Experimental Status
of the Longitudinal Structure Function

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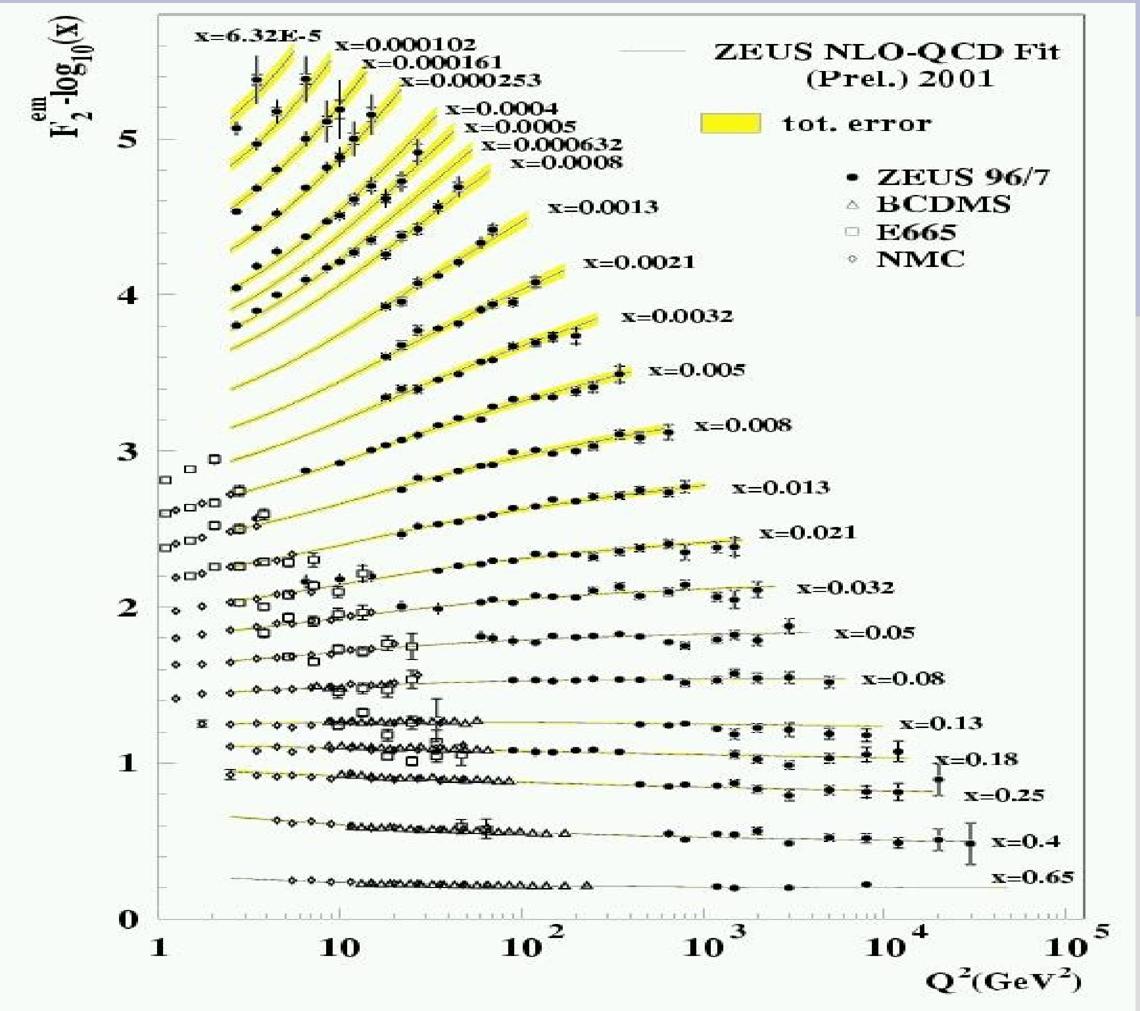
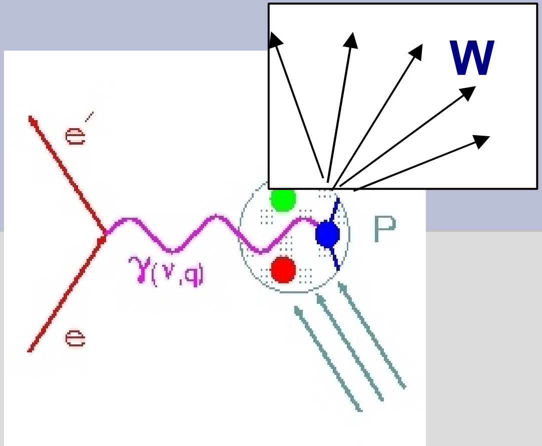
Hampton University

HighX2010 @ JLab - October 14, 2010





While the proton and deuteron F_2 has been measured to high precision over many orders of magnitude in *x* and Q^2,

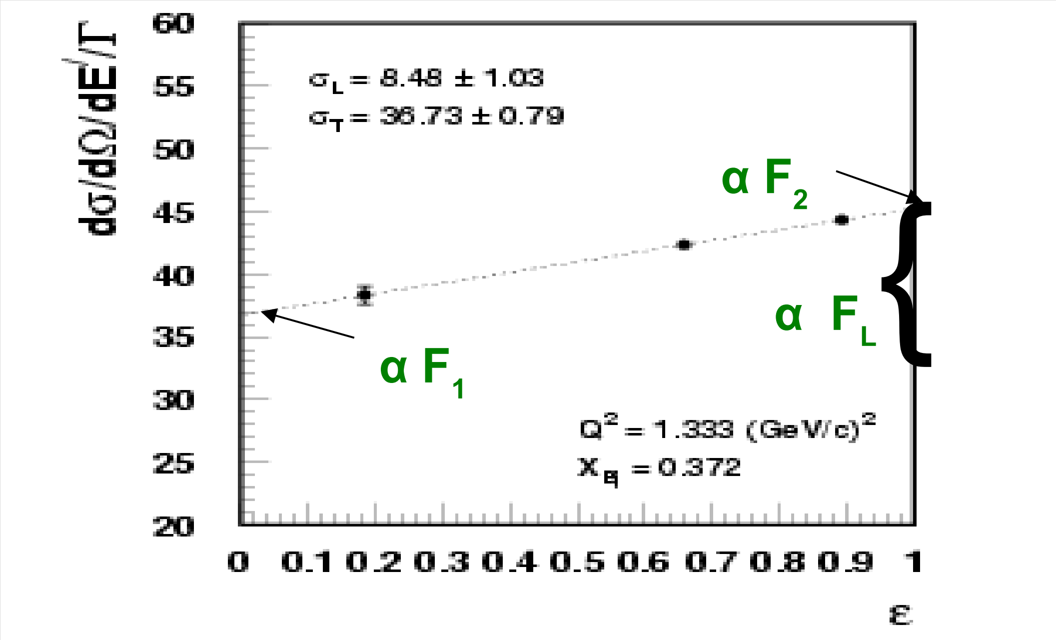
F_L data from charged lepton scattering is relatively sparse and much less precise.

Rosenbluth (L/T) Separations

Reduced cross-section:

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

- **Fit reduced cross section linearly with ε at fixed W^2 and Q^2 (or x, Q^2).**
- **Linear fit yields:**
  - σ_L = Slope
  - σ_T = Intercept



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

Extraction of F2 depends on R and ε !

Important for Jlab kinematics

$R = \sigma_L/\sigma_T = F_L/2xF_1$ ~ 0.25 for much of Jlab kinematics

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

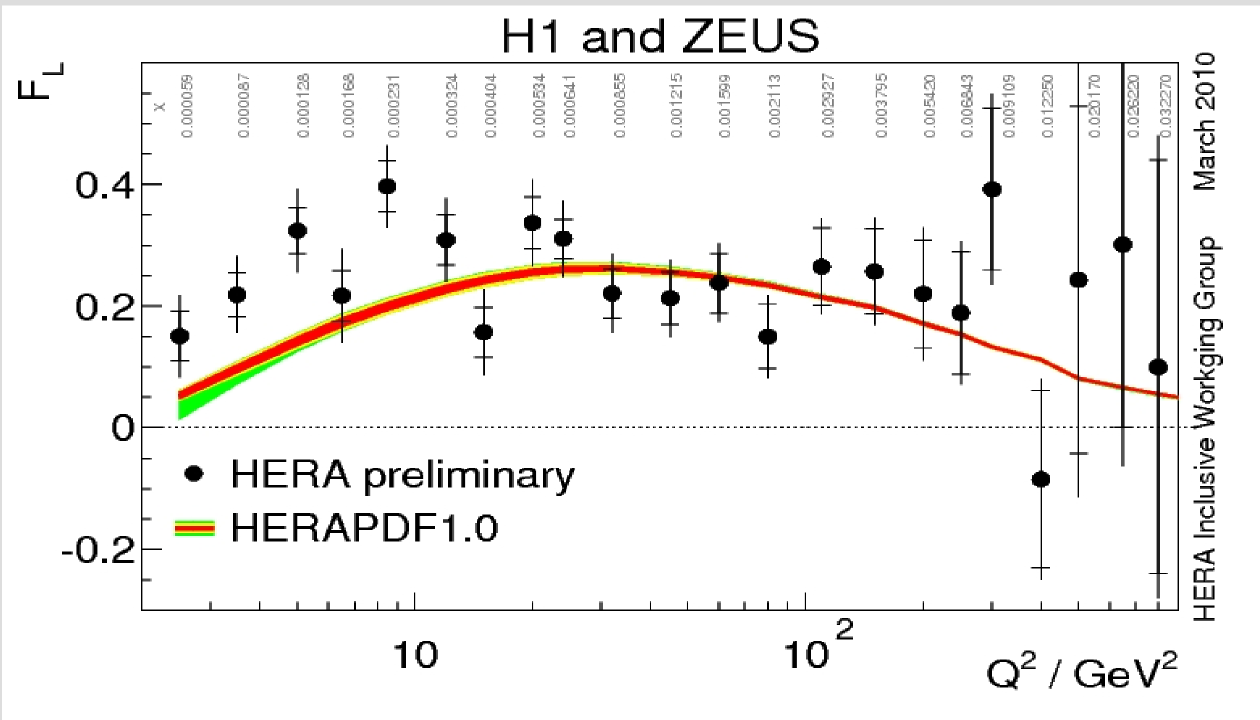
→ Requires multiple beam energies and spectrometer settings for multiple ε.

Very challenging experimentally!

Experimental Status of Proton F_L

Several new data sets available in last few years:

1. Model independent HERA H1 and ZEUS data at low-*x.*



Important for Constraining gluon since F(L) is directly Sensitive to G(x)!

