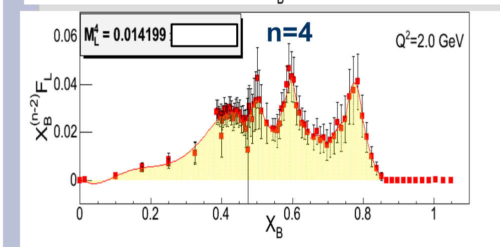
→ Include SLAC data

→ 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

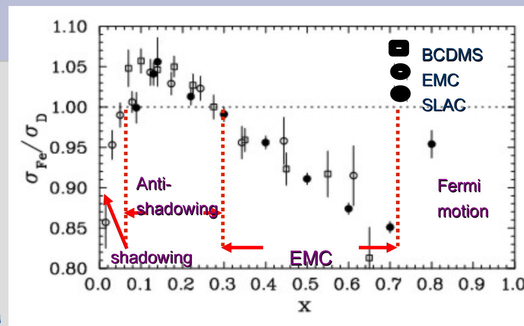
N	F_L^d	$F_L^p - F_L^n$
2:	0.089 (5)	*Coming*
4:	0.0142 (9)	*Soon!*

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

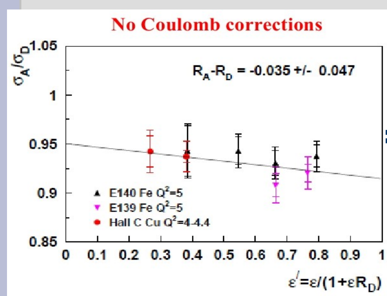
→ SLAC analysis showed *no clear evidence* for $R_A \neq R_d$ ... However

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

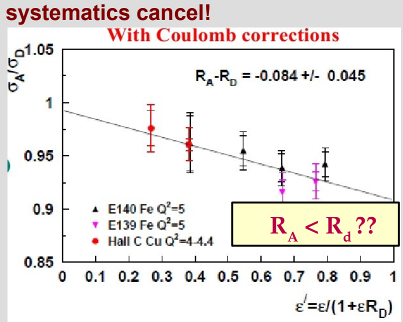
Following Dasu *et.al*
Analysis of SLAC
(PRD.49.5641)

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

→ Much of systematics cancel!

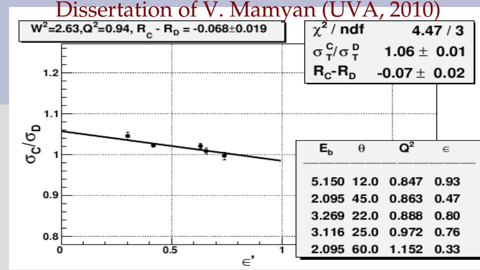


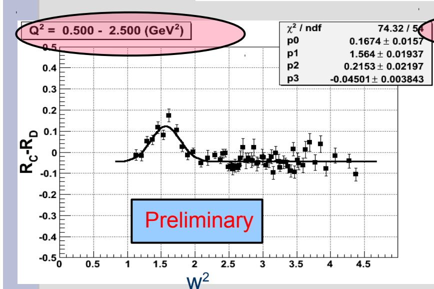
=>

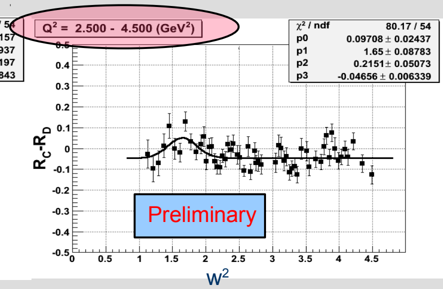


Preliminary results from JLab E06-109(D), E04-001 (A)

Dissertation of V. Mamyan (UVA, 2010)







A consistent Picture seems to be emerging...

Evidence that $R_A < R_d$ for $1 < Q^2 < 5$ and moderate to large *x*.

Further investigation forthcoming

→ Anticipate publication of R (F_L) results from 2007 data this year focusing on $2 < Q^2 < 4$.

→ Anticipate publication of full data set including 2005 low Q^2 data early 2013 for $0.25 < Q^2 < 4$.

