The Abdus Salam
International Centre for Theoretical Physics

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SMR.1751 - 5

Fifth International Conference on
PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

22 - 26 May 2006

Quark-Hadron Duality

(presented by P. Bosted)

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Quark-Hadron Duality

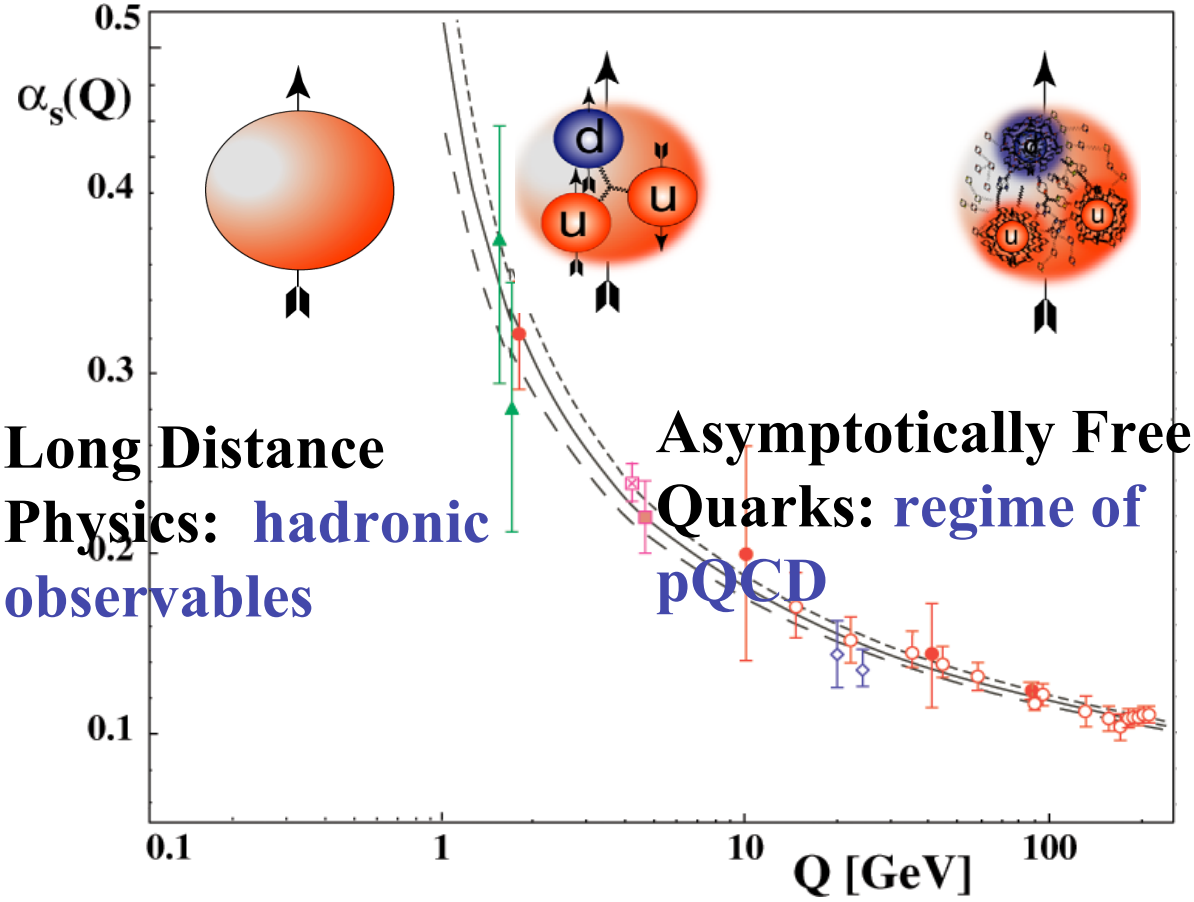
Cynthia Keppel
(presented by Peter Bosted)
Hampton University / Jefferson Lab

Fifth International Conference on
Perspectives in Hadronic Physics

Trieste, Italy

May 2006

Duality and the Transition to Perturbative QCD



Long Distance Physics: hadronic observables

Asymptotically Free Quarks: regime of pQCD

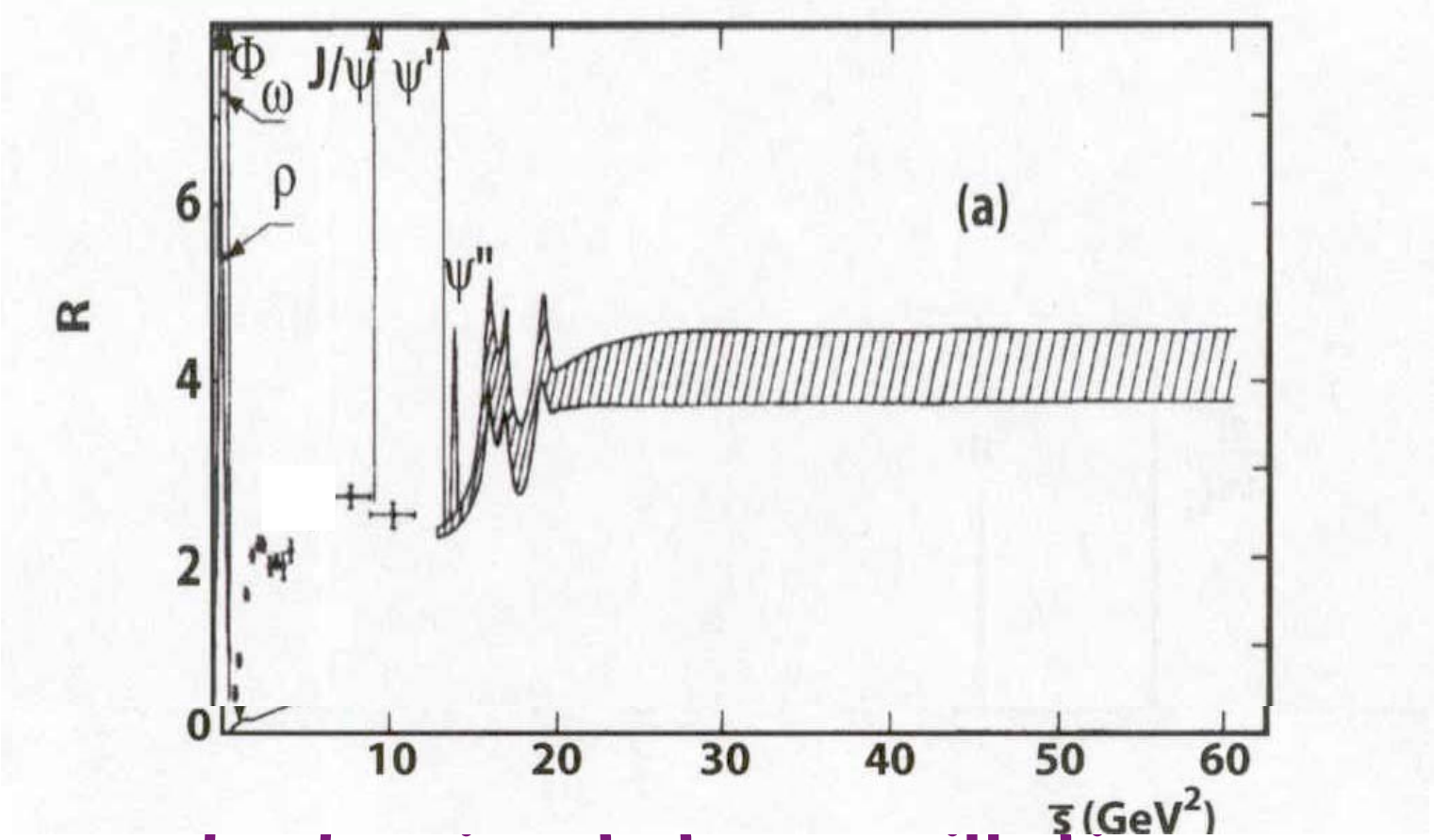
Asymptotically **the photon couples to quarks, yet** ***confinement*** **ensures that only hadronic final states are observed.**

Duality is intimately related to the transition from soft to hard QCD.

Textbook Example: e^+e^- → hadrons

$$R = \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

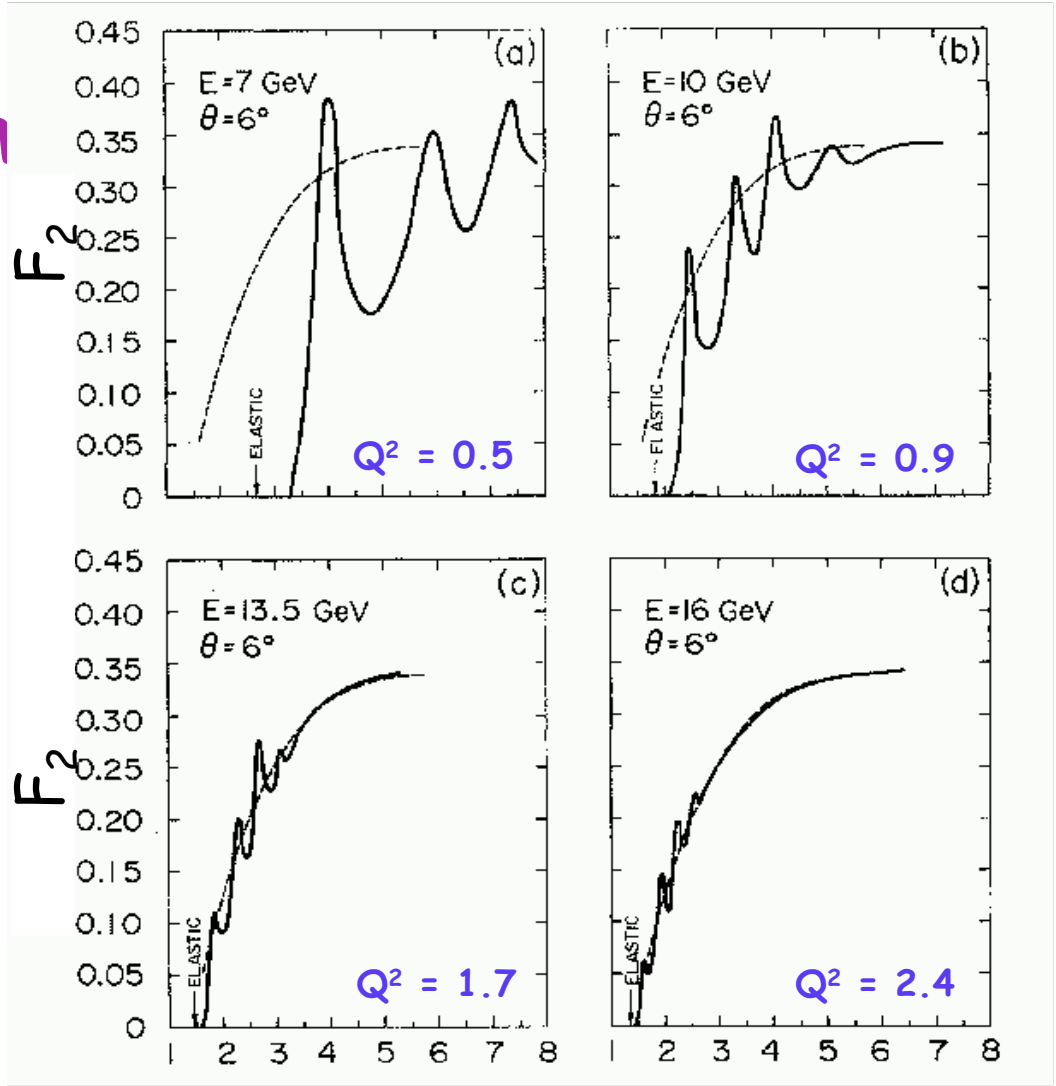
$$\lim_{E\to\infty} \frac{\sigma(e^+e^- \to X)}{\sigma(e^+e^- \to \mu^+\mu^-)} = N_c \sum_q e_q^2$$