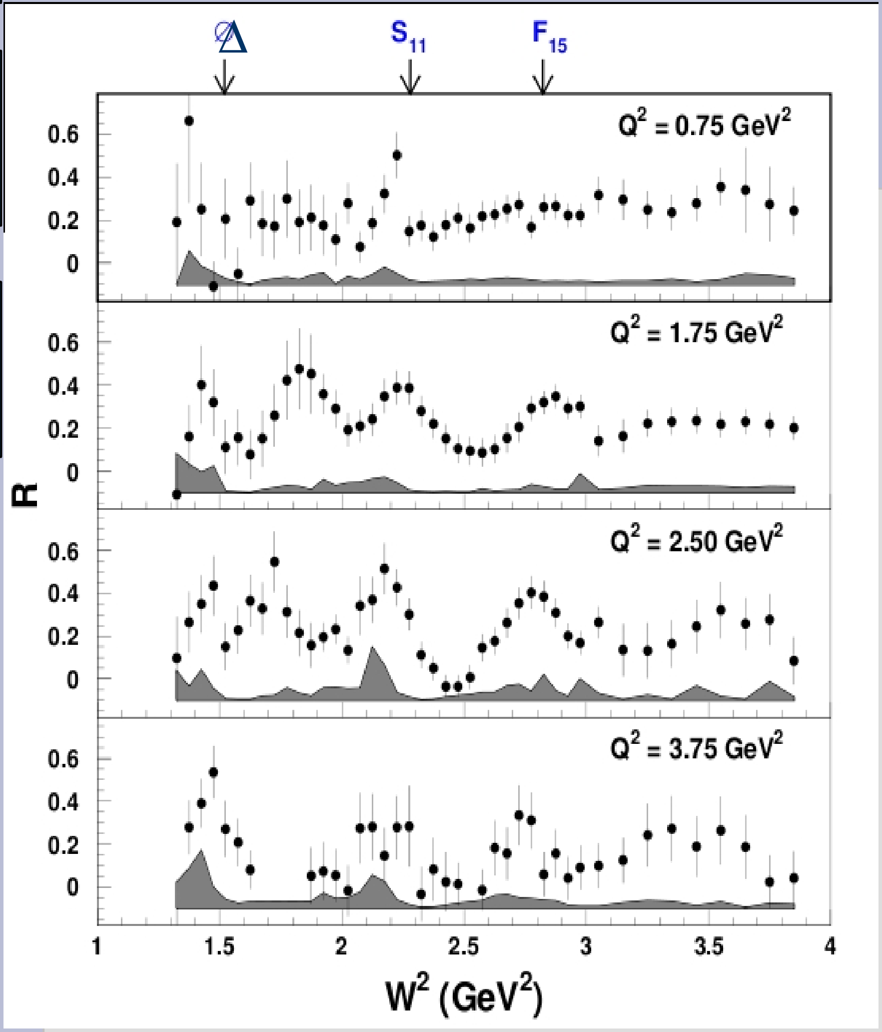
2. *JLab Hall C data at $Q^2 < 4$.*

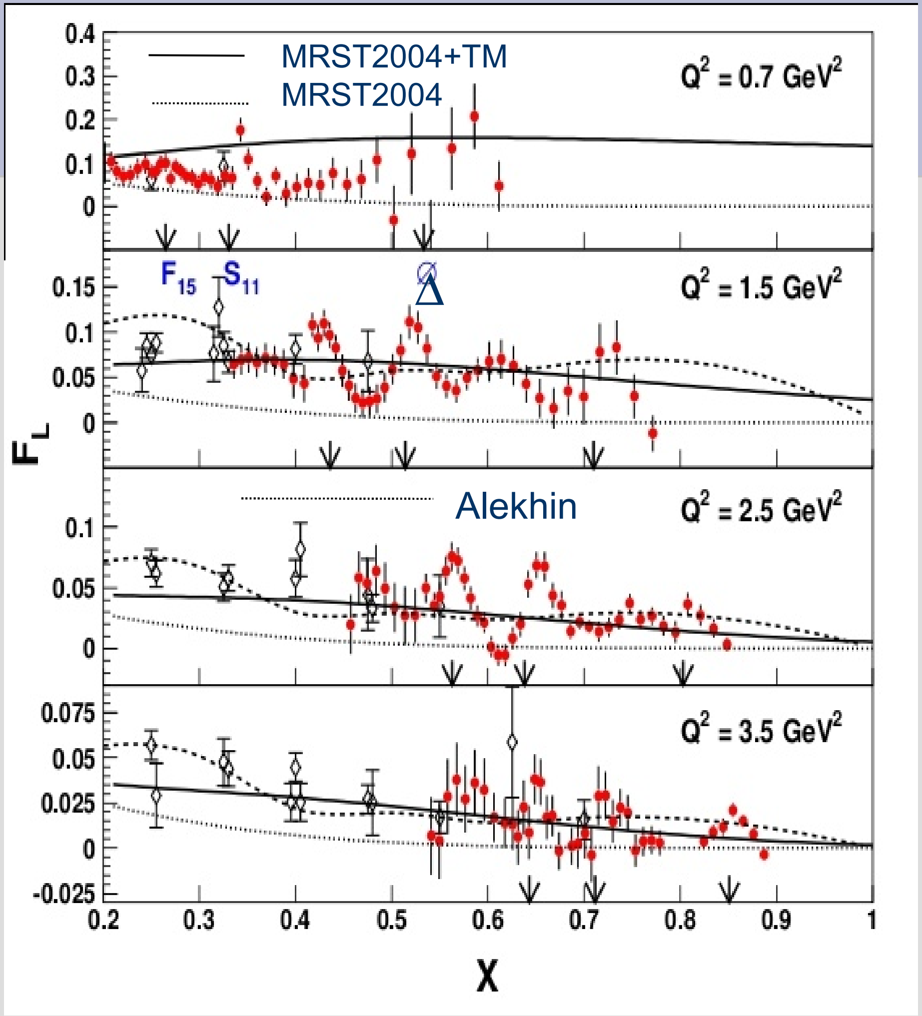
Lots of new L/T data from Jlab Hall C

Experiment	target(s)	W range	Q^2 range	Status
E94-110	p	Res	0.3 - 4.5	nucl-ex/0410027
E99-118	p,d	DIS+RR	0.1 - 1.7	PRL98:14301
	C,Al,Cu,			Finalizing analysis
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	Finalizing analysis
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	Finalizing analysis

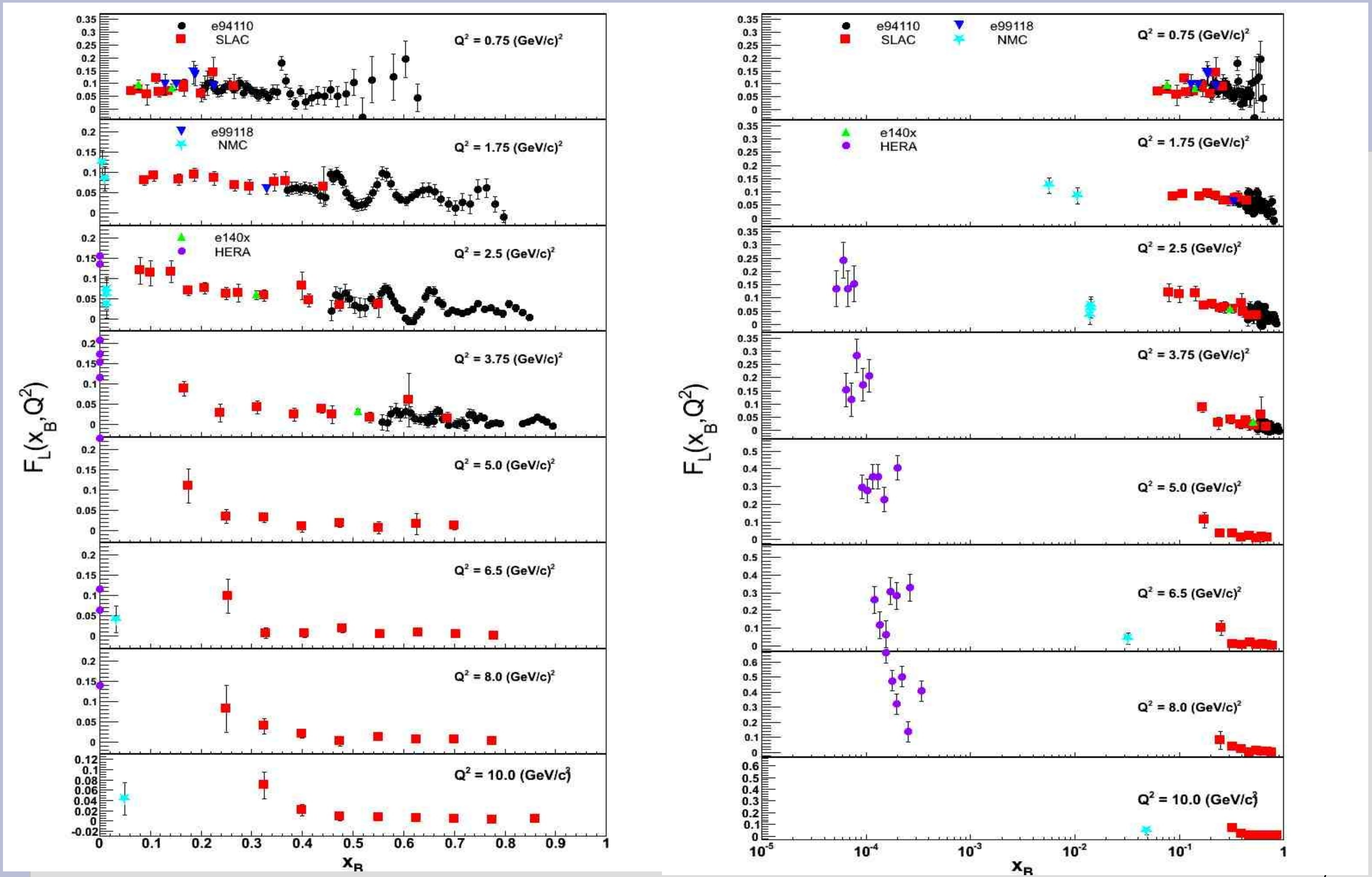
Lots of results expected in coming year!

E94-110 results (proton)

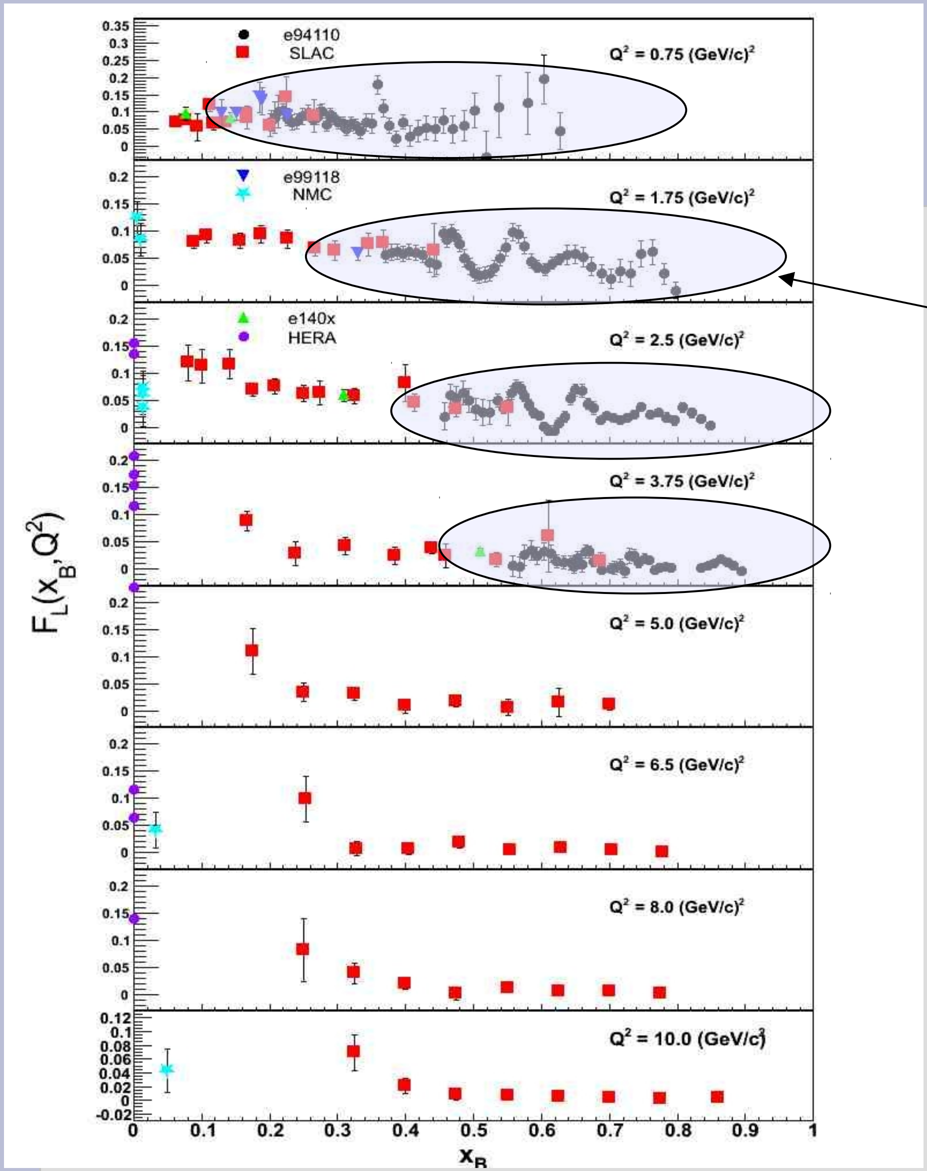




Status of the Proton F_L data



Status of the Proton F_L data



JLab data adds some of the most precise F_L determinations

And covers the large-*x* and mainly in the resonance region.