One of the extremely useful
Off-shoots of this work is global fits

→ Global fits to cross sections / structure functions were performed

For ra>diative corrections and bin-centering corrections.

→ nucleon structure function (F1p, F2p, FLp, F1n) were determined

from fits to proton and deuteron data.

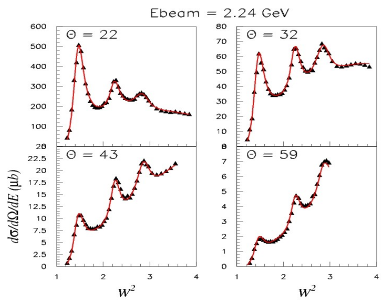
→ QE contribution determined from either sampling wf momentum

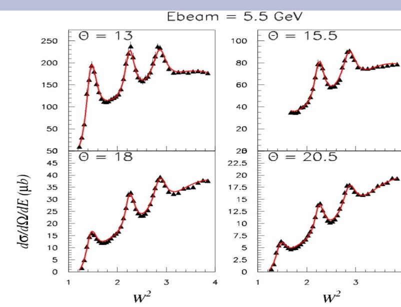
Distribution (D2) or using Super-scaling formalism of Donnelly-Sick

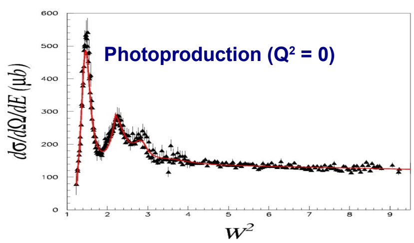
(A > 2)... See talk by M. Barbaro..

Resonance Proton fit

M.E.C. and P.E. Bosted, PRC 81,055213







Kinematic range of fit:

$0 < Q^2 < 8$ and $W < 3$

- reproduces cross section data to ~3%
- Fit to both σ_T and σ_L
- Similar fit to deuteron (smeared n+p)

P.E. Bosted and MEC , PRC 77, 065206

D_2 (n) fit

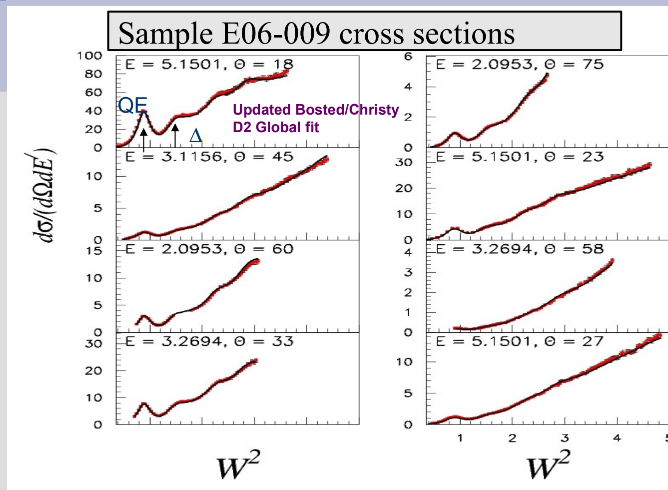
→ In published version Rd = Rp is assumed.

→ Only F1n is parameterized.

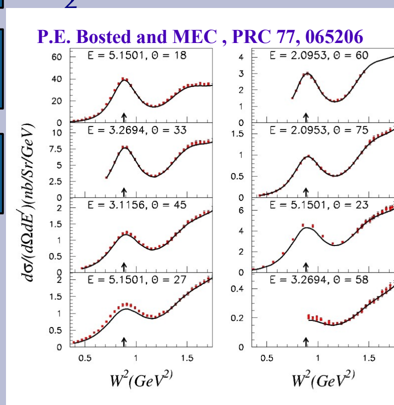
→ Both proton and neutron elastic form factors are taken from fit by P. Bosted. New fits to larger data set are now available.