Narrow hadronic states oscillating around step function determined by quark properties

Bloom-Gilman Duality

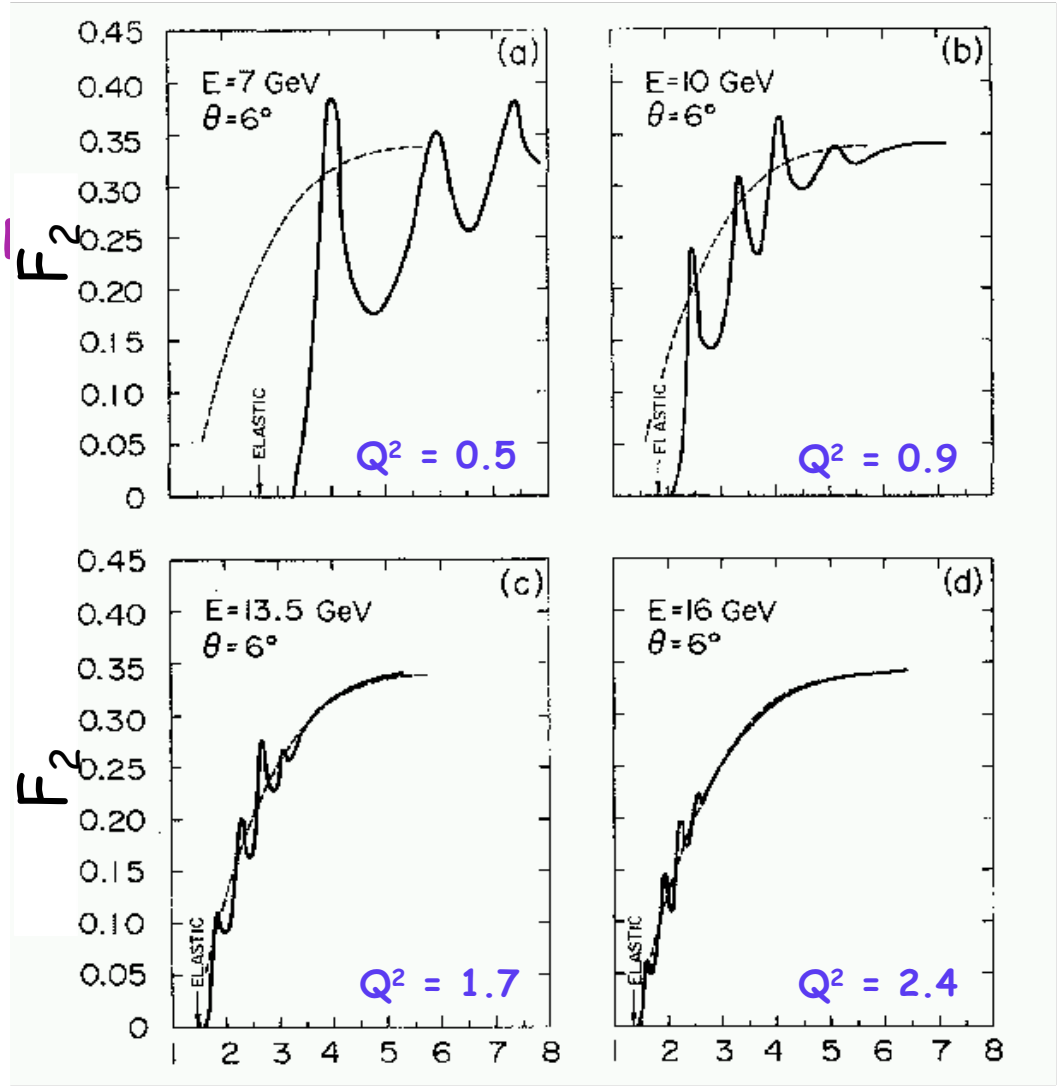
- First observed ~1970 by Bloom and Gilman at SLAC by comparing resonance production data with deep inelastic scattering data using ad hoc variable



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

Bloom-Gilman Duality

- Integrated F_2 strength in nucleon resonance region equals strength under scaling curve.
- Resonances oscillate around curve - *at all* Q^2

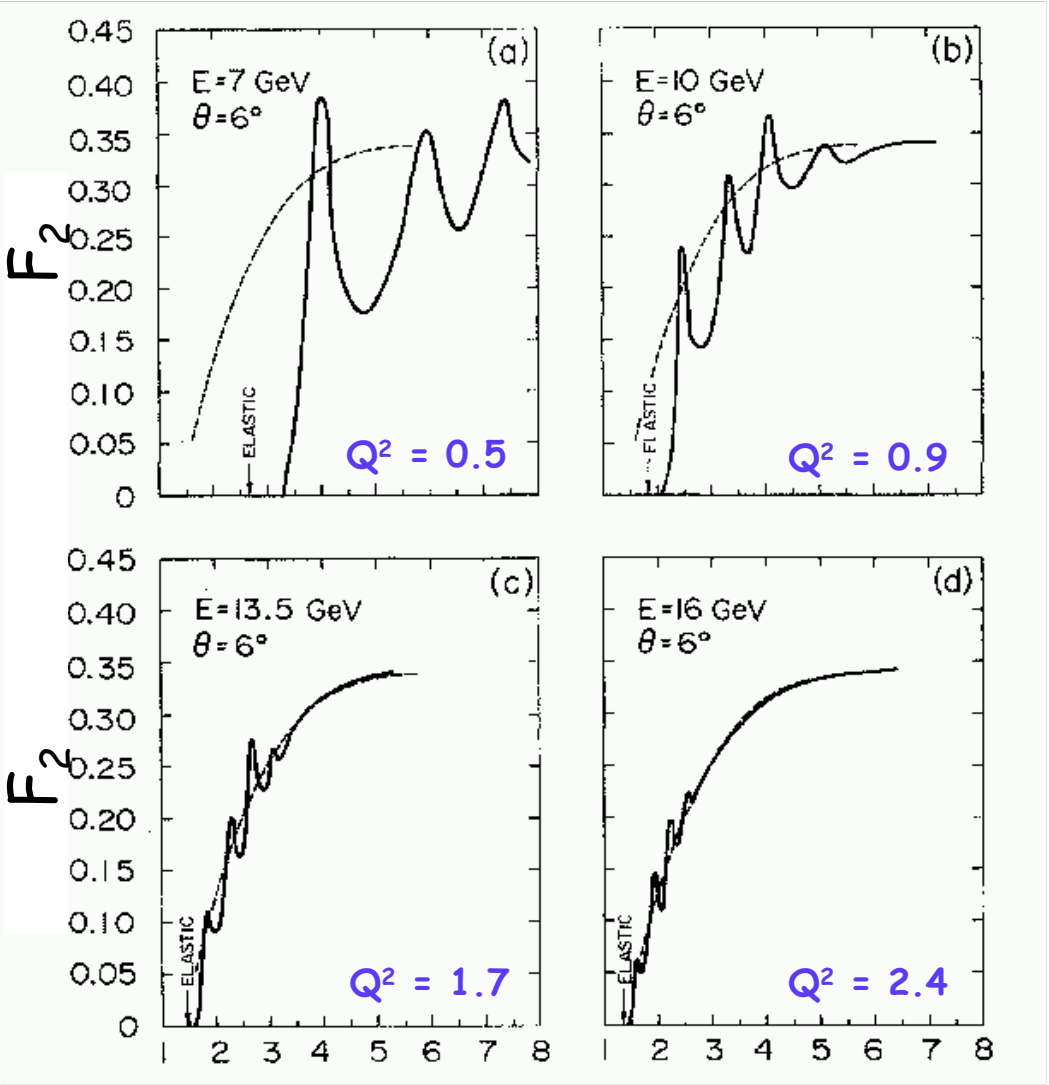


$\omega' = 1+W^2/Q^2$

Bloom-Gilman Duality

Shortcomings:

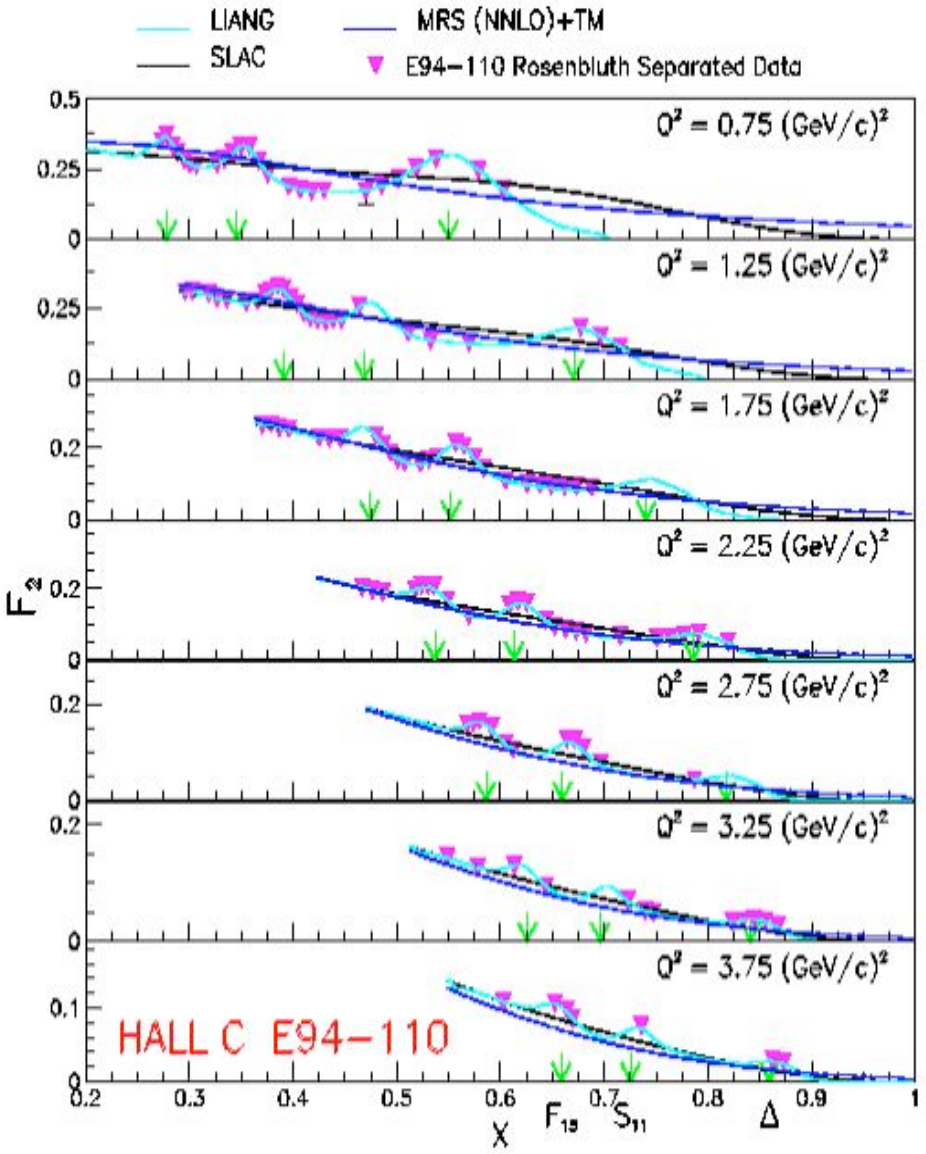
- Only a single scaling curve and no Q^2 evolution (theory inadequate in pre-QCD era)
- No σ_L/σ_T separation F_2 data depend on assumption of R = σ_L/σ_T
- Only moderate statistics



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

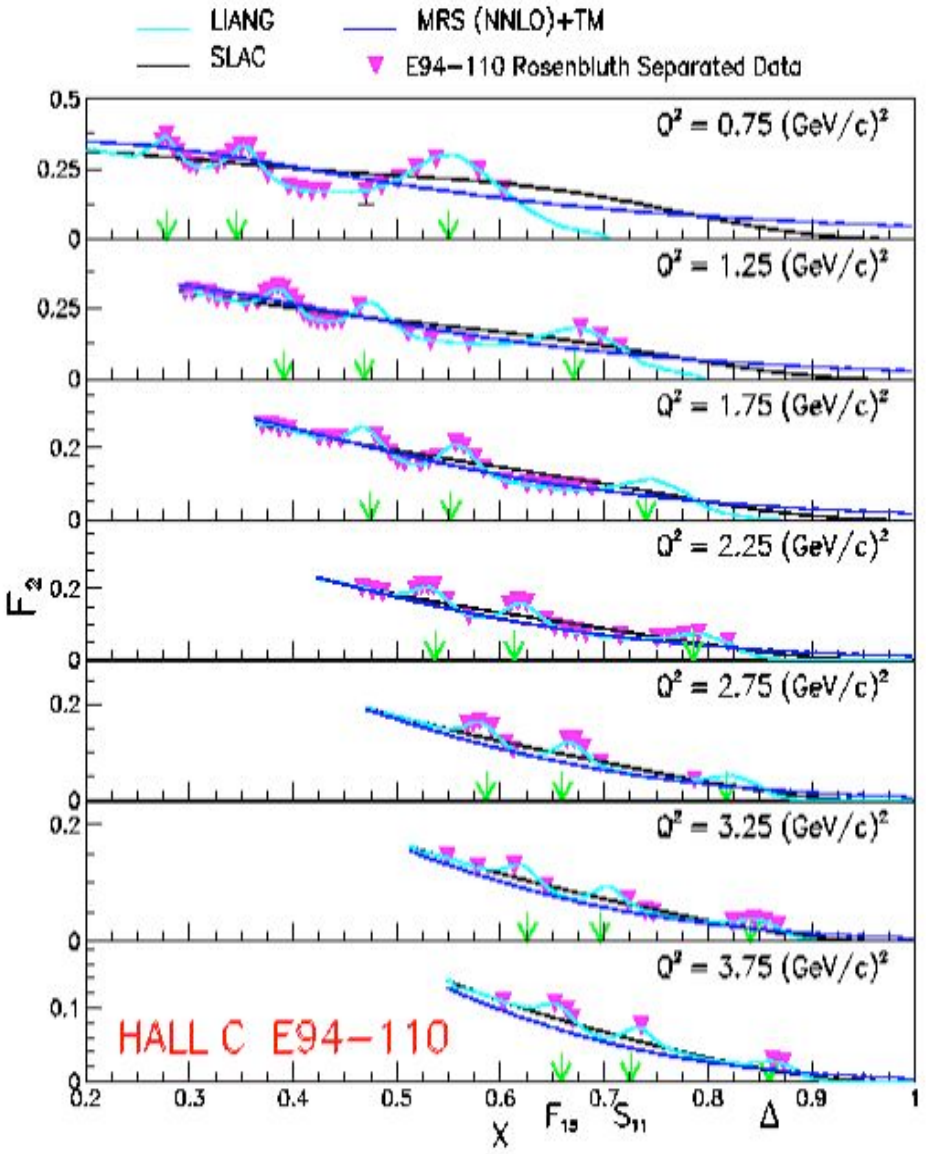
Bloom-Gilman Duality in F_2 Today

- F_2 DIS well-measured over several orders of magnitude in x, Q^2
- QCD established theory
- Perturbative predictions (based on extracted PDF's, evolution) available

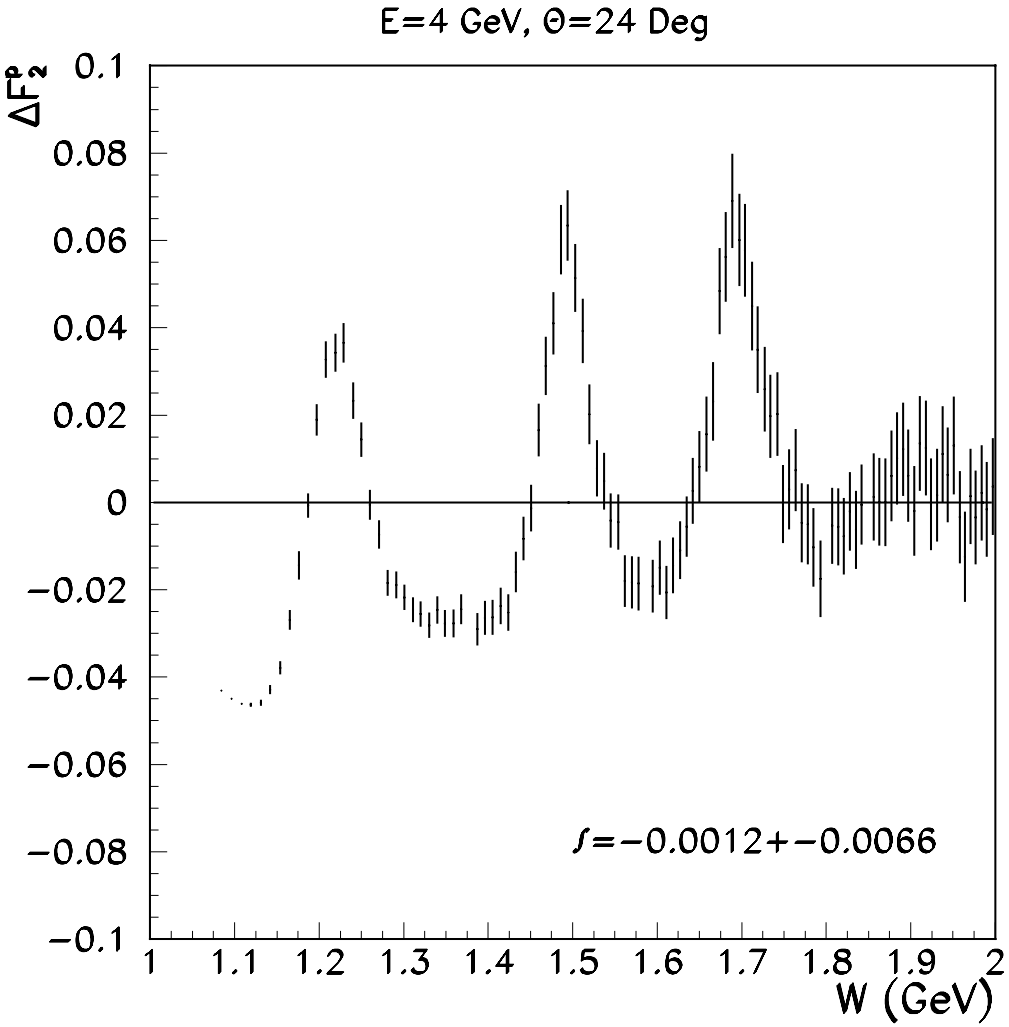


Bloom-Gilman Duality in F_2 Today

- Target mass prescription
- Quark-Hadron Duality quantifiable (more later….)
- *Shown to hold to better than 5% above $Q^2 \sim 0.5$ GeV^2*
  - *F_2 average*
  - *Q^2 dependence*