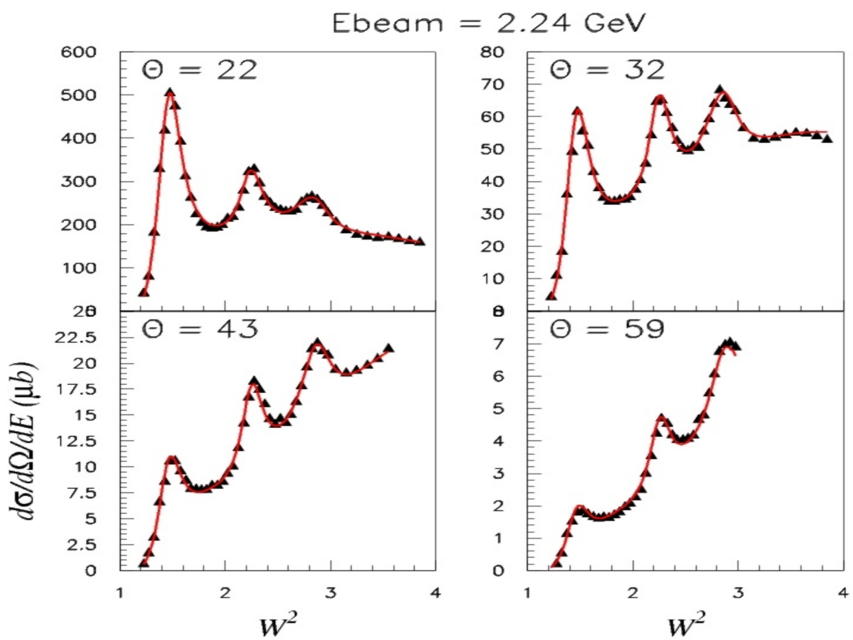
Important for accurately determining the structure function moments at $Q^2 < 5$

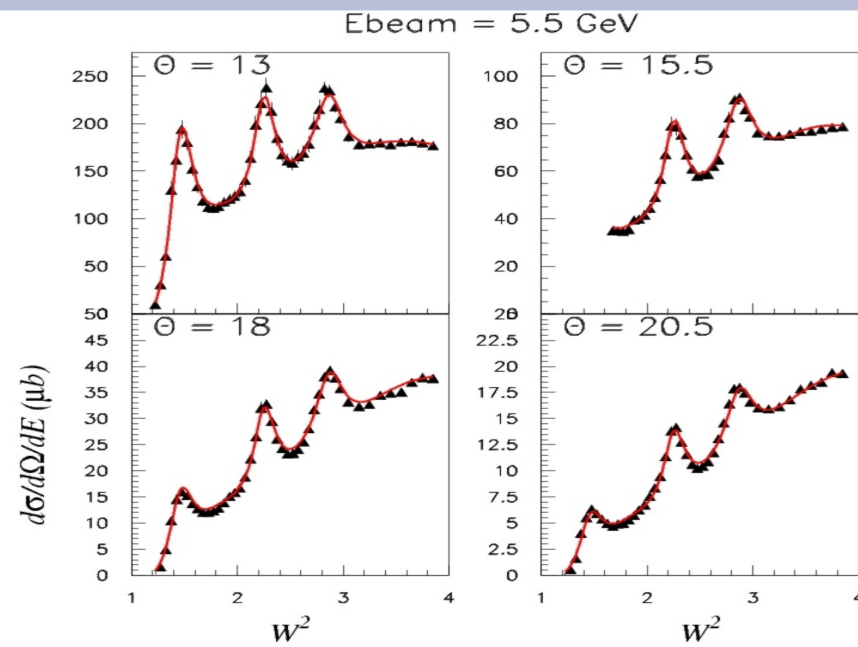
Will soon have comparable data For A = d, C, Al, Fe/Cu

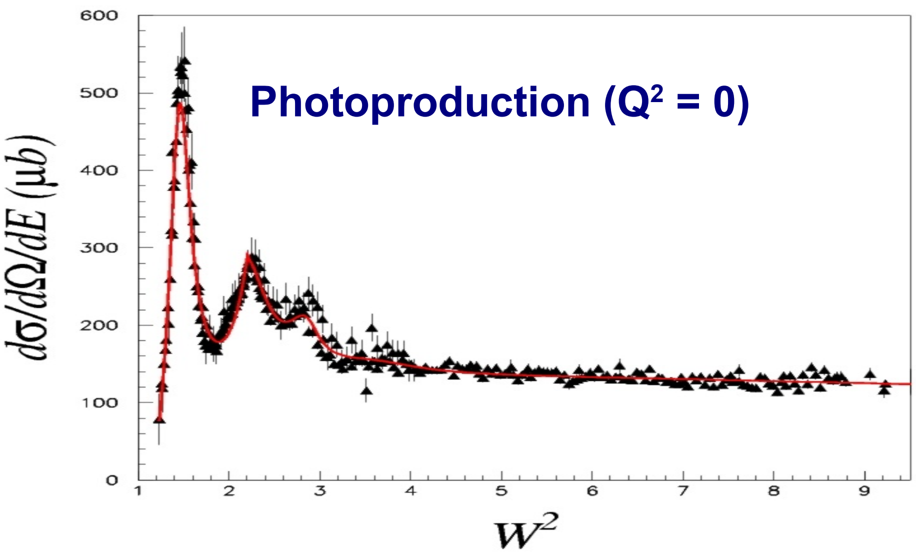
For the calculation of moments and many other studies, parameterizations of the Q^2 and *x* (W^2) dependence of the *separated* structure functions have been developed.

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

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 **$x > 1x10^{-4}$***

F_L^p Data Sets

Data Set	Q^2_{Min} (GeV^2)	x_{min}	Q^2_{Max} (GeV^2)	x_{max}	# Data Points
BCDMS [1]	15	0.07	50	0.65	10
EMC [2]	15	0.041	90	0.369	28
NMC [3]	1.31	0.0045	20.6	0.11	10
SLAC (Whitlow [18])	0.63	0.1	20	0.86	90
SLAC (E140x [19])	0.5	0.1	3.6	0.50	4
H1 [?]	25	0.00062	90	0.0036	5
E99-118 [20]	0.273	0.077	1.67	0.320	7

Fit Form

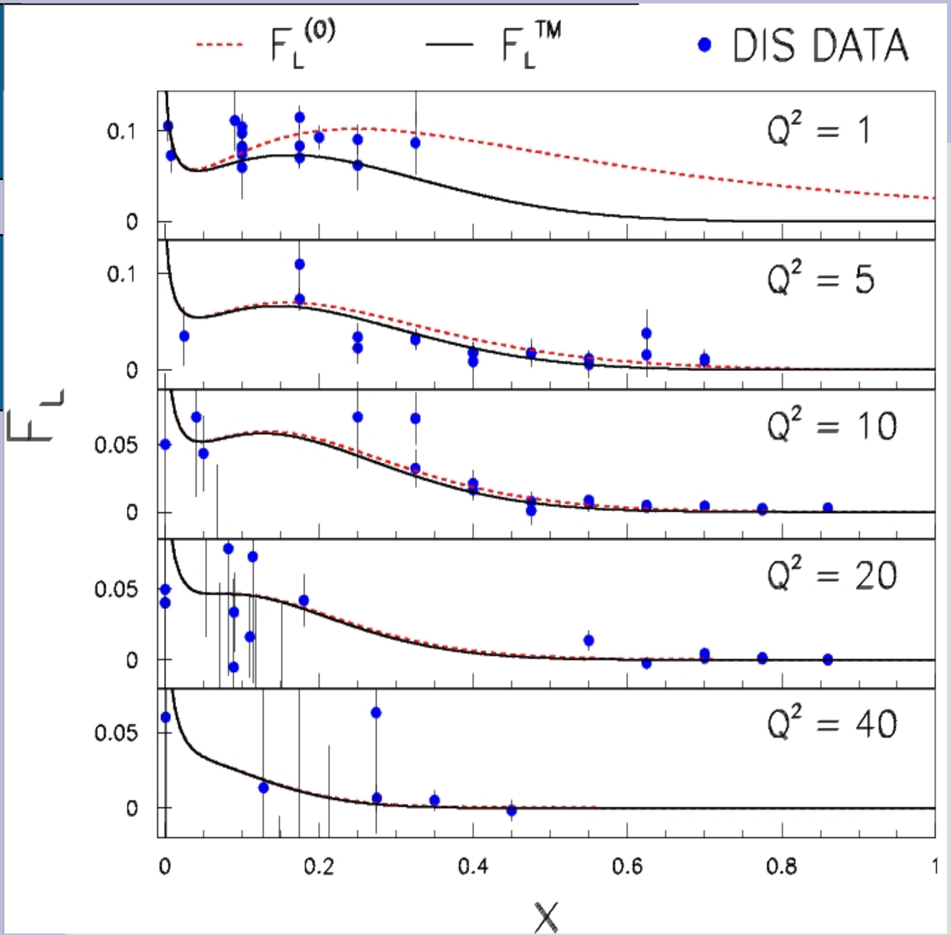
$$F_{2,L}^{(0)}(x) = Ax^B(1-x)^C(1+D\sqrt{x}+Ex),$$

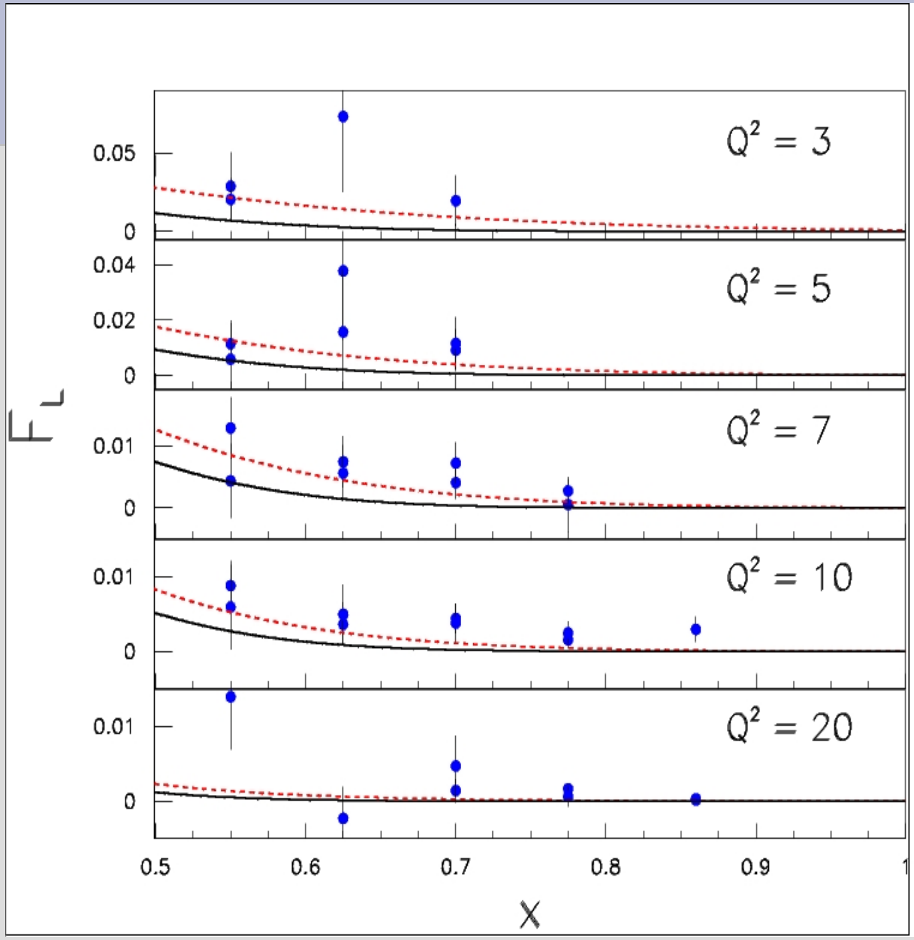
F_2 parameter Q^2 dependence

$$A(Q^2) = A_1 + A_2 e^{-Q^2/A_3} + A_4 \log(0.3^2 + Q^2)$$

*Same form for **A**, **B**, **C**, **D**, and **E***

F_L^p results from TMC fit
(MEC, J. Blumlein, H. Bottcher)