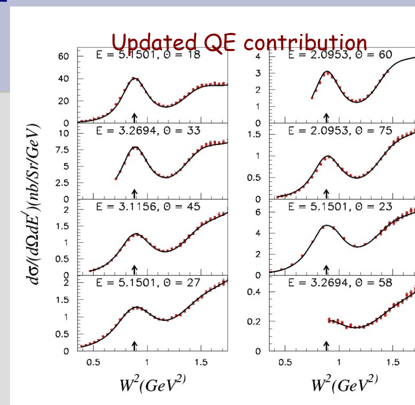
→ Smearing is done by sampling momentum distribution from Paris wf

D_2 (n) fit comparison to E06-009



D_2 (n) fit QE comparison to E06-009





→ Replaced QE smearing with convolution model of W. Melnitchouk.
→ Will study with different potentials & off-shell effects, including BONUS n
→ Replaced p,n form factors with modern parameterizations including new GMN data from CLAS. (biggest contribution to difference)

A>2 fit

→ For QE use superscaling formalism of Sick, Donnelly, Maieron (nucl--th/0109032)

$$\frac{d^2\sigma}{d\Omega d\omega}\frac{1}{\sigma_{Mott}}\epsilon\left(\frac{q}{Q}\right)^4 = \epsilon R_L(q,\omega) + \frac{1}{2}\left(\frac{q}{Q}\right)^2 R_T(q,\omega)$$

$$f_{L,T} \equiv k_F \frac{R_{L,T}}{G_{L,T}}$$

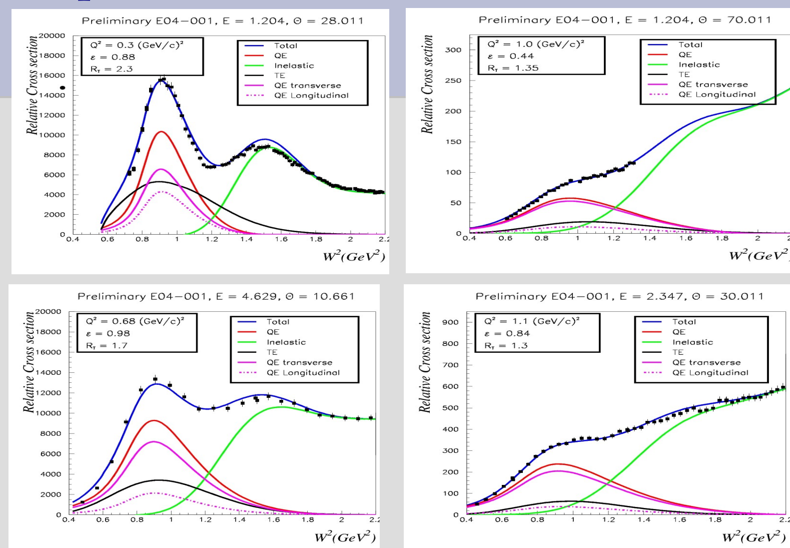
→ Developed by Peter Bosted and tuned by Vahe Mamyan for E04-001.

→ uses nucleon fits by by Bosted and Christy as input and Fermi smears for nuclear targets using FG.

→ nuclear modifications to inelastic structure functions are determined from fit parameters.

→ Uses existing world data.

Comparison to selected E04-001 data



Bosted-Mamyan fit

In order to fit the data on nuclear targets we find that a ***TE component is needed***.

We take the TE component from the fit, Integrate up to $W^2 = 1.5$, and extract $R_T(Q^2) = (QE_{trans} + TE)/QE_{trans}$

Assign a conservative systematic error to R_T (since some of the transverse excess may be produced with final state pions)

(In future we plan to improve it with updated L-T separated data from E04-001)

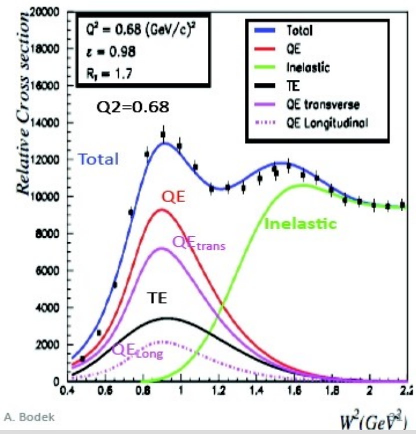
Primary purpose of this preliminary fit was as input to radiative corrections.