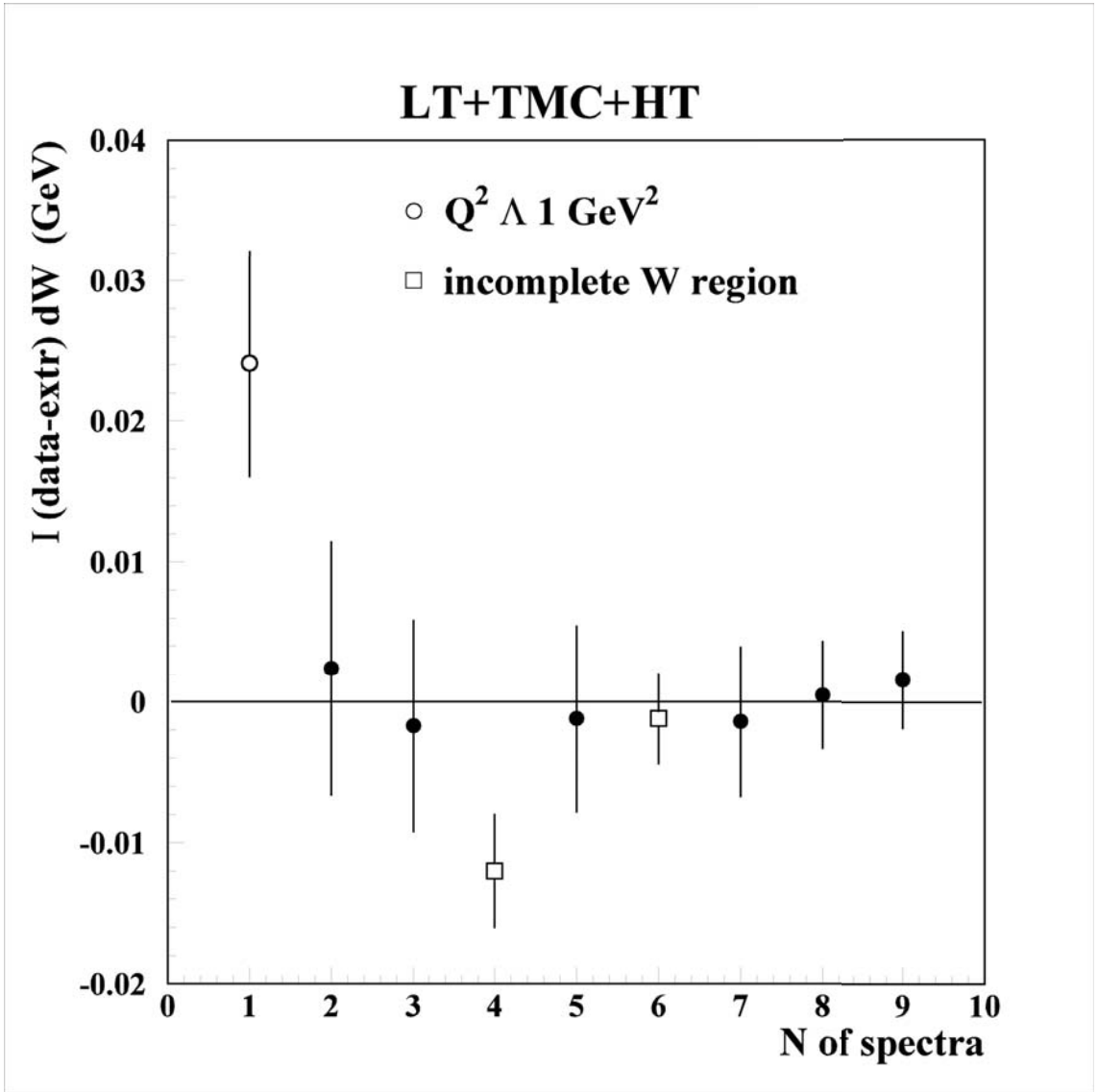
Bloom-Gilman Duality in F_2 Today



Difference between Alekhin NNLO curve (formed from lepton-nucleon scattering only) and resonance data,

Bloom-Gilman Duality in F_2 Today

Difference between Alekhin NNLO curve (formed from lepton-nucleon scattering only) and resonance data, *integrated for many spectra*

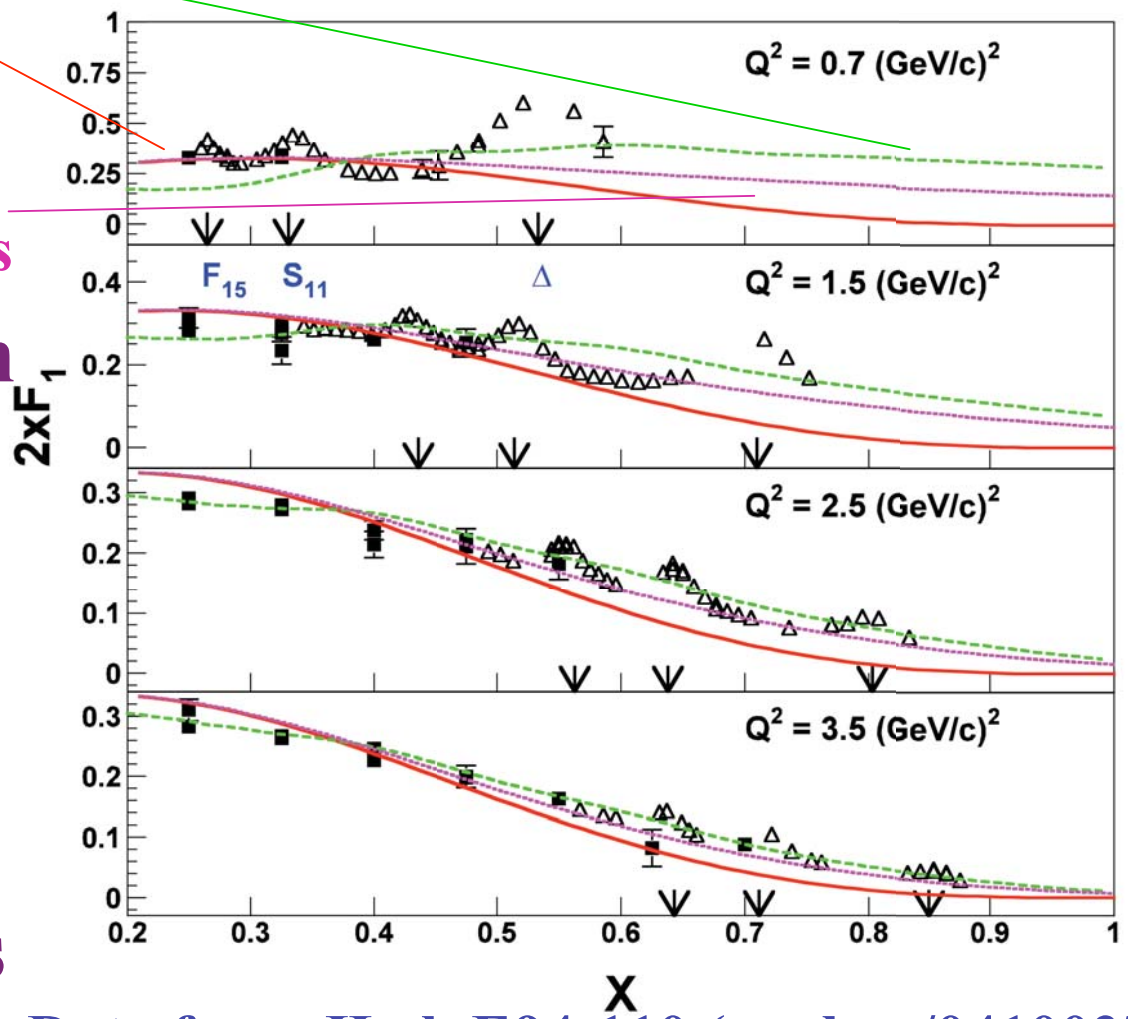


Experimental Status of L/T Separated Structure Functions: $2xF_1$

Alekhin NNLO

MRST NNLO

MRST NNLO with Barbieri Target Mass Corrections



- Smooth transition from DIS (solid squares) to resonance region
- Resonances oscillate about perturbative curves

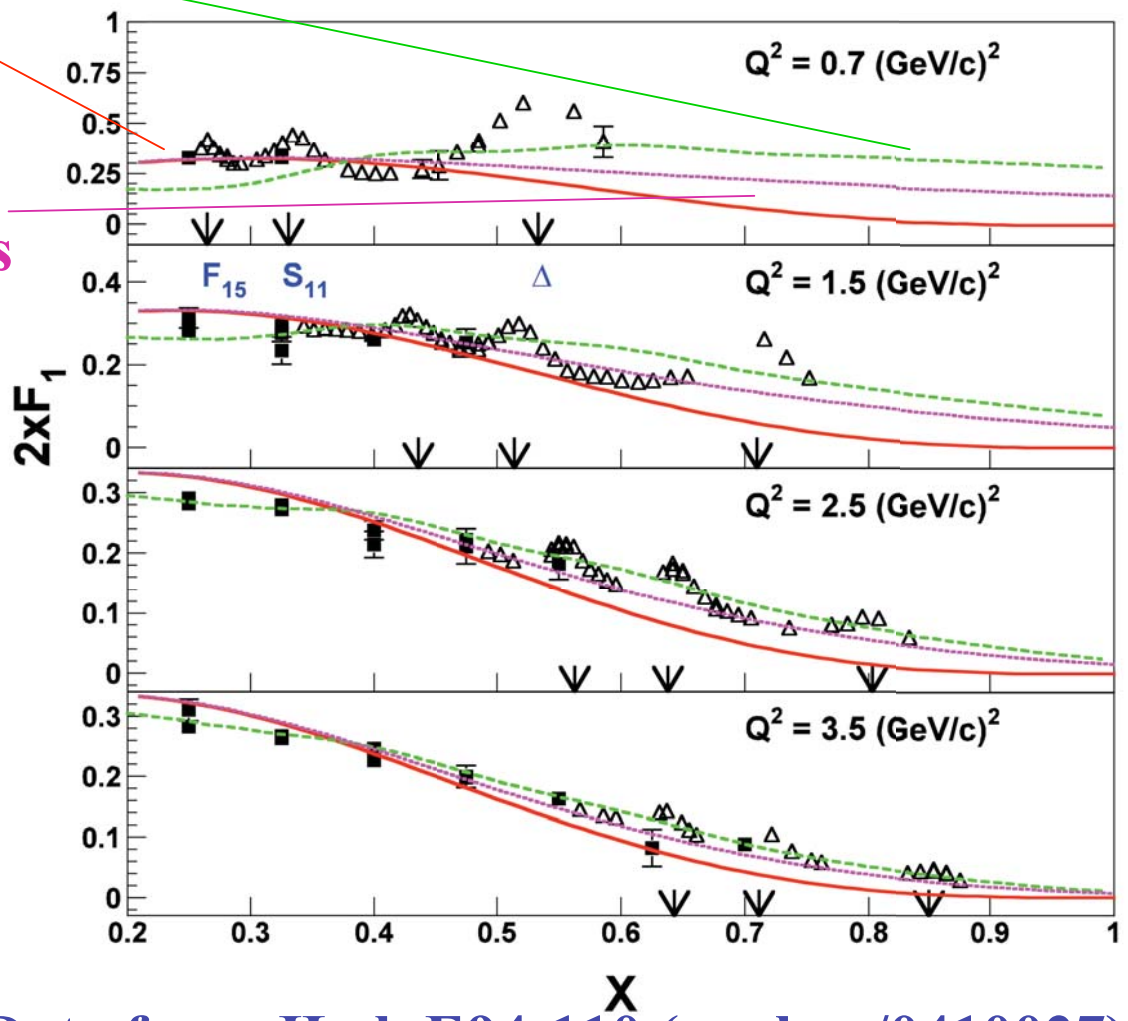
Data from JLab E94-110 (nucl-ex/0410027)

Experimental Status of L/T Separated Structure Functions: $2xF_1$

Alekhin NNLO

MRST NNLO

MRST NNLO with Barbieri Target Mass Corrections



- Target mass corrections large and important (subject of much recent theory work - Steffens, Melnitchouk, Qiu, Reno, Kretzer,…)