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

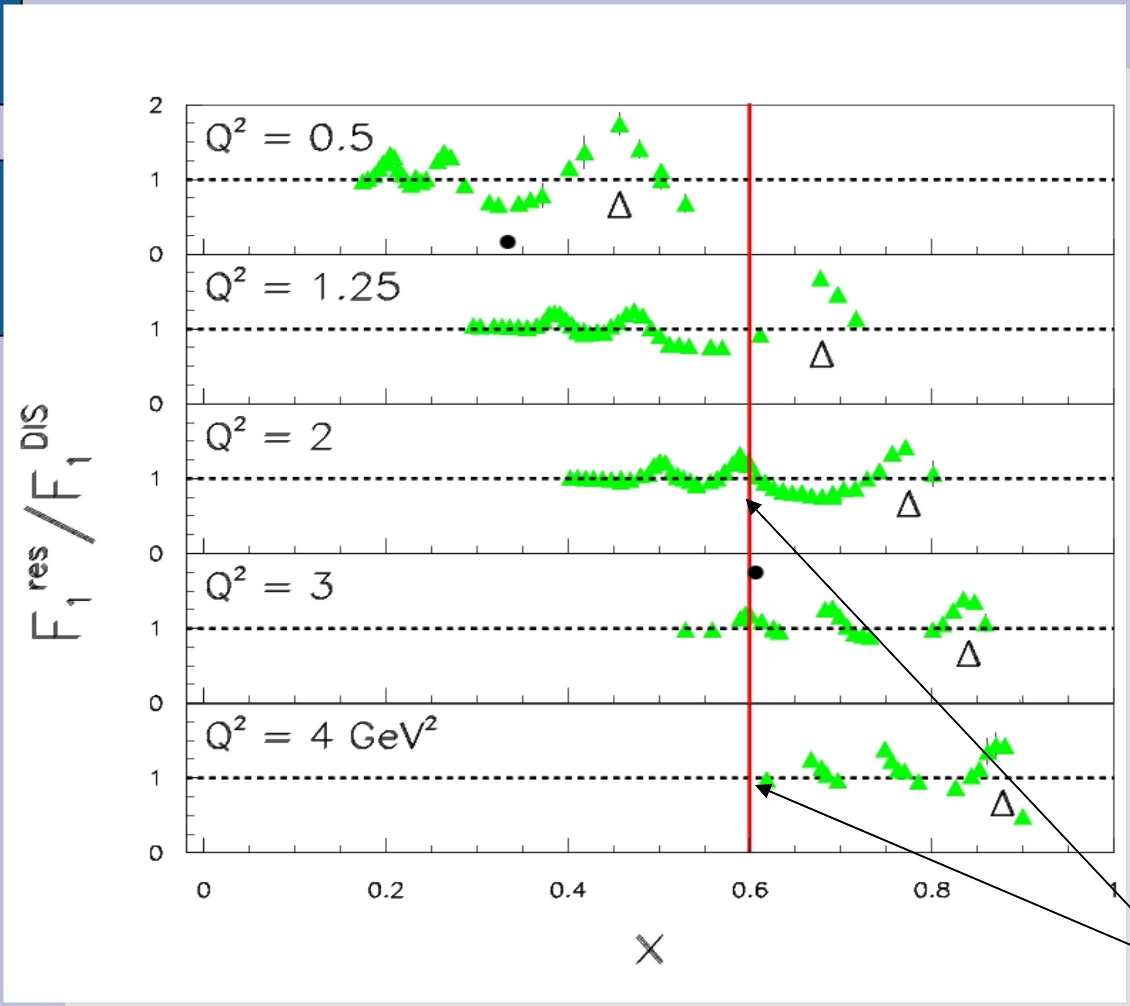
→ Further duality studies using as 'scaling' curve

Can we use duality to help constrain large-*x*?

ie. Are 'duality averaged' data in the resonance region consistent with Q^2,*x* dependence of structure functions at Larger W^2?

Comparison of Hall C resonance data to DIS fit.

Comparison of Rosenbluth separated F_1



DIS fit:

F_2ALLM fit to F_2

H.Abramowicz and A.Levy, hep-ph/9712415

+

R_{1990} to $R = \sigma_L / \sigma_T$

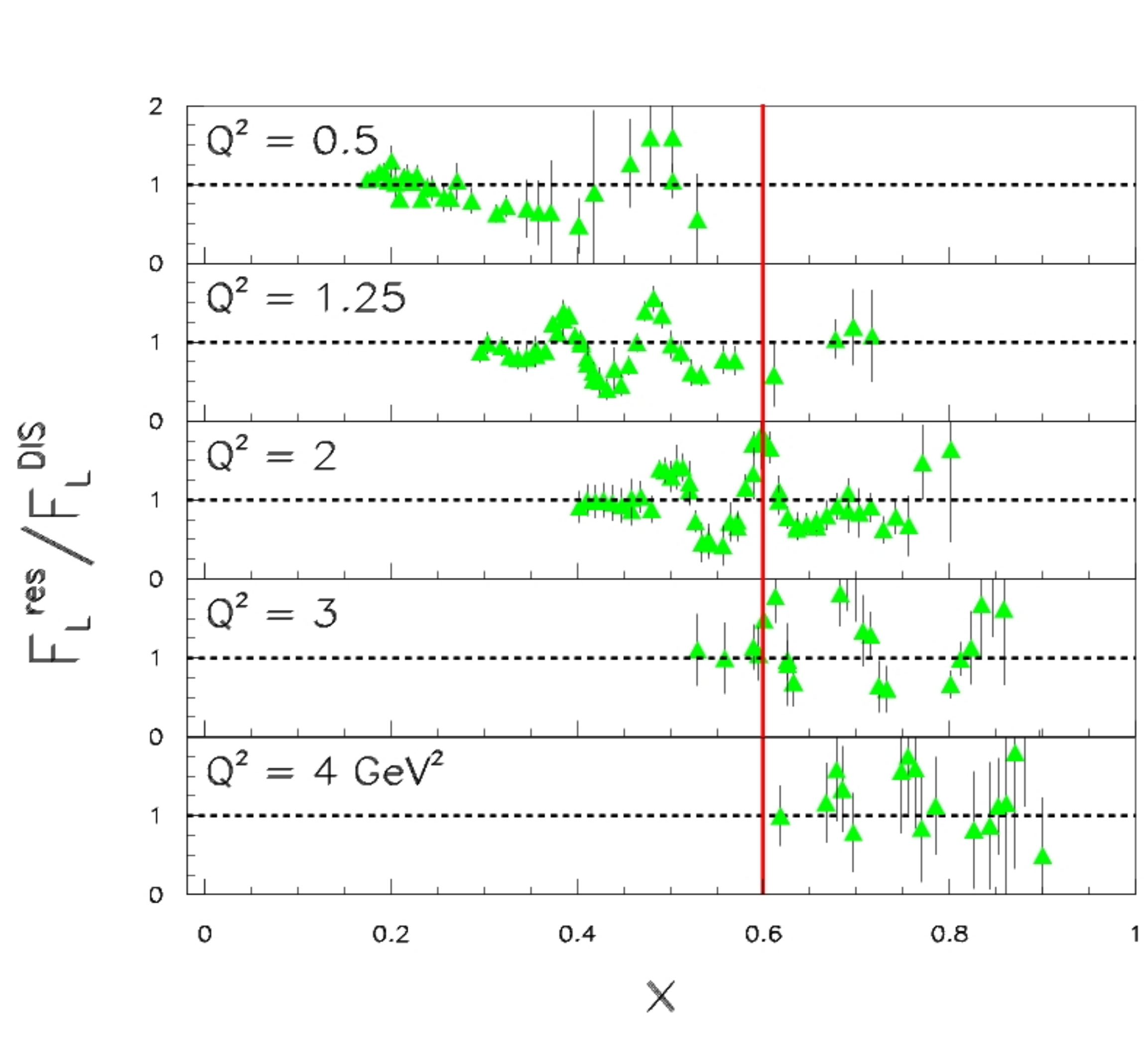
K. Abe et.al Phys.Lett.B452:194-200,1999

Observation

* Resonances oscillate about DIS fit and qualitatively have same Q^2 dependence, even down to $Q^2 \sim 0.5$.

* At fixed x=0.6, different resonances contribute at different Q^2.

Similar results for F_L



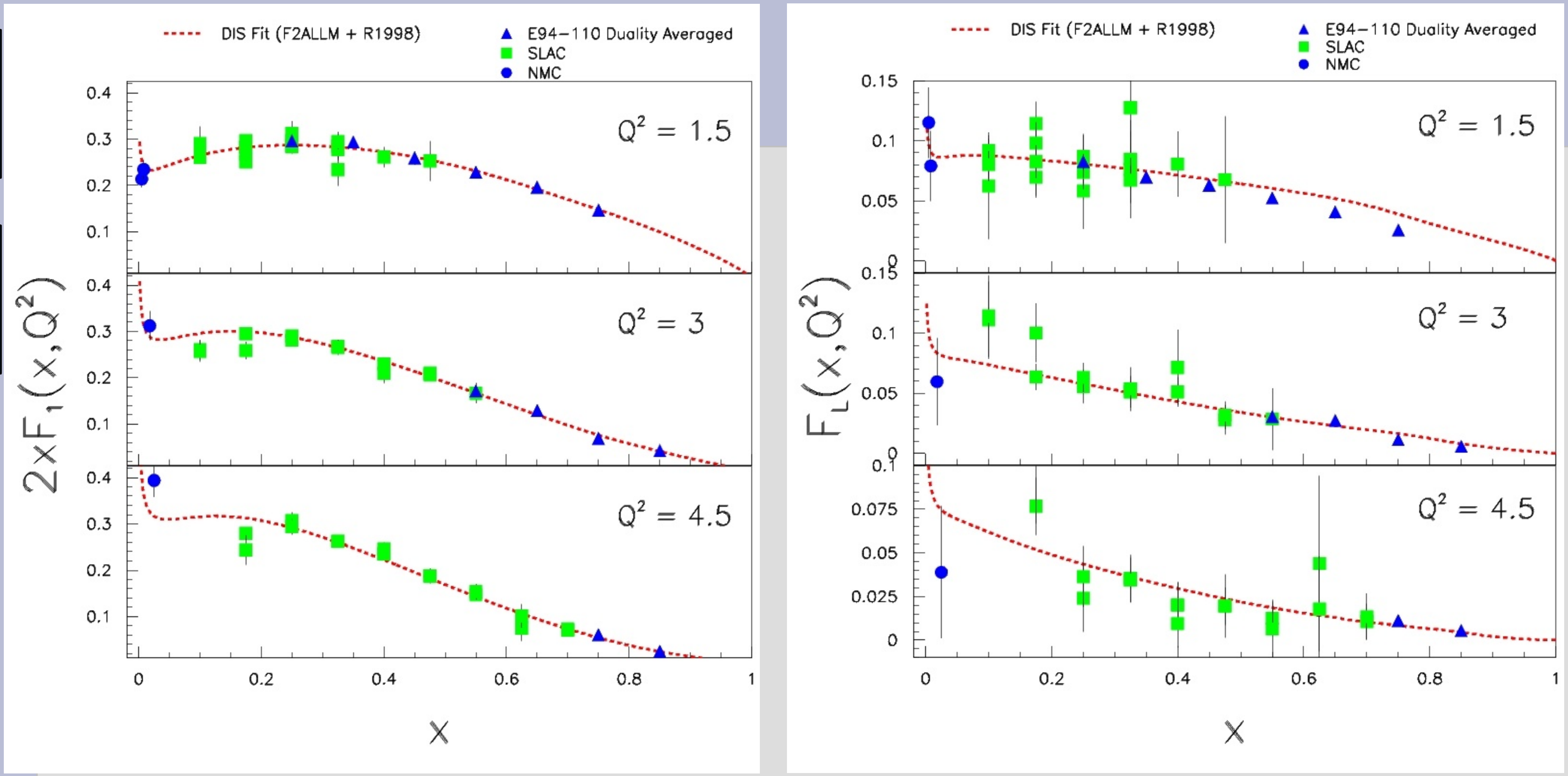
Observation

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?

Duality averaging results for low Q^2 proton data



- Good consistency with DIS and relatively smooth x dependence.
- Note different Q^2 dependence in averaged F_L from fit at lowest Q^2.
- Will include in future TMC fits.

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!