A spinoff of the fit is the TE component versus Q2

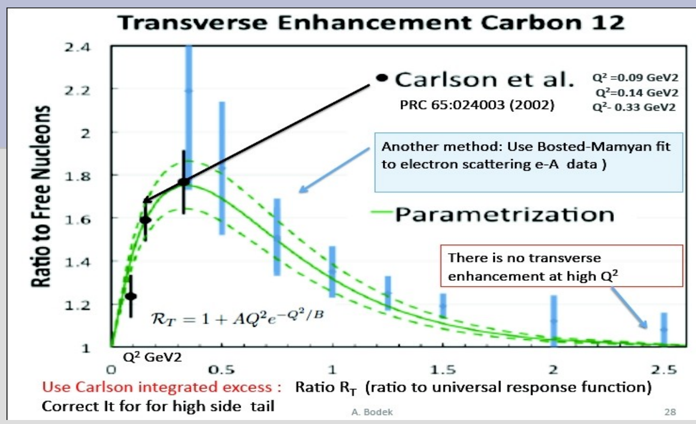
Extracting Transverse enhancement at Q^2>0.3 GeV2

$$\mathcal{R}_T = \frac{QE_{transverse} + TE}{QE_{transverse}}$$

Preliminary E04-001, E = 4.629, Θ = 10.661



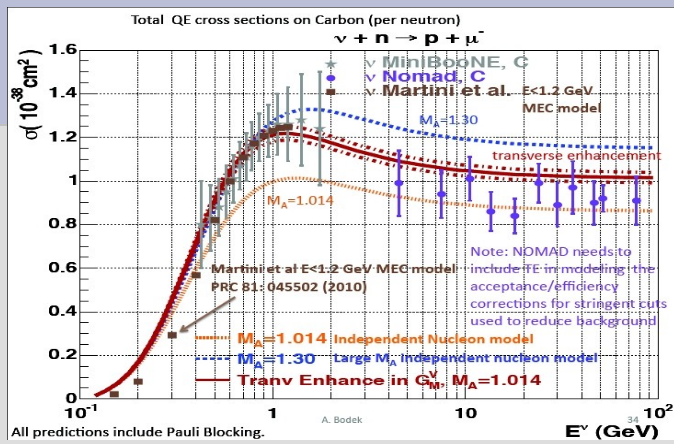
A. Bodek



→ Include TE in vector form factors => predict neutrino cross section

$$G_{Mp}^{nuclear}(Q^2) = G_{Mp}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}$$
$$G_{Mn}^{nuclear}(Q^2) = G_{Mn}(Q^2) \times \sqrt{1 + AQ^2 e^{-Q^2/B}}.$$

A. Bodek, H. Budd, M.E.C., Eur.Phys.J.C71:1726,2011 (arXiv:1106.0340)



→ TE resolves most of tension between high and low E_ν data.

→ Enhancement is relative to independent nucleon FG, whether Underlying physics is MEC or not.

Summary

→ Lots of new JLab results for F_L and R for nucleons and nuclei with publications coming very soon.

→ Fits available which describe the data to few % on average

→ Plenty of physics studies coming in the future

Stay tuned....

And Thank You!

Backup Slides

but additional contributions at finite Q^2, e.g.

Kinematic 'Target Mass' Corrections':

Fractional nucleon momentum carried by the struck quark away from Bjorken limit

$$\xi = 2x/(1+r) \qquad \text{With} \qquad r = 1+\nu^2/Q^2 = \sqrt{1+\frac{4M^2x^2}{Q^2}}$$

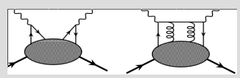
$$F_2^{TM}(x,Q^2) = \frac{x^2}{r^3}\frac{F_2^{(0)}(\xi,Q^2)}{\xi^2} + 6\frac{M^2}{Q^2}\frac{x^3}{r^4}\int_\xi^1 dx'\, \frac{F_2^{(0)}(x',Q^2)}{x'^2} + 12\frac{M^4}{Q^4}\frac{x^4}{r^5}\int_\xi^1 dx' \int_{x'}^1 dx''\, \frac{F_2^{(0)}(x'',Q^2)}{x''^2}$$