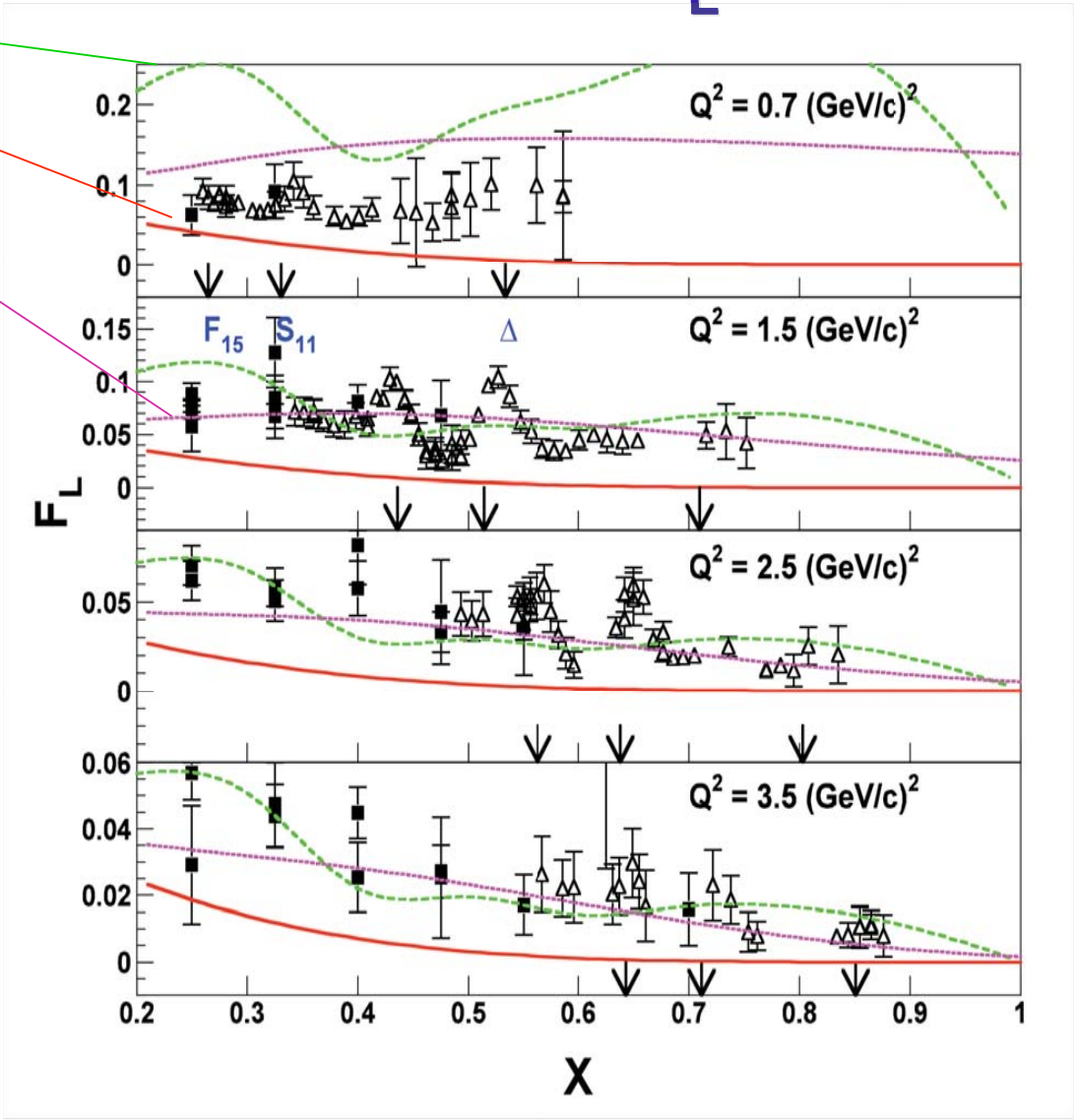
Data from JLab E94-110 (nucl-ex/0410027)

Experimental Status of L/T Separated Structure Functions: F_L

Alekhin NNLO

MRST NNLO

MRST NNLO with Barbieri Target Mass Corrections

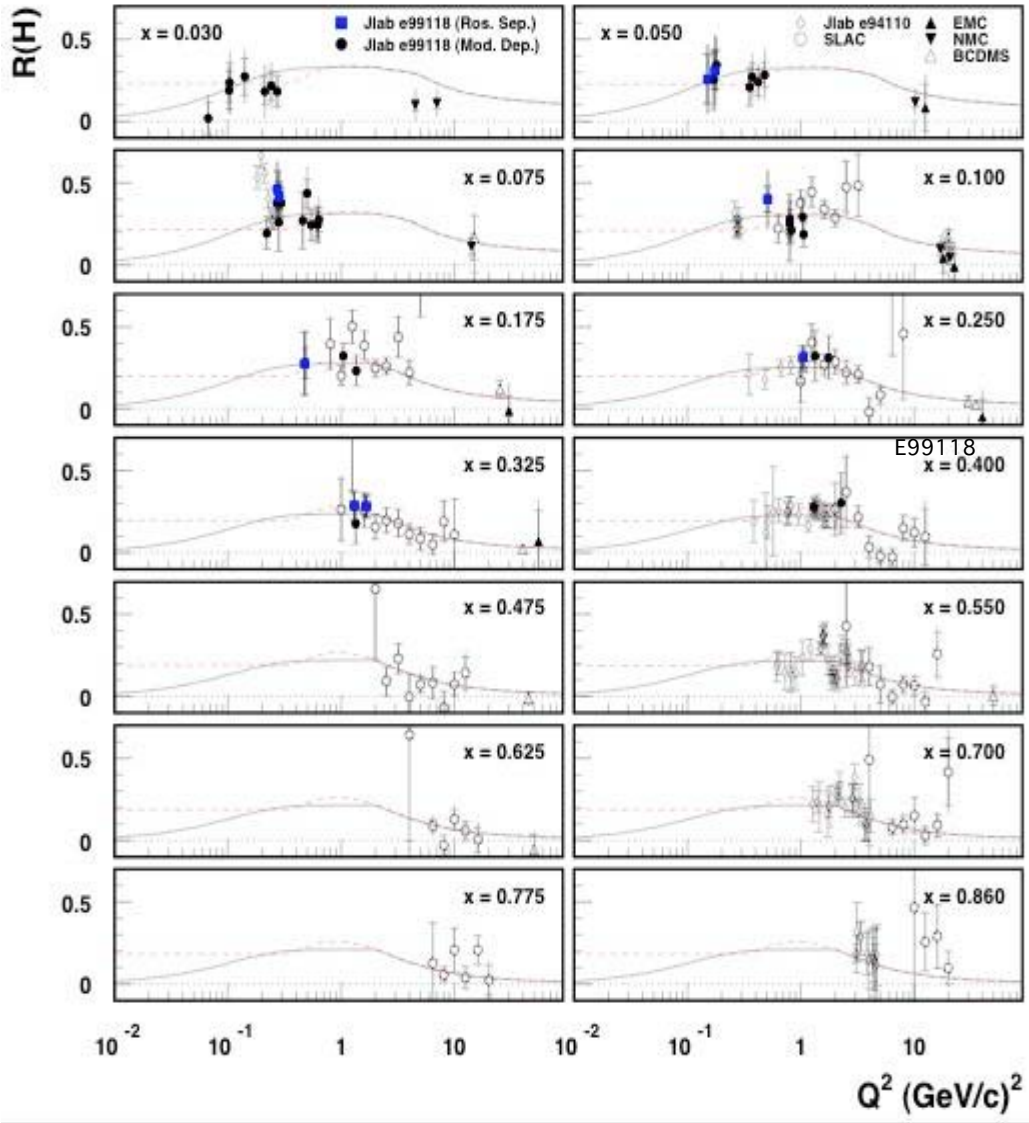


- Target mass corrections large and important
- Fun side note…what's that mass below the S_{11}?

R at Low Q^2 < 0.5: An interesting aside…

and a warning to anyone using low Q^2 structure function data

Preliminary:

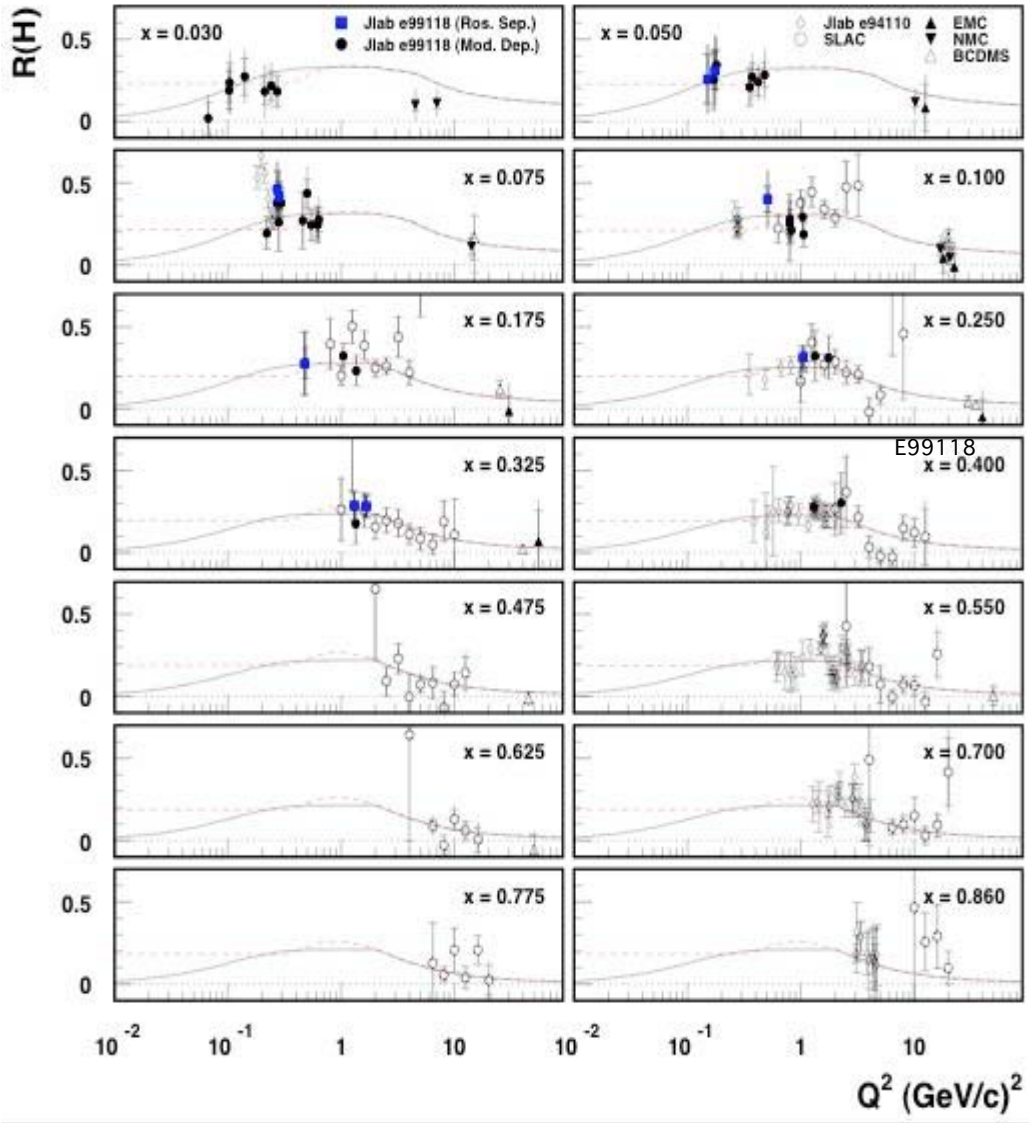


(The x < 0.2, Low Q^2 (~0.1 GeV^2) region pushed the envelope of the E94-110 and E99-118 experiments. Dedicated data for this region were taken in 2004, more results expected this year