Operator Product Expansion

- $M_n(Q^2) = \sum \, (nM_0^2/ Q^2)^{k-1} B_{nk}(Q^2)$

  higher twist pQCD

The determination of structure function moments allow us to study

the transition of QCD from asymptotic to confinement scales..

Determination of Proton F_L Moments

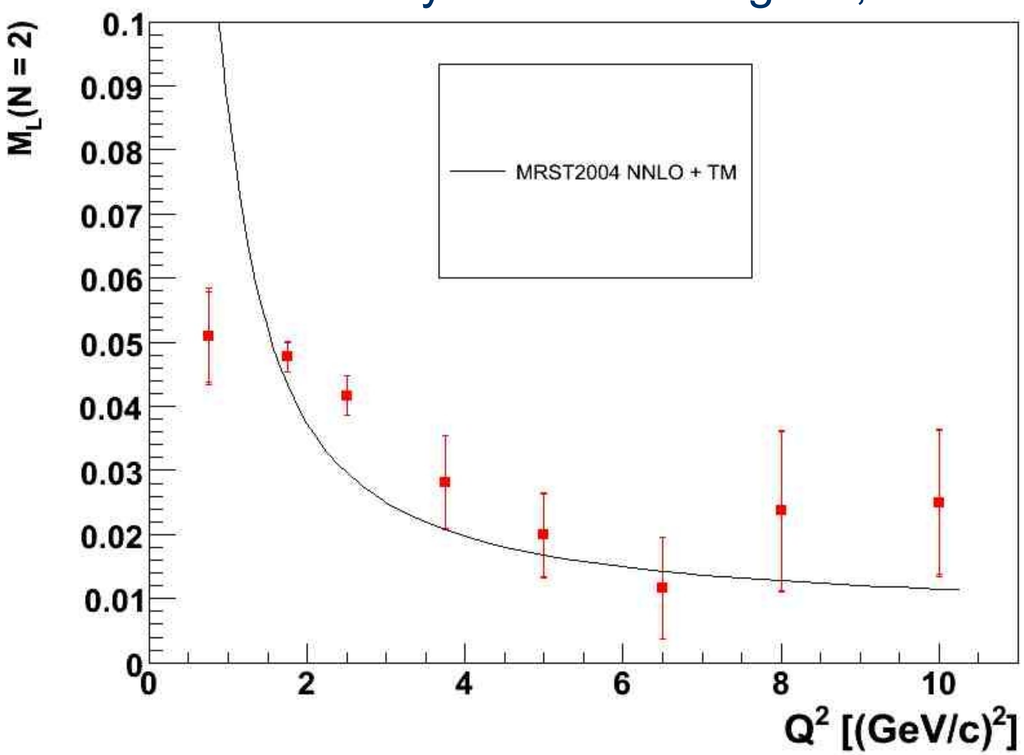
- *Methodology*

- Bin data in fine x bins and perform Simpsons Rule integral.
- Utilize resonance and DIS fits to interpolate between data points, where necessary.
- Determine uncertainties in moments from uncorrelated uncertainties by generating 100 'pseudo' data sets with individual F_L values randomly sampled within their uncertainties.

Results for Proton F_L Moments

(elastic contribution is Not included)

Analysis of P. Monoghan, et. al



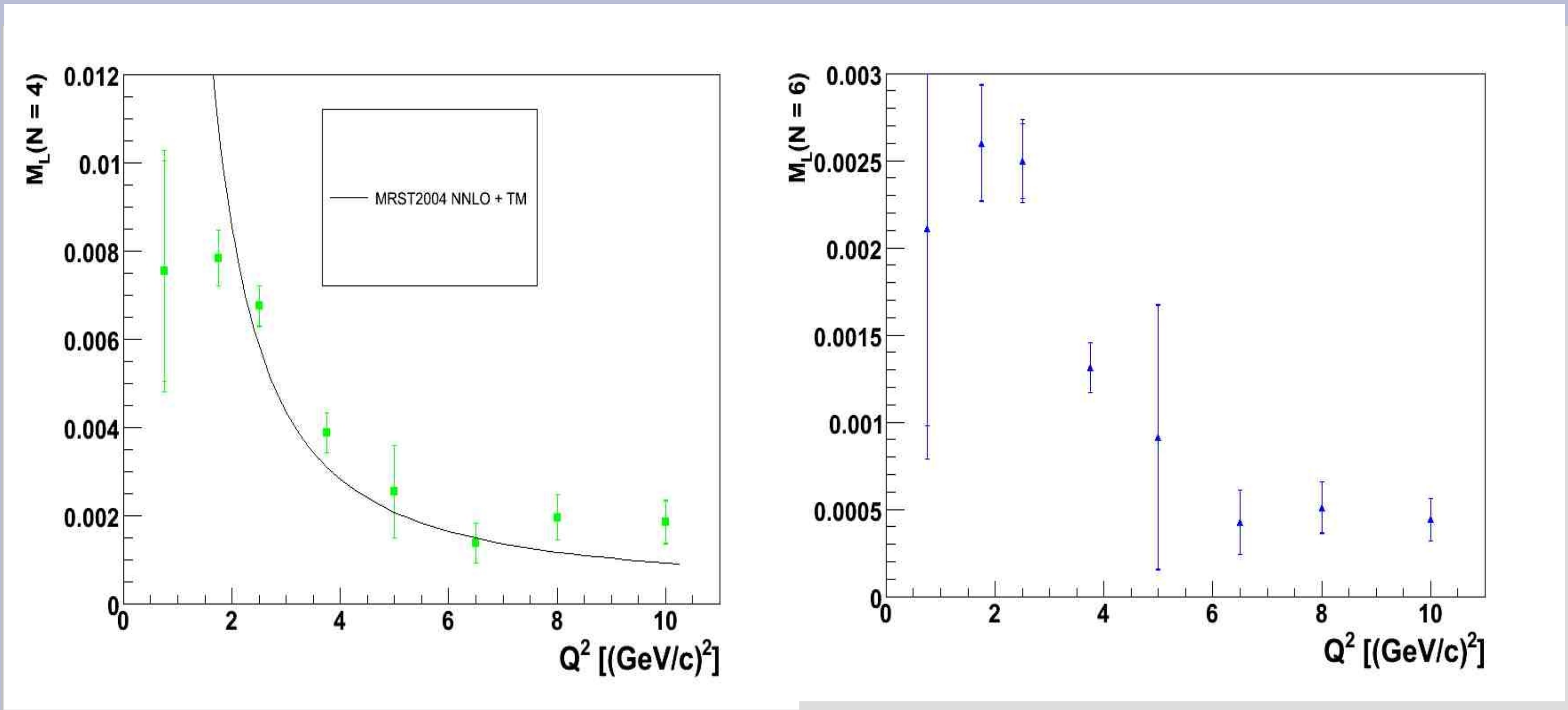
→ **Inclusion of precision Jlab data results in small uncertainties at $Q^2 < 3$.**

→ **Comparison to PDF fit is fairly good for $Q^2 > 2$, once TM contribution is included.**

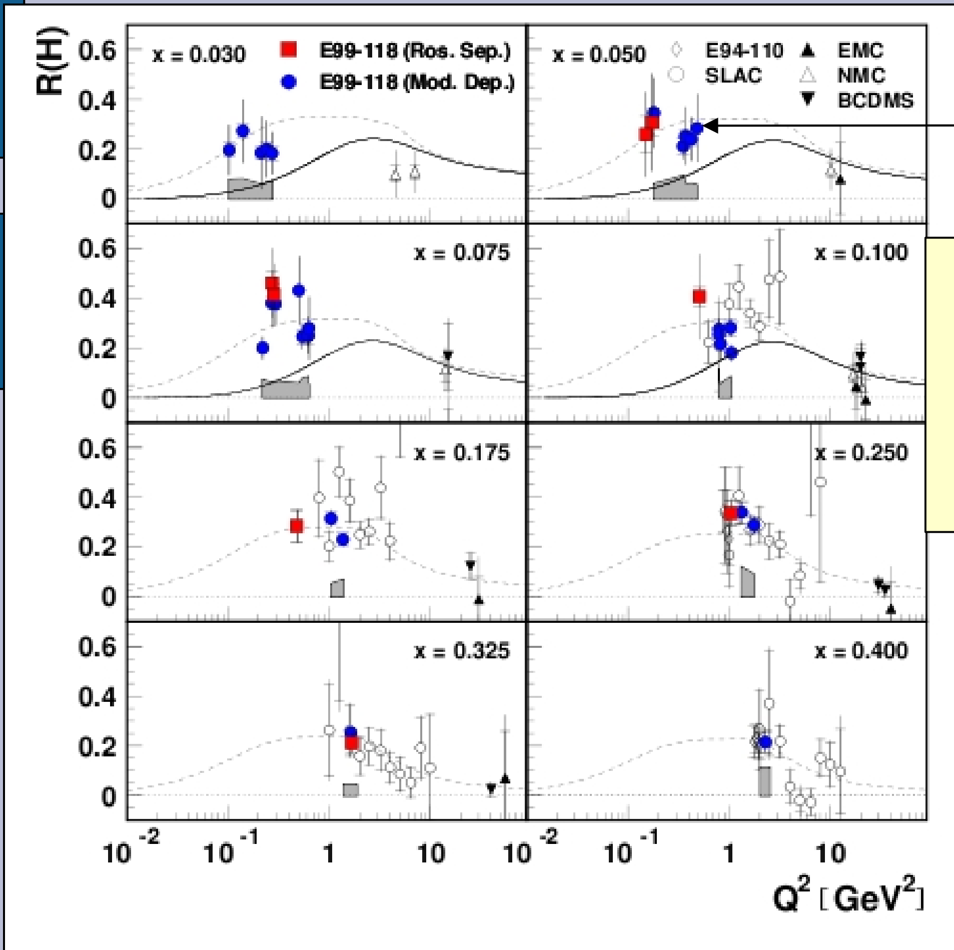
→ **Need more strength in gluon?**

Results for Proton F_L higher Moments

(elastic contribution is Not included)



E99-118 results



From current conservation

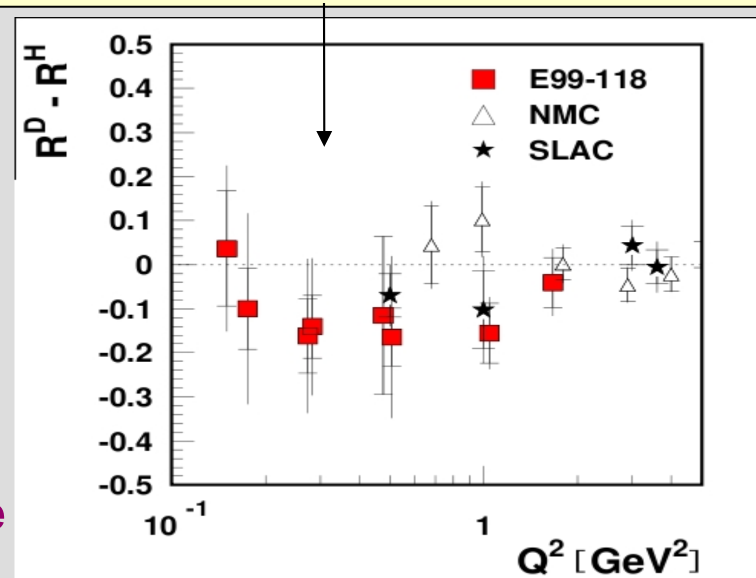
R → Q^2 for Q^2 → 0

But this behavior is not yet observed.