What experiments measure — **'Massless' limit described by PDFs**

Geogi, Politzer / Barbieri, et.al, '76

Higher Twist contributions (H-T):

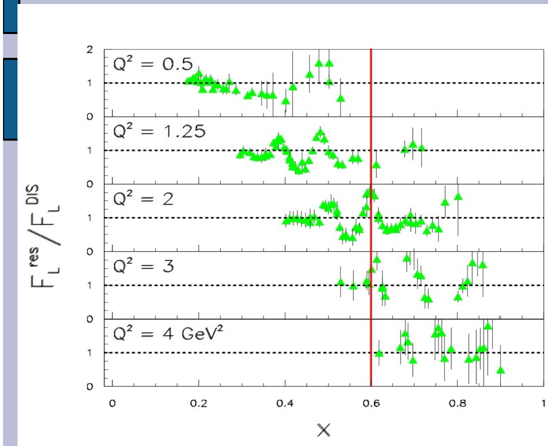
Quark-Quark correlations: eg. gluon exchange between struck and spectator quarks.



Suppressed as powers of $1/Q^2$

Q-H duality: comparisons to empirical DIS fits

- F_2ALLM fit to F_2 H.Abramowicz and A.Levy, et.all., hep-ph/9712415
- R_{1998} to $R = \sigma_L / \sigma_T$ K. Abe et.al Phys.Lett.B452:194-200,1999



Observations

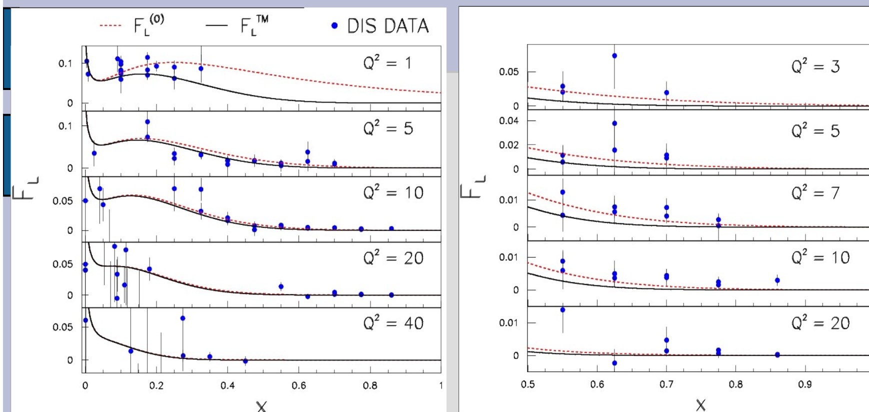
As Q^2 increases, different resonance peak and valleys pass through x=0.6

=> Averaging over a range in Q^2 at fixed x effectively averages out the variations due to the resonance contribution to the structure function.

Can we use this to provide DIS-like data?

F_L^p results from TMC unfolding procedure

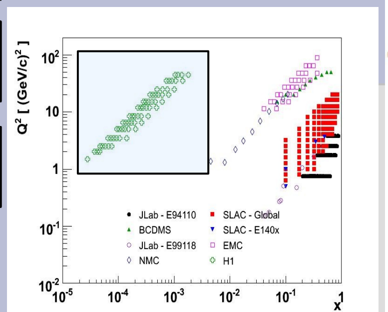
(MEC, J. Blumlein, H. Bottcher – in preparation)

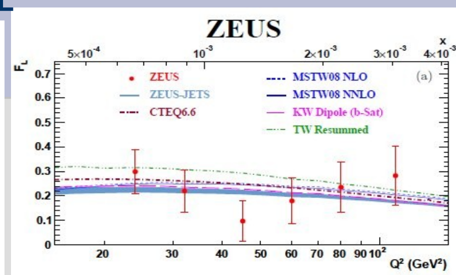


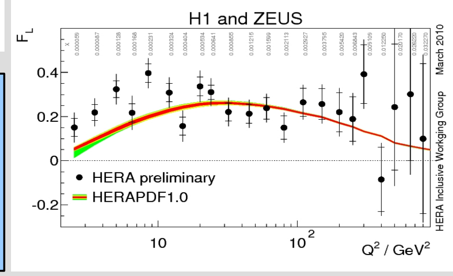
Use to → test pQCD evolution of extracted $F_{L,2}^{(o)}$