R at Low Q^2 < 0.5: An interesting aside…

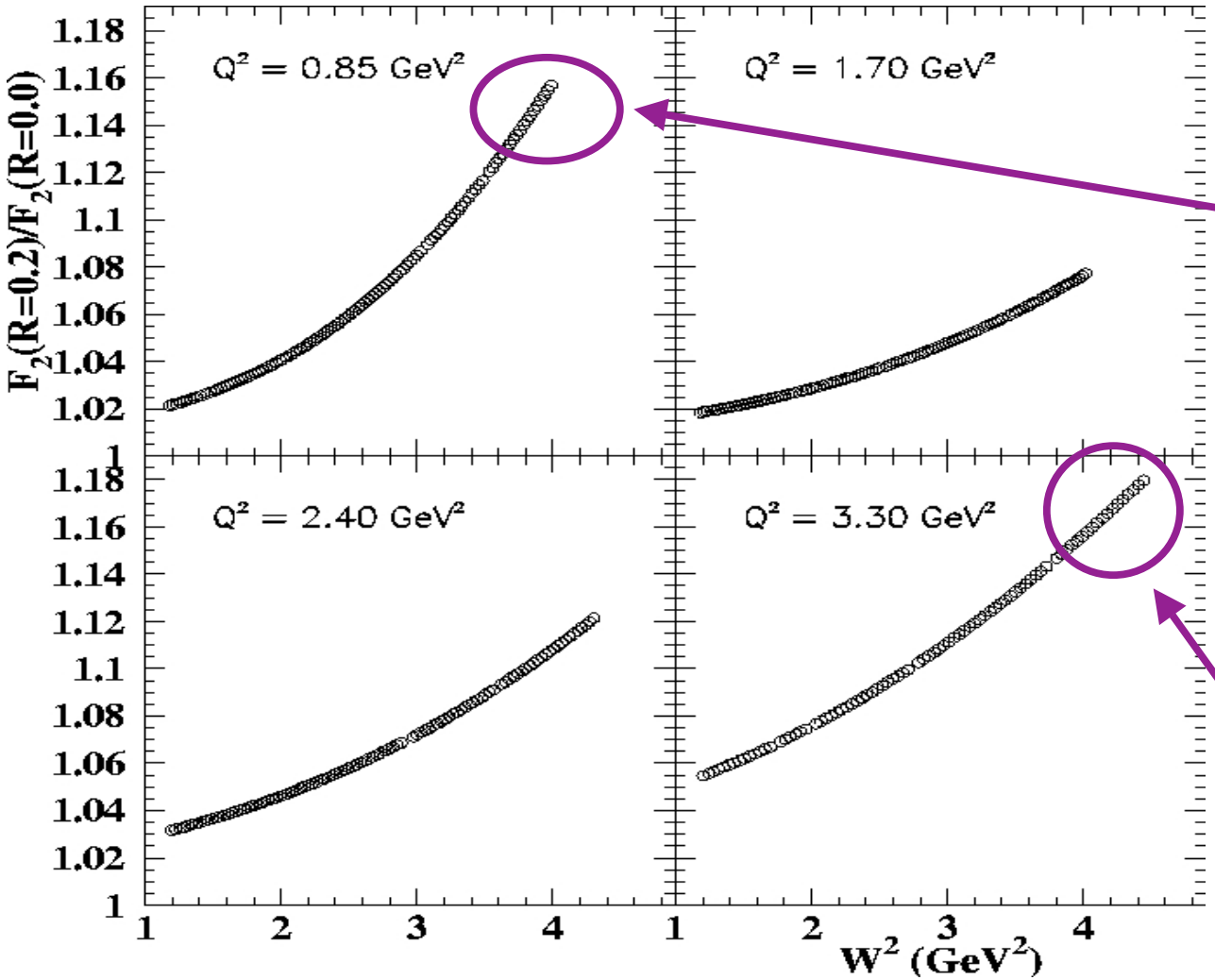
and a warning to anyone using low Q^2 structure function data

Preliminary:



R shows surprisingly flat Q^2 behaviour down to very low Q^2 (also shown by SLAC R1998 parameterisation) → does not appear to follow current conservation expectation of going to 0 yet.

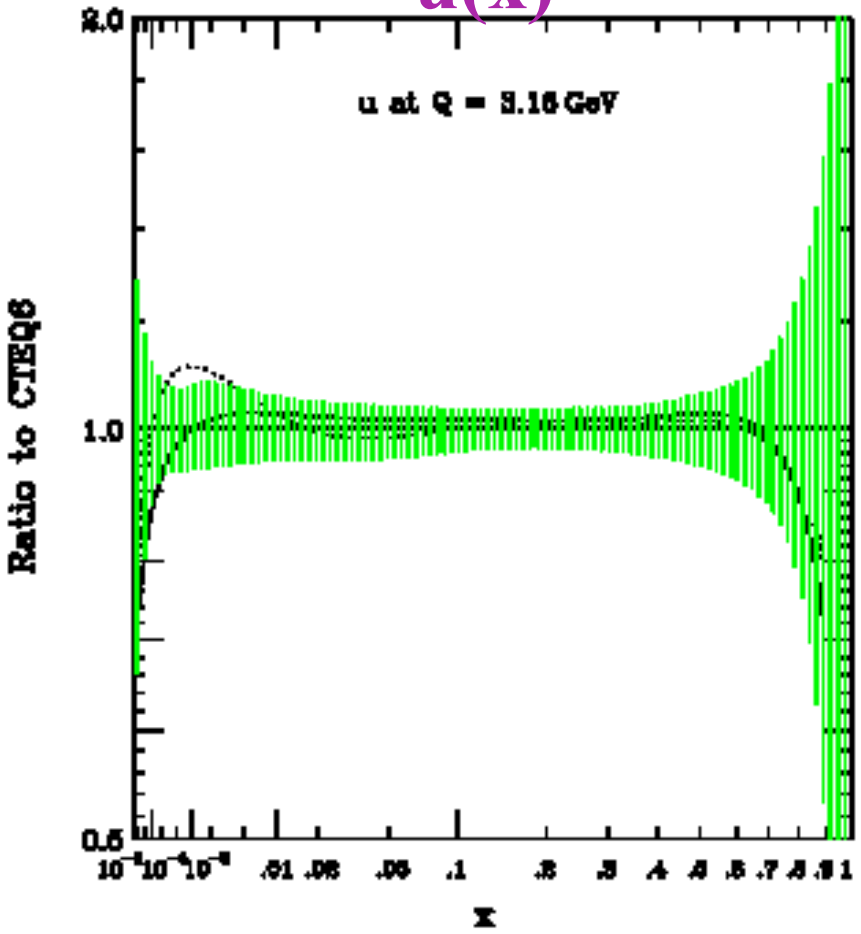
Just an example of R effect on F_2….



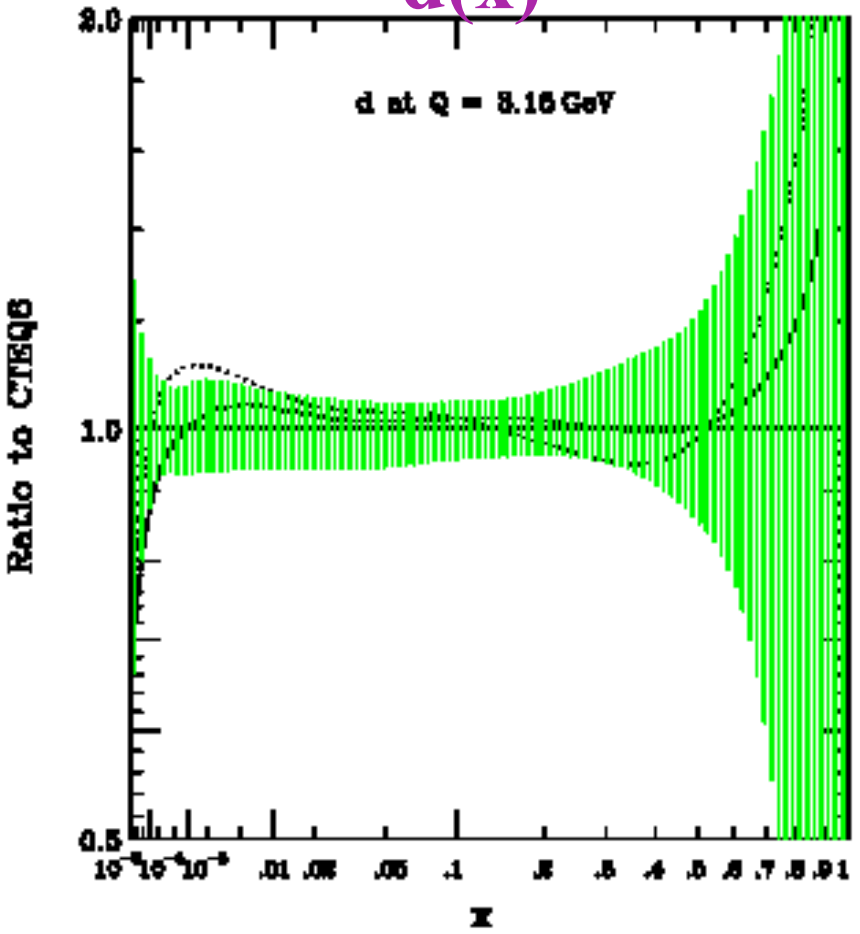
At W^2 = 4 GeV² and Q2 < 1 GeV², F_2 will vary by 15% depending on the choice of R = 0 or R = 0.2. At higher Q^2, this can be as much as 20%.