For first time, intriguing hint that

$$R_d < R_p$$

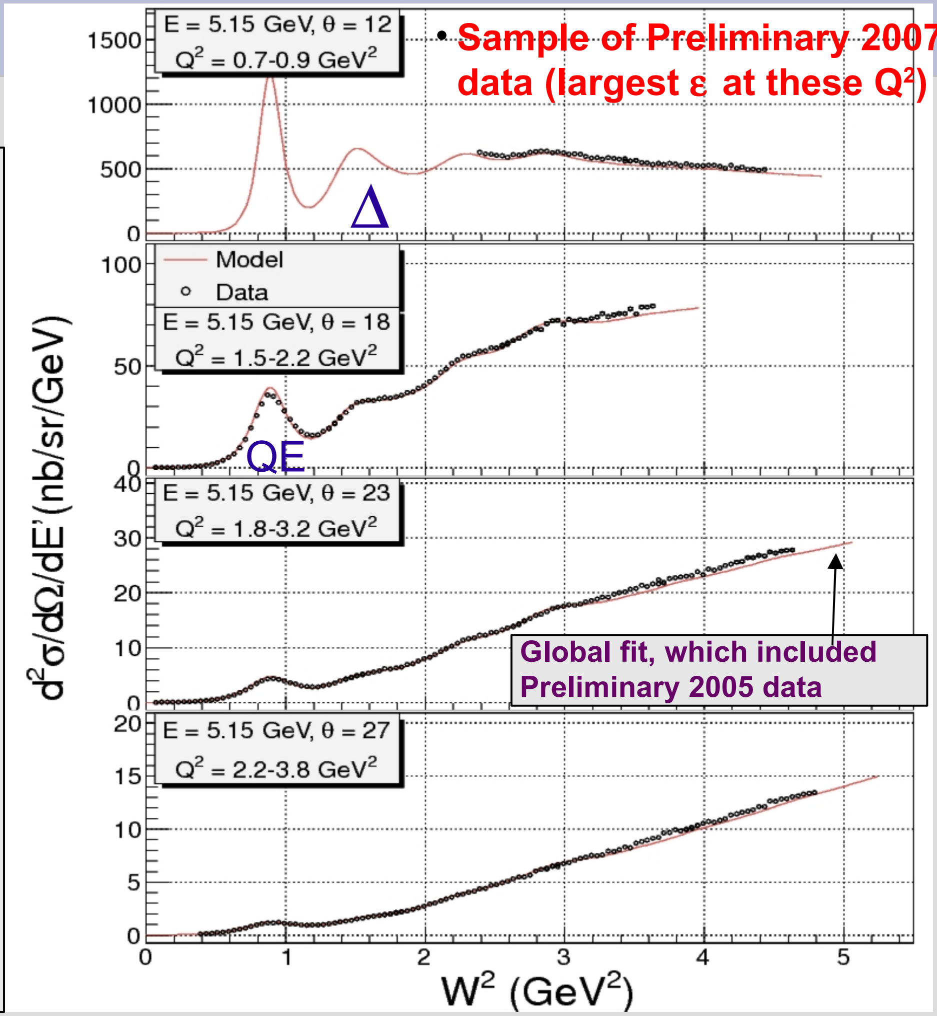
Shadowing effect or difference in neutron?



New data from E00-002 will help resolve These open questions.

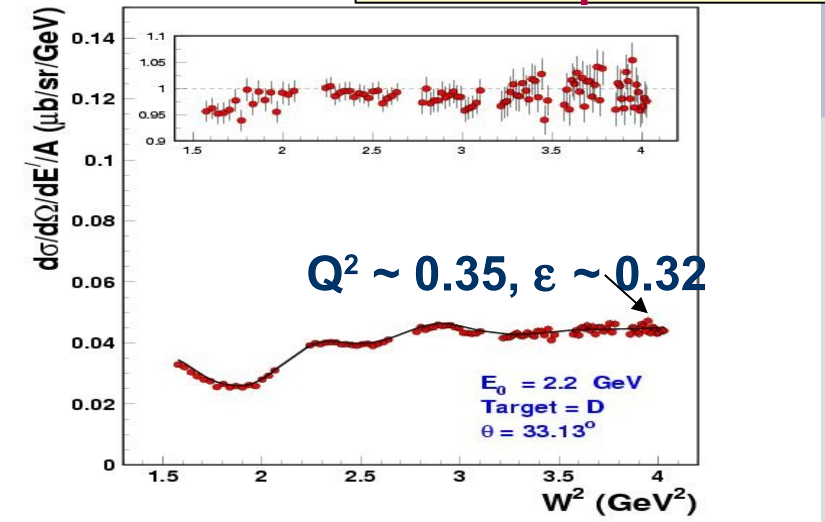
Study of deuteron F_L, and separation of singlet and non-singlet moments – E02-109, E06-009

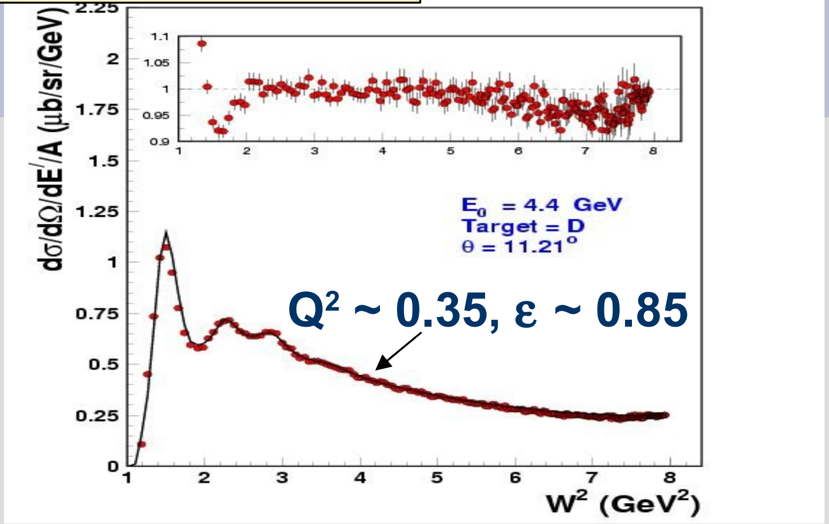
- ◆ Extend resonance L/T separations to deuteron.
- ◆ Allow study quark-hadron duality for neutron in both transverse and longitudinal structure.
- ◆ Allow higher precision non-singlet moment extractions for F_2, F_1 (compare to lattice predictions at Q^2 = 4 GeV^2).
- ◆ Comparisons of F_L^p and F_L^d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



E00-002 Results

Sample deuteron cross sections

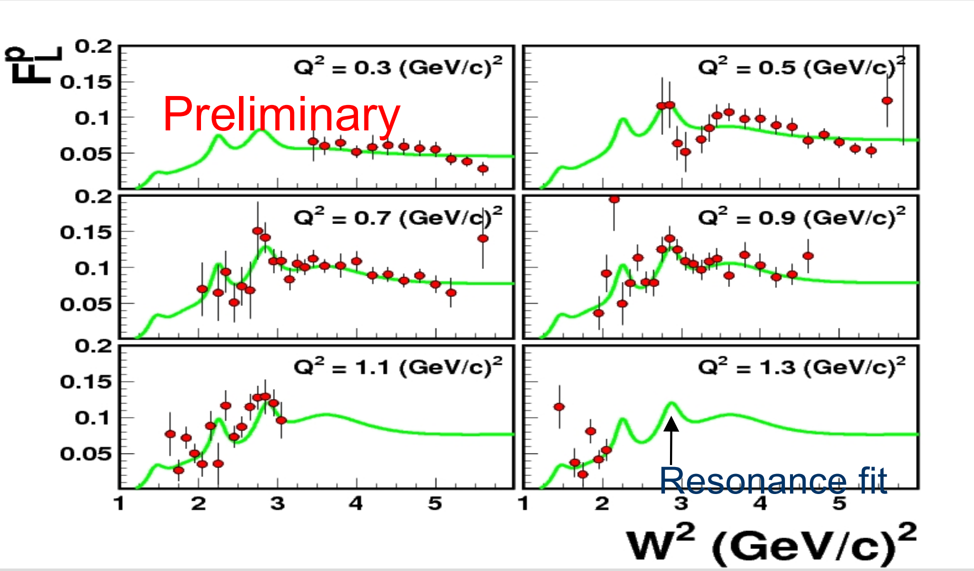




Preliminary results for F_L^p

Consistent with resonance global fit.

Results for deuteron and R_d-R_p coming soon.



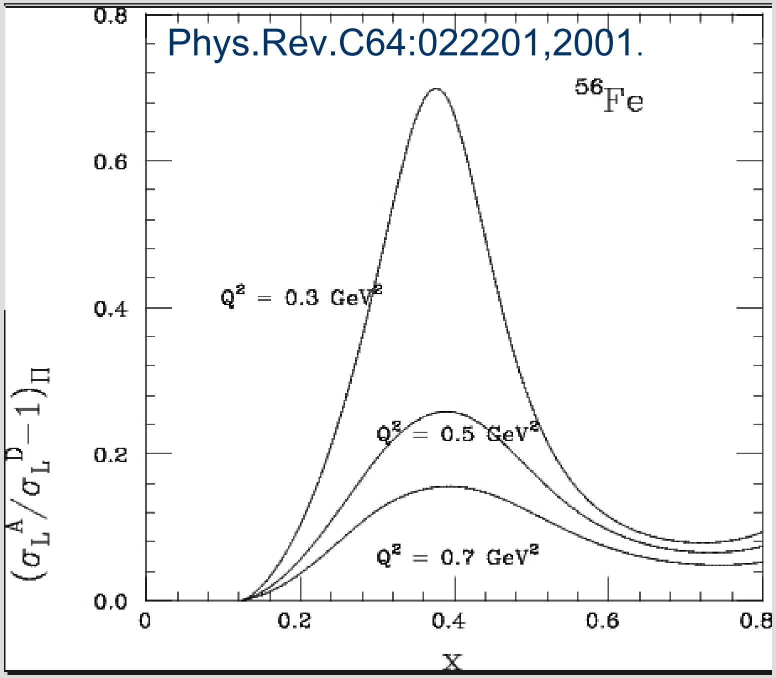
Lot's more F_L data to be finalized

including deuteron,

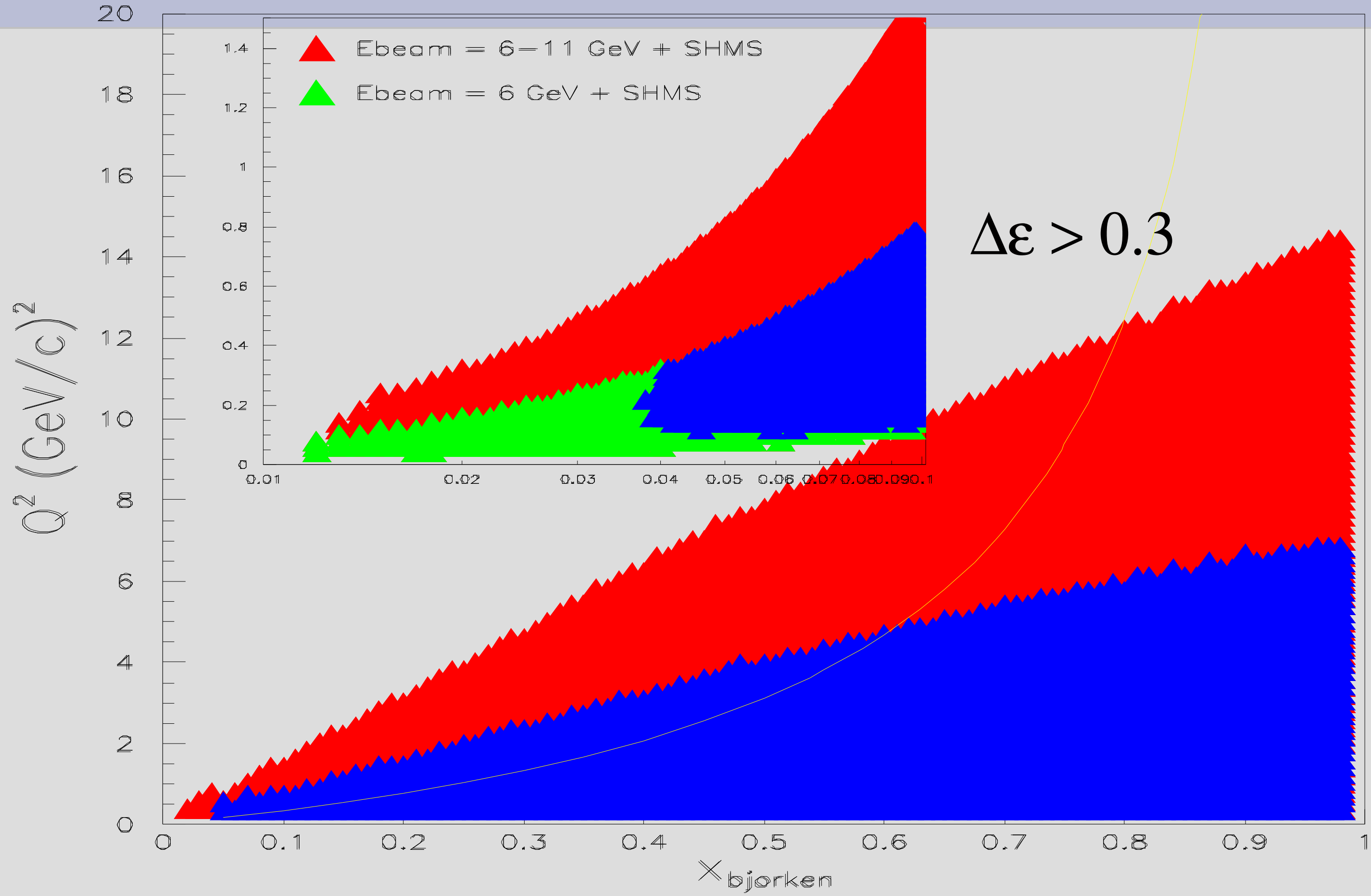
as well as C, Al, Fe, and Cu targets
to study nuclear dependence of F_L / R
(E04-001).