→ Further duality studies using as 'scaling' curve

New HERA F_L data at low x



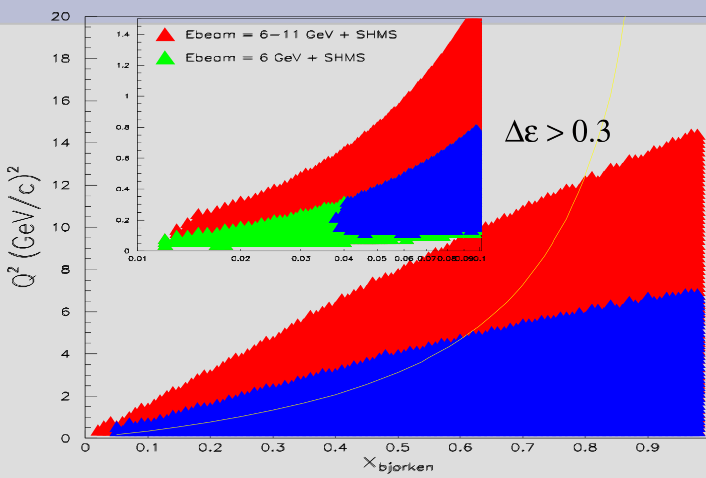




→ Lowering of beam energy during Last years of HERA allowed L/T separations to be performed by both H1 and ZEUS.

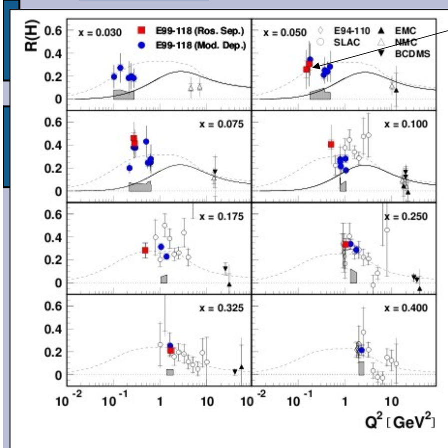
→ provides important constraint on g(x).

Can significantly increase Q^2 Accessible for F_L at 11 GeV JLab



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

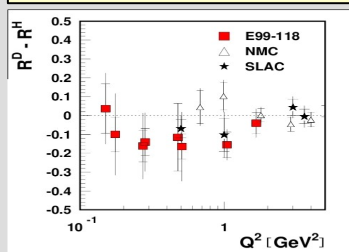
E99-118



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

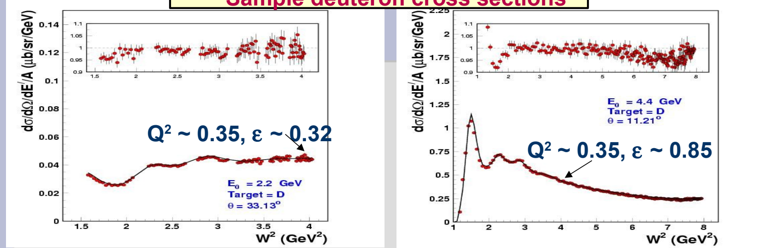
$R_d < R_p$

Difference in neutron?