OK, back to business…Parton Distribution Functions

u(x)



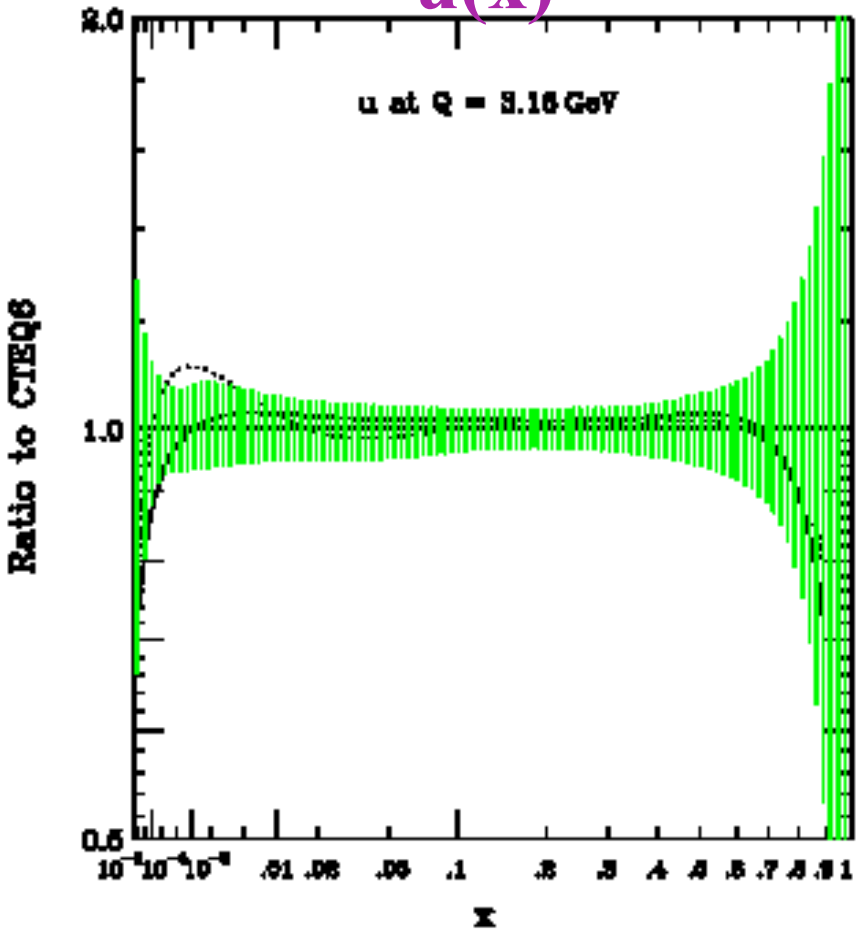
d(x)



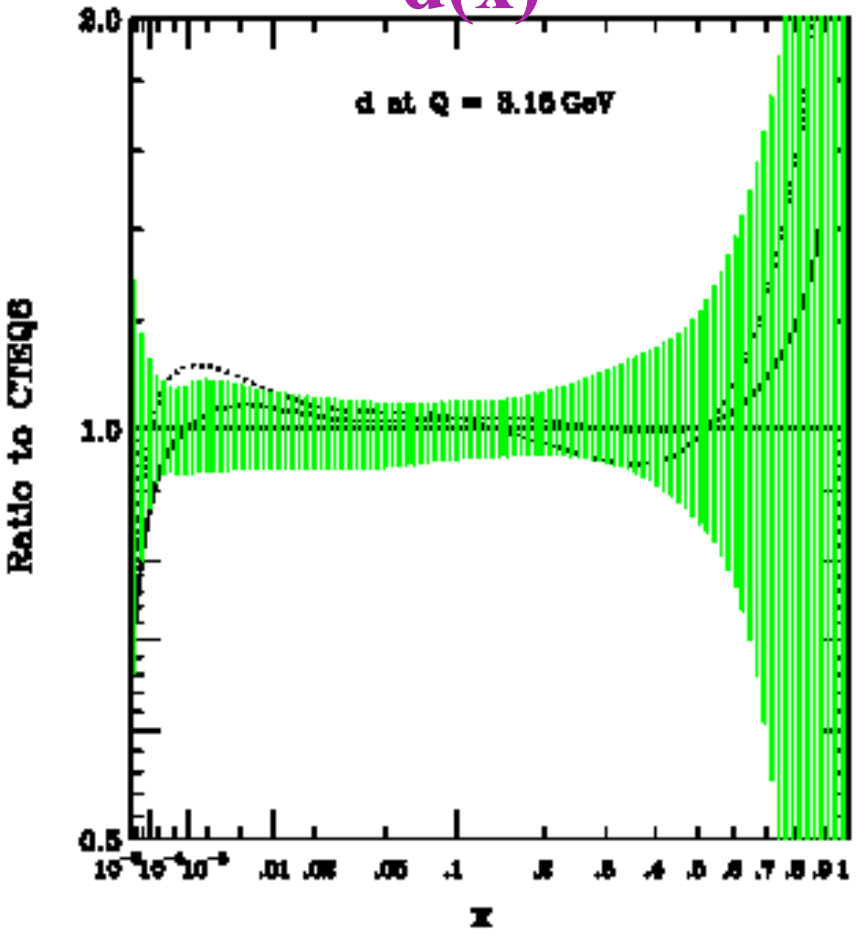
PDF's not well known at large x – poses a problem for further duality quantification,

OK, back to business…Parton Distribution Functions

u(x)



d(x)



an opportunity (USE duality for large x regime! CTEQ is currently looking at this.)

Duality in QCD

- **Moments of the Structure Function**

$$M_n(Q^2) = \int_0^1 dx\, x^{n-2} F(x,Q^2)$$

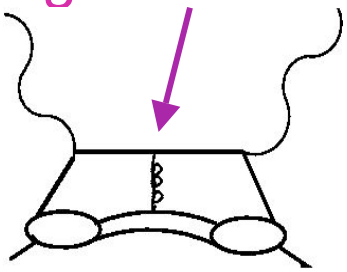
If n = 2, this is the Bloom-Gilman duality integral!

- Operator Product Expansion

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

higher twist

logarithmic dependence (pQCD)



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

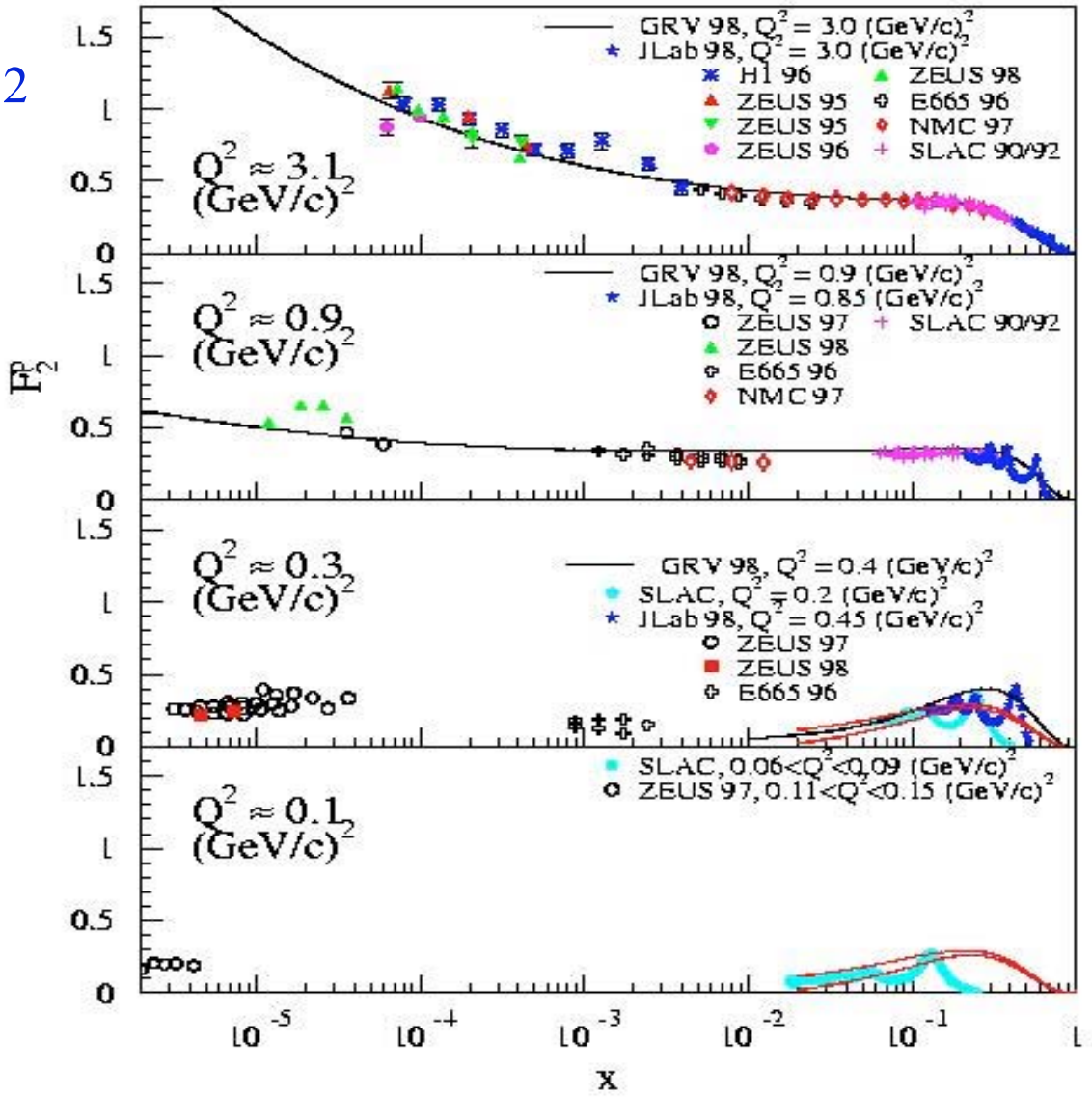
$$M^n(Q^2) = \int_0^1 dx\, x^{n-2} F(x,Q^2)$$