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

Stay tuned....



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

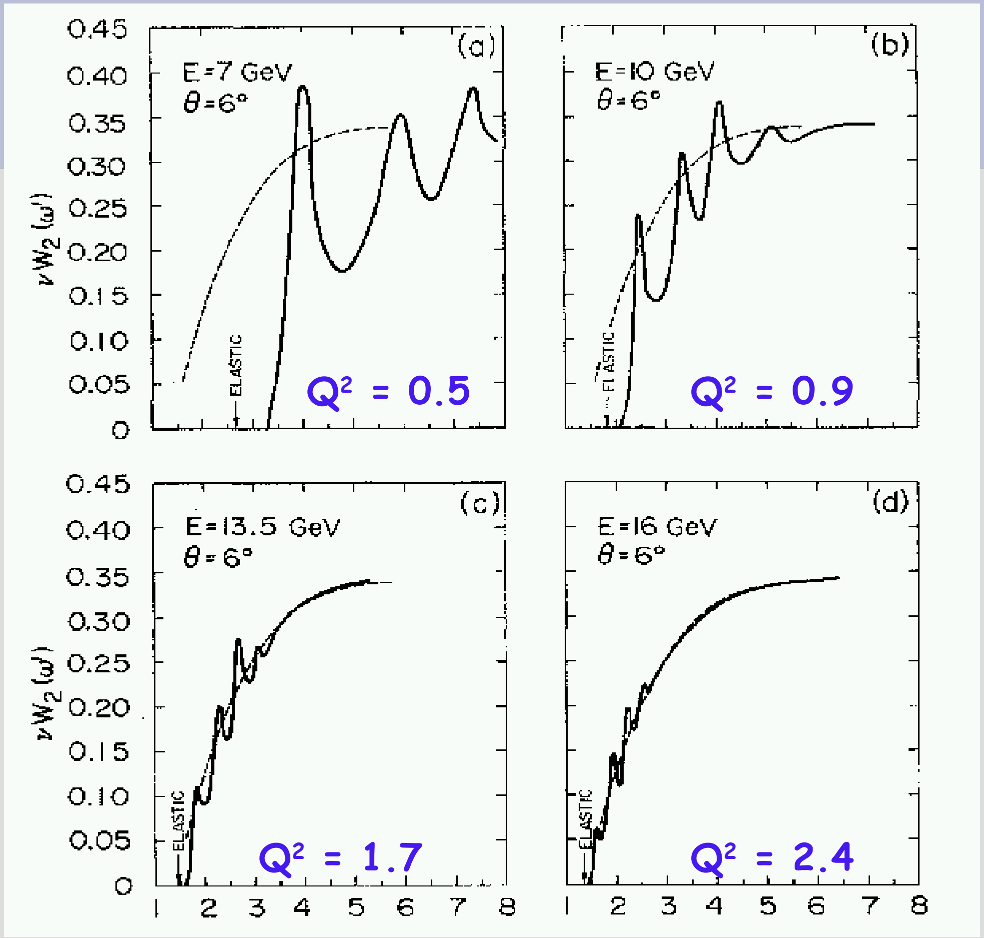


Backup Slides

Quark-Hadron Duality - a reminder

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

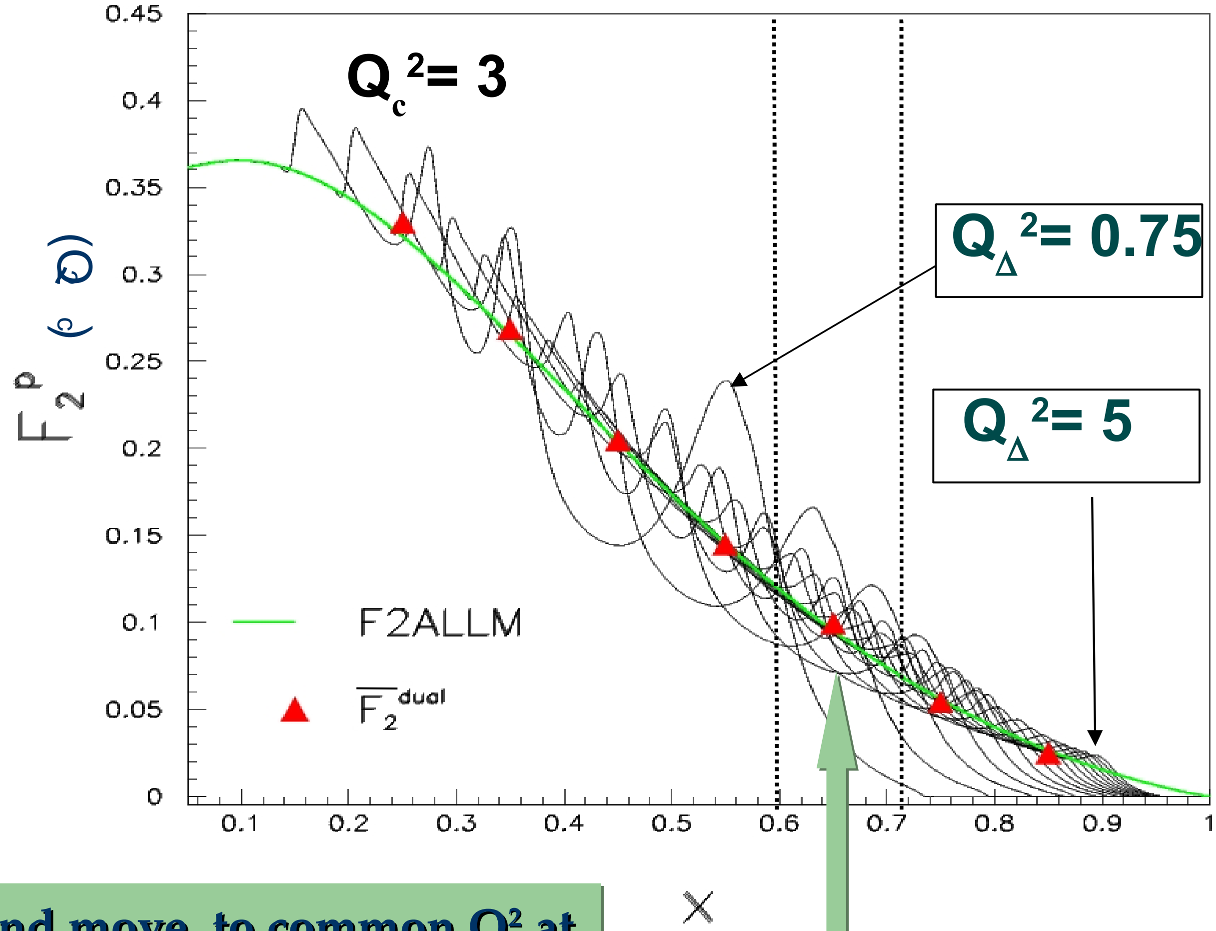
➢ Noted that resonances oscillate around a 'scaling' curve at all Q^2.
- *hadrons follow the DIS scaling behavior.*



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

Novel observation that was generally left unstudied for next 30 years.

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.

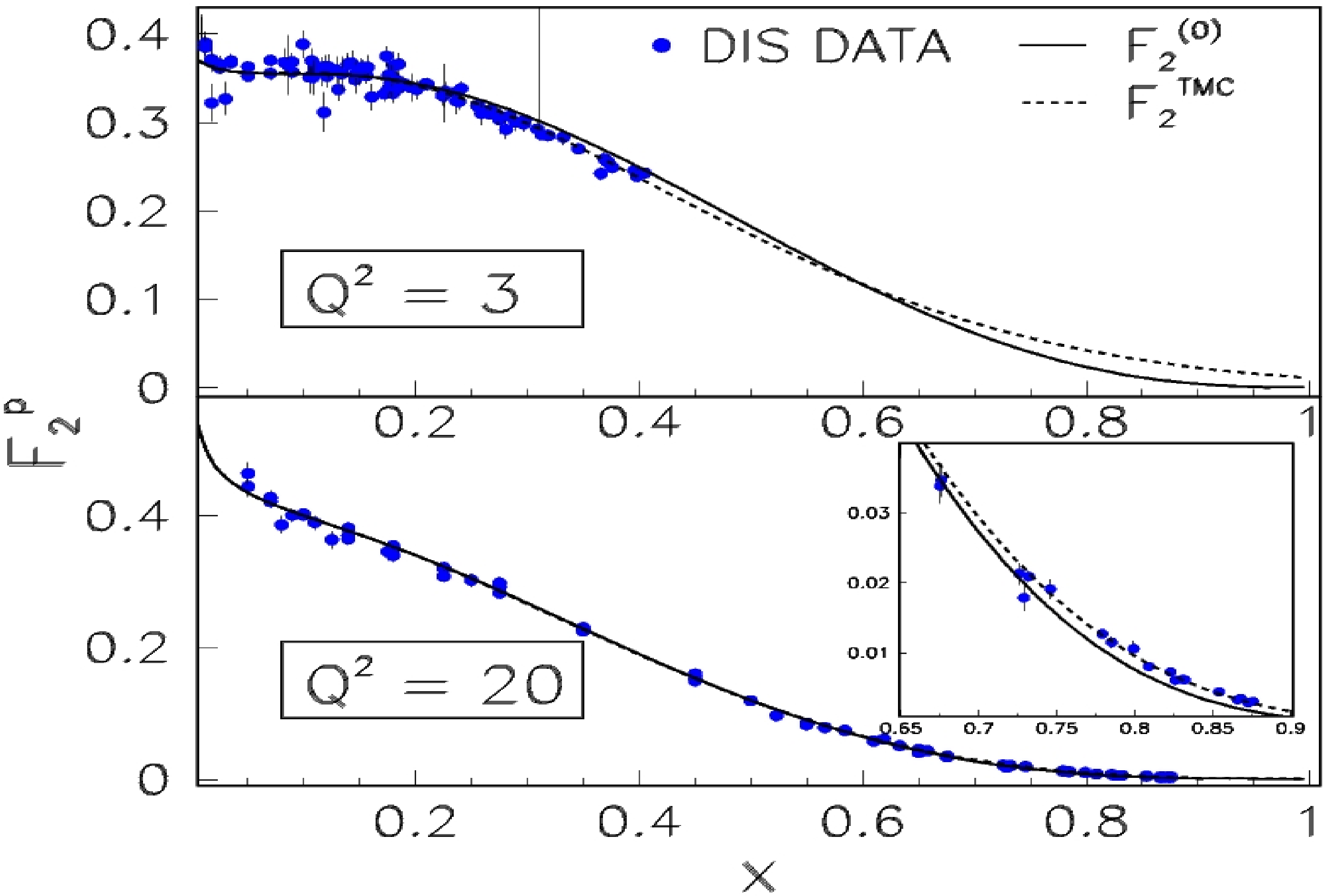
For F_2 resonance average is very close to DIS fit!