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

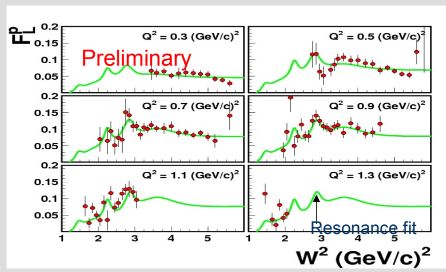
E00-002 Results

Sample deuteron cross sections

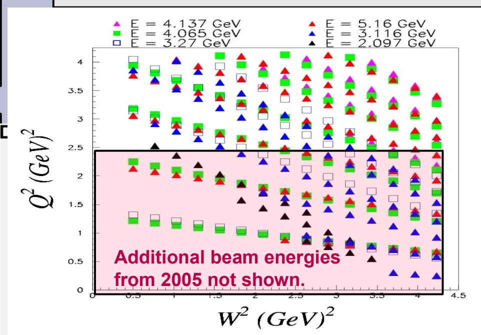


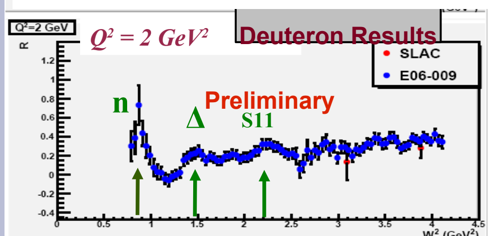
Preliminary results for F_L^p
Consistent with resonance global fit.

Results for deuteron and R_d-R_p coming soon.



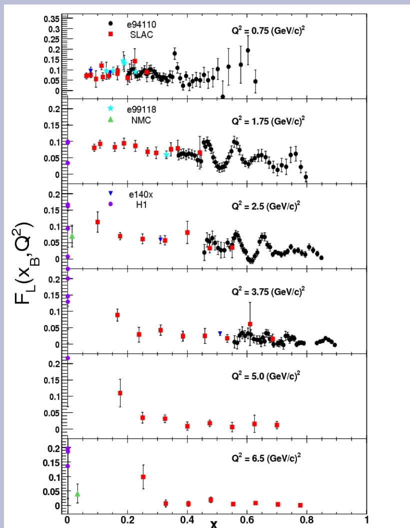
F_L, R on Deuterium and heavier targets
JLab Hall C: E02-109, E04-001, E06-009

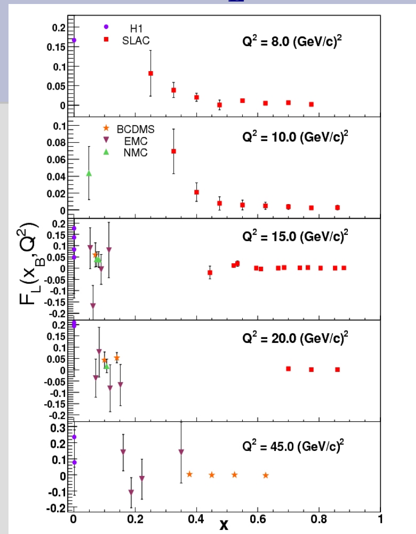




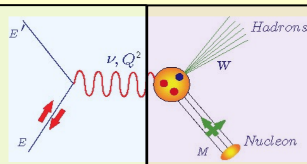
- Precision extraction separated structure functions on D, Al, C, Fe/Cu
- Search for nuclear effects in F_L, R.
- Neutron and p-n moment extractions (non-singlet / singlet).
- Allow study quark-hadron duality for neutron, nuclei separated structure function.

Global status of the Proton F_L data





Scattering of virtual photons from nucleons



Calculable in Quantum Electrodynamics (QED)

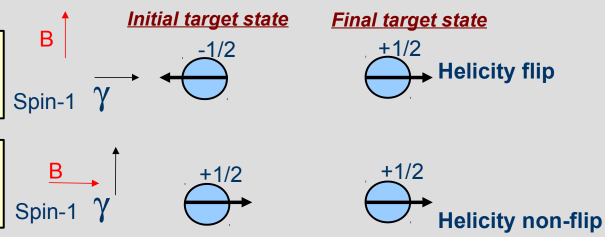
Physics of interest (proton/neutron structure)

→ Virtual photon scatters from nucleon or from constituents.