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

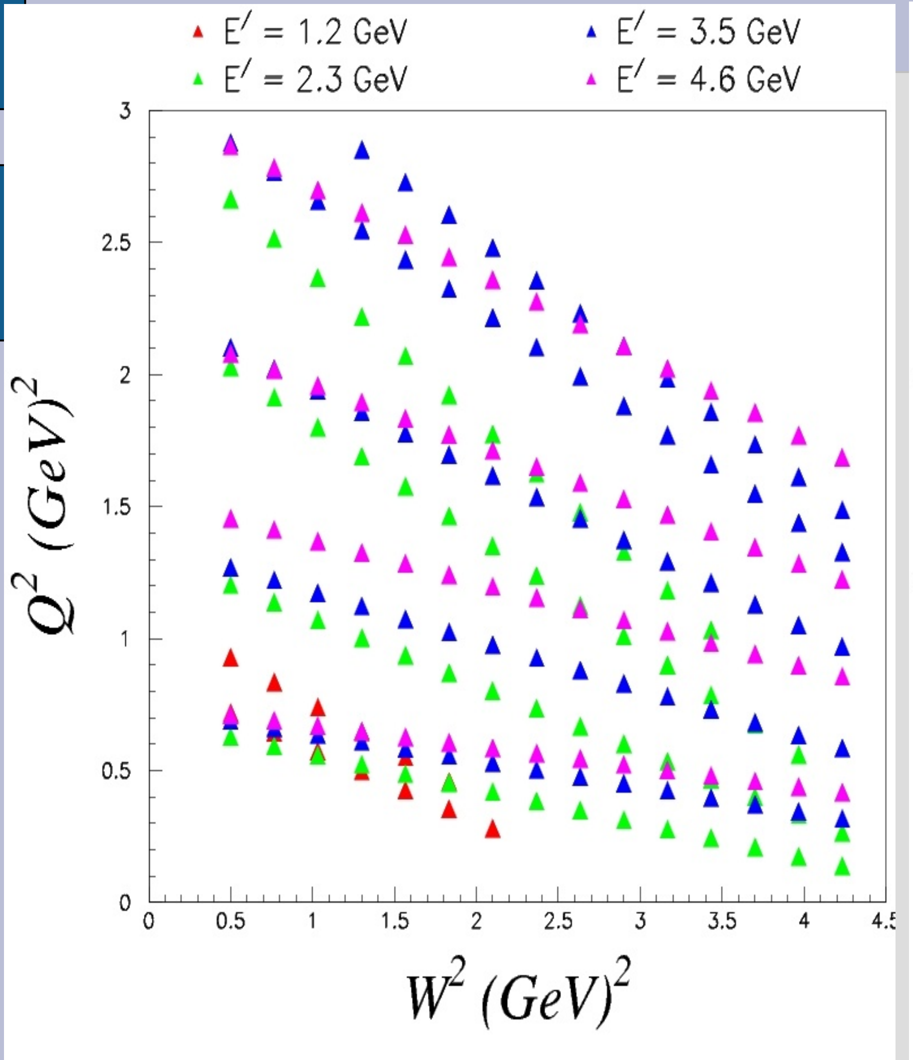
=> 'DIS-like' data

F_2 fit results

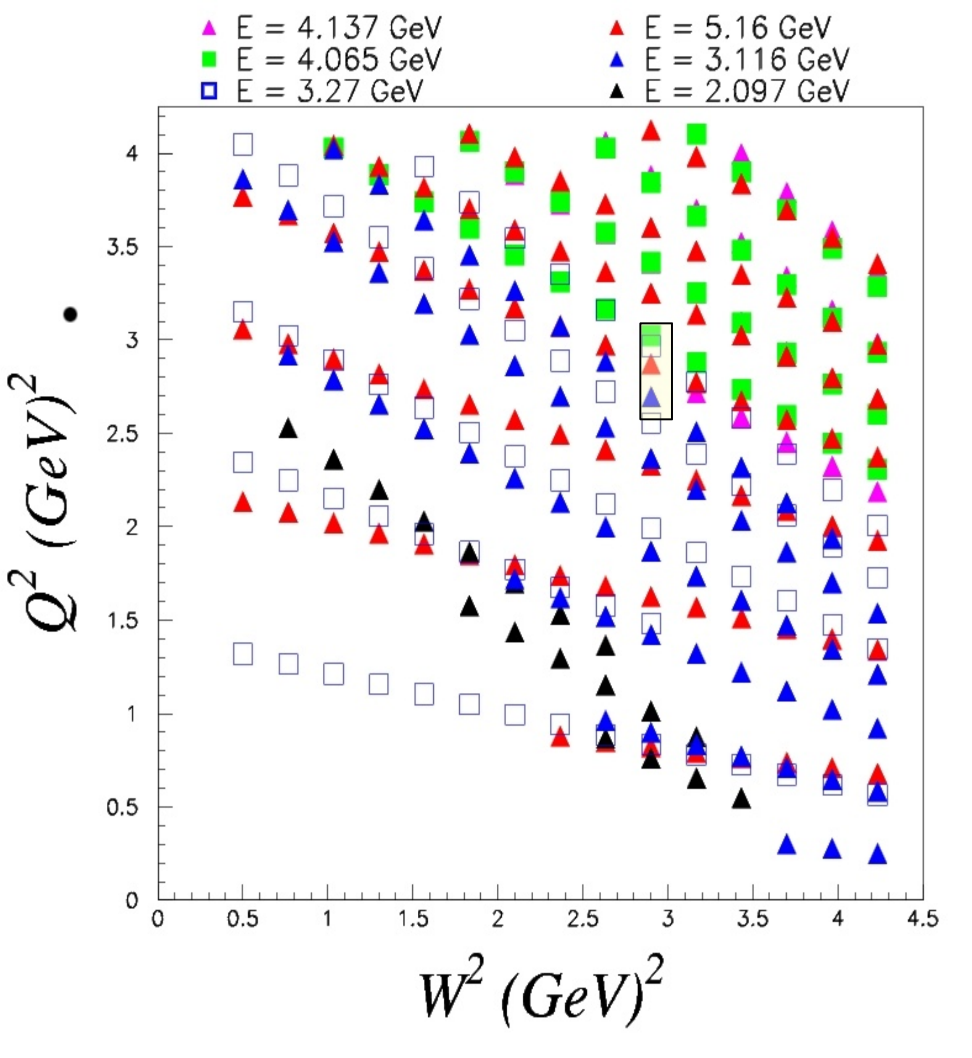


L/T kinematics (d, C, Al, Cu, Fe)

2005



2007



However, we need corrections to pQCD Structure Functions at large-x to compare with data.

To extract SFs at large-x from DIS (Drell-Yan?) data, several effects must be corrected for:

(1) Dynamic higher-twist (H-T)

(2) Kinematic H-T (Target-Mass corrections) ← Addressed in this talk

(3) Soft gluon resummation

In addition,

Limited Q^2 lever arm ← Addressed in this talk

Large nuclear corrections for extracting neutron from deuteron

Provide clean separation of nucleon singlet / non-singlet contributions

Target Mass Corrections

Finite mass nucleon =>

modification of massless limit structure functions in parton model

- **Original OPE prescription due to Geogi & Politzer '76**

- **For modern update for electroweak structure functions**

  S. Kretzer and MH Reno, Phys. Rev. D 66, 113007 (2002)

- *For Recent review see*

  I. Schienbein et.al, J. Phys. G: Nucl. Part. Phys. 35 (2008) 053101

Different formalism approaches to TMCs

Collinear Factorization

New extension to this approach by *Accardi & Qiu*

OPE

Traditional approach of Georgi-Politzer and others.

Nachtmann Moments.

$x \to 1$ problem (same as classic collinear factorization)

See recent review

I. Schienbein et.al, J. Phys. G: Nucl. Part. Phys. 35 (2008) 053101

Target Mass Corrections in Operator Product Expansion

The correction for non-zero nucleon mass leads to

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

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

These are what we measure! ***Note that the integrals for both F_1 and F_2 are the same.***

$$F_L^{\mathrm{TMC}}(x, Q^2) = r^2 F_2^{\mathrm{TMC}}(x, Q^2) - 2x F_1^{\mathrm{TMC}}(x, Q^2)$$

In G&P original paper $2xF_1^{(0)} = F_2^{(0)}$ => $F_L^{(0)} = 0$

i.e. Callan-Gross is built in. This is because they considered twist-2 operators at *LO only*.

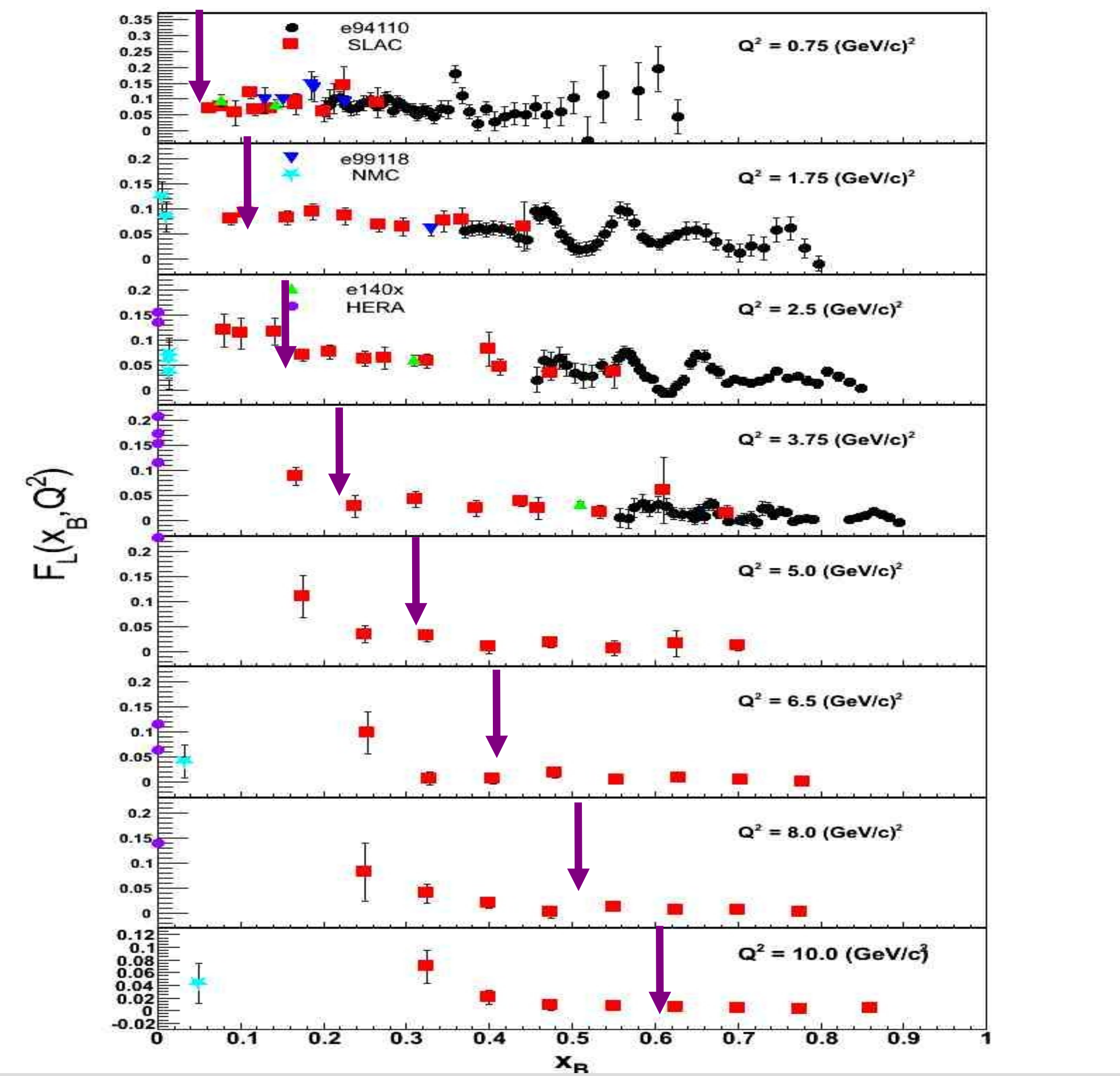
However, the formalism works to ***all*** orders for twist-2 operators.

(*in principle, HT operators can have different TMC*)

In the limit $M^2/Q^2 \rightarrow 0$

$$\text{Note } F_j^{(0)}(\xi) \neq (\lim_{M\to 0} F_j(\xi))$$

$$F_j^{(0)}(\xi, Q^2) \equiv (\lim_{M\to 0} F_j^{\mathrm{TMC}}(x, Q^2))|_{x=\xi}$$



Minimum *x* at 11 GeV

With JLab *only* data.

Can improve F_L at lower *x* by combining JLab and SLAC data.