→ Exchanged photon can have helicity (0,+/-1) corresponding to **B**-field (longitudinal, transverse)

Transverse Photon exchange (helicity -1 or +1)

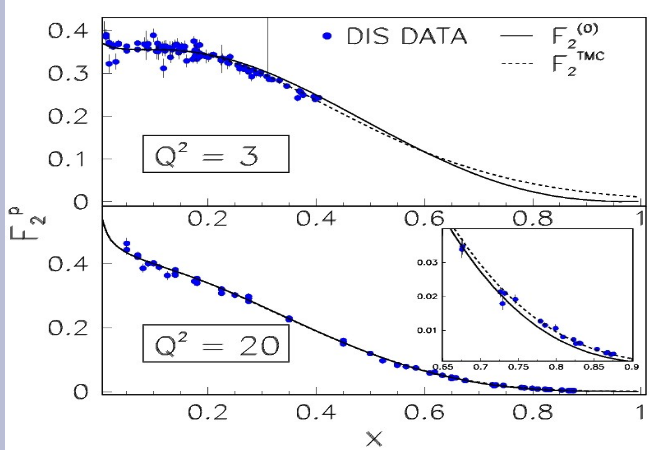
Longitudinal Photon exchange (helicity 0)



-Numbers given are for one year of running

-Line shows the W2=4 mark, formal res-dis regions

F_2 fit results



Are the CN moments of data what should be compared to pQCD?

In pQCD $$M_2^{(n)}(Q^2) = \int dx\, x^{n-2} F_2^{(0)}(x)$$

This is not true for finite M^2/Q^2 due to TMCs. However, *Nachtmann (1973)* found a way to project out the massless limit contribution via

$$\begin{aligned} M_L^{(n)}(Q^2) &= \int_0^1 dx\, \frac{\xi^{n+1}}{x^3} \{F_L(x,Q^2) \\ &+ \frac{4M^2x^2}{Q^2} \frac{(n+1)\xi/x - 2(n+2)}{(n+2)(n+3)} F_2(x,Q^2)\} \end{aligned} \quad (1)$$

→ Here F_2, F_L are the *experimental* structure functions.

→ Nachtmann moment effectively removes the TM contributions.

How do we determine the Proton F_L Nachtmann Moments?

- Bin data in fine x bins over ($0.01 < x < 1$).

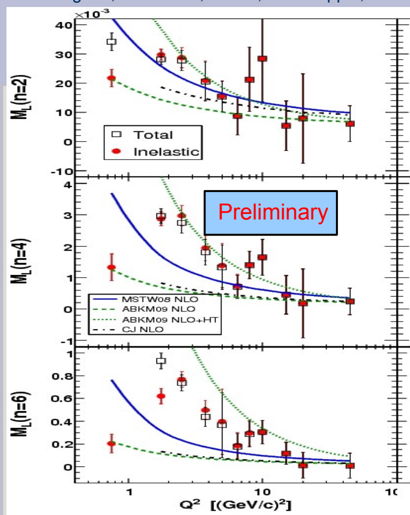
- Utilize resonance and DIS fits to interpolate between data points, where necessary.

- Determine uncertainties in moments from uncorrelated uncertainties by generating 1000 'pseudo' data sets with individual F_L values randomly sampled within uncorrelated uncertainties.
  → produces set of 1000 moment values with uncorrelated uncertainty given width of distribution.

* Nachtmann F_L moment requires F_2 moments be determined.

Results for Proton F_L Nachtmann Moments

P. Monaghan, A. Accardi, M.E.C, C.E. Keppel, W. Melnitchouk, L. Zhu



→ 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.

→ Different PDF NLO results are similar at $Q^2 > 20$, but are significantly different at Low Q^2.

→ Note that only ABKM includes H-T terms in fit. Contribution partially absorbed in MRST gluon?

→ Differences in higher moments likely due to underestimated Gluon strength at high x and/or H-T contributions.

Cornwall-Norton Moments of F_L

- Moments of the Structure Function

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

$$M_n^1(Q^2) \equiv \int_0^1 dx \;\; x^{n-1} \, F_1(x, Q^2).$$

If n = 2 → Bloom-Gilman duality integral!

(integral of DIS or resonance curve is the same)

Operator Product Expansion

$M_n(Q^2) = \Sigma \; (nM_0^2/ Q^2)^{k-1} B_{nk}(Q^2)$ K=1 term is twist-2, eg *free* partons

higher twist pQCD

→ Duality is described in the Operator Product Expansion *as higher twist effects being small or cancelling* - **DeRujula, Georgi, Politzer (1977)**

→ The determination of structure function moments allow us to study the transition of QCD from asymptotic to confinement scales..