F_2

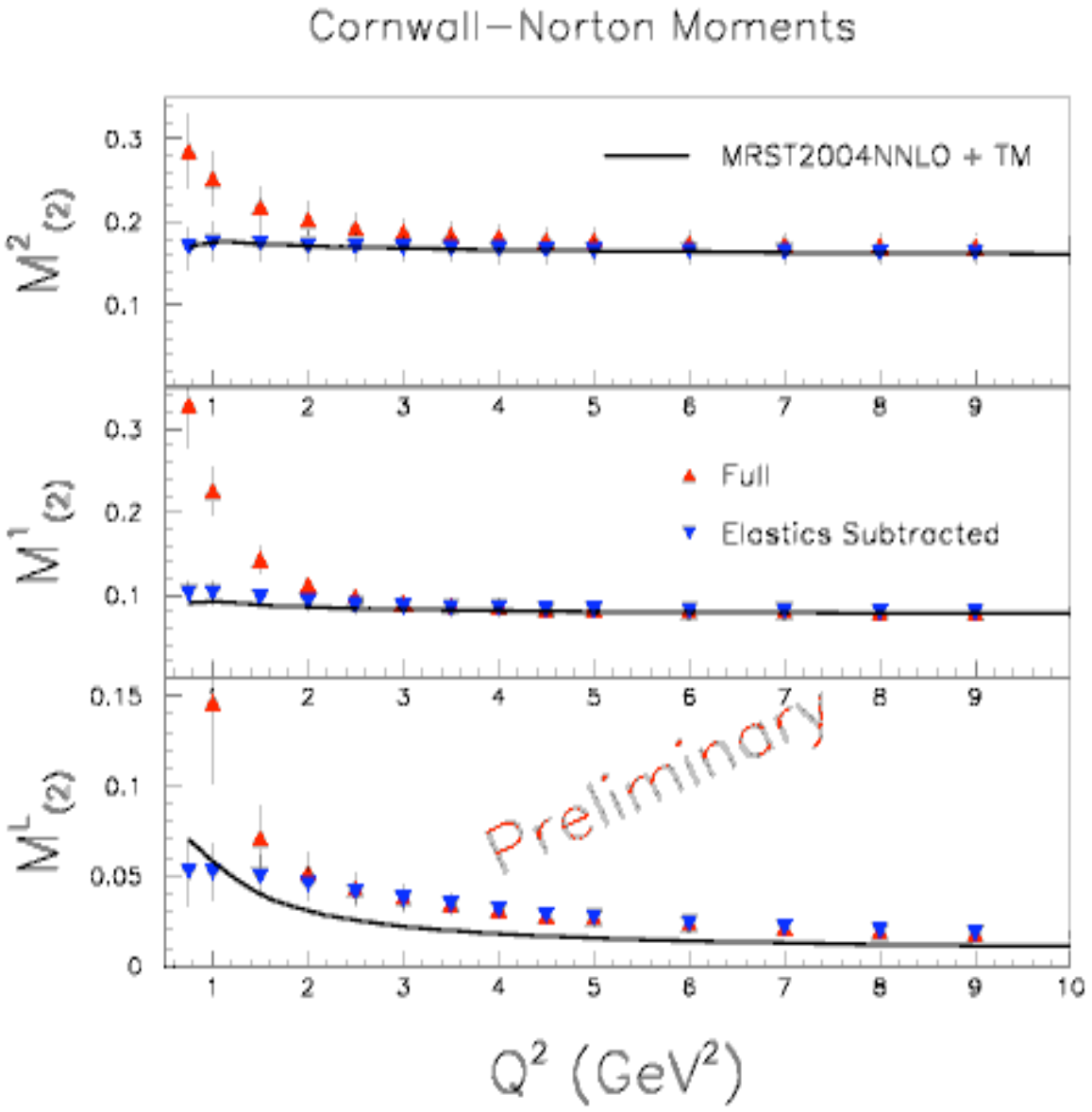
Need data covering wide range in x, at fixed Q2

Large x increasingly important at large n

+ elastics……



n = 2 Cornwall-Norton Moments

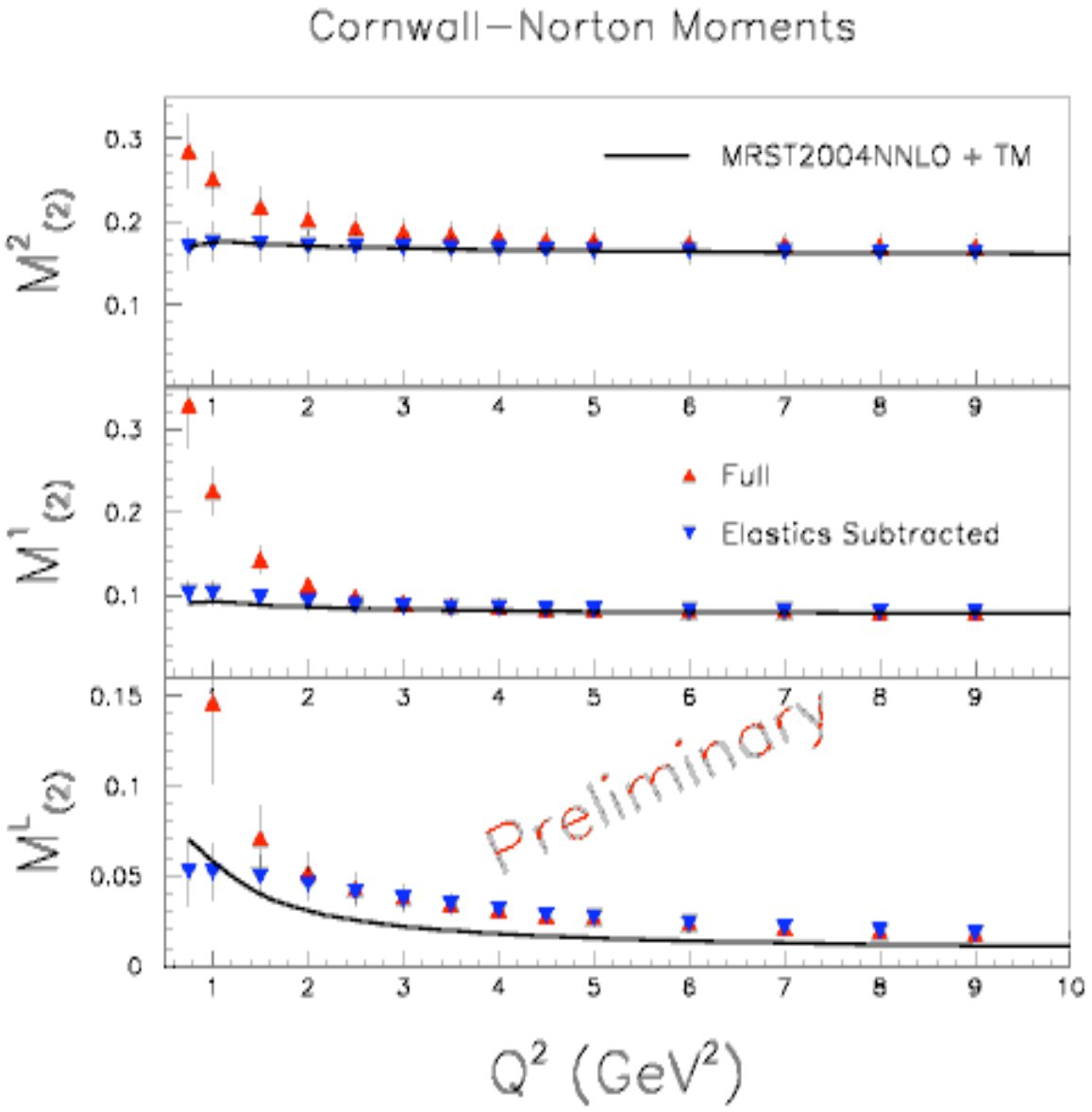


F_2, F_1 in excellent agreement with NNLO + TM above $Q^2 = 2$ GeV^2

No (or canceling) higher twists

Yet, dominated by large x and resonance region

n = 2 Cornwall-Norton Moments



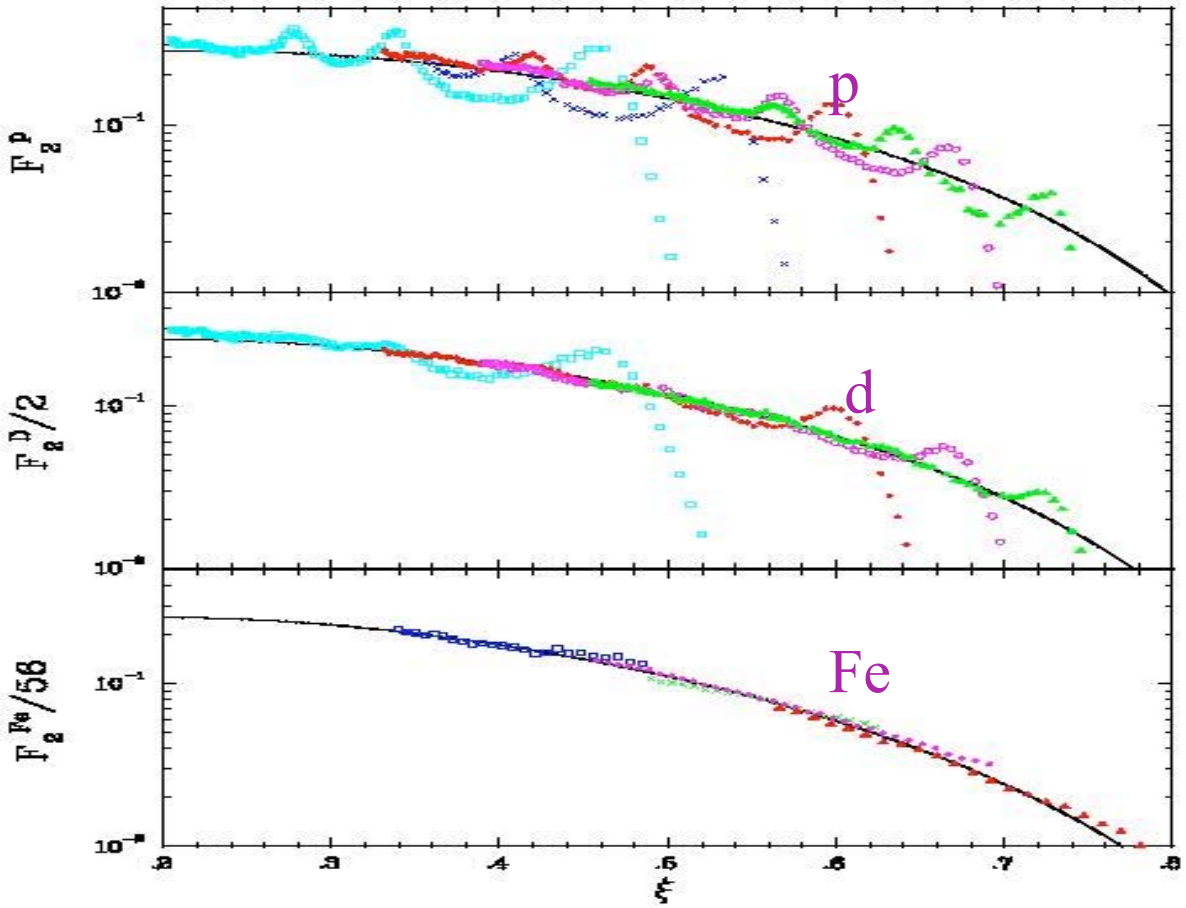
Remove known HT (a bit novel), the elastic, and there are no more down to $Q^2 = 0.5$ GeV^2

The case looks different for F_L (target mass larger issue - still under study)

Duality Works in Nuclei, Too! (F_2)

$$\xi = 2x\left[1 + (1 + 4M^2x^2/Q^2)^{1/2}\right]$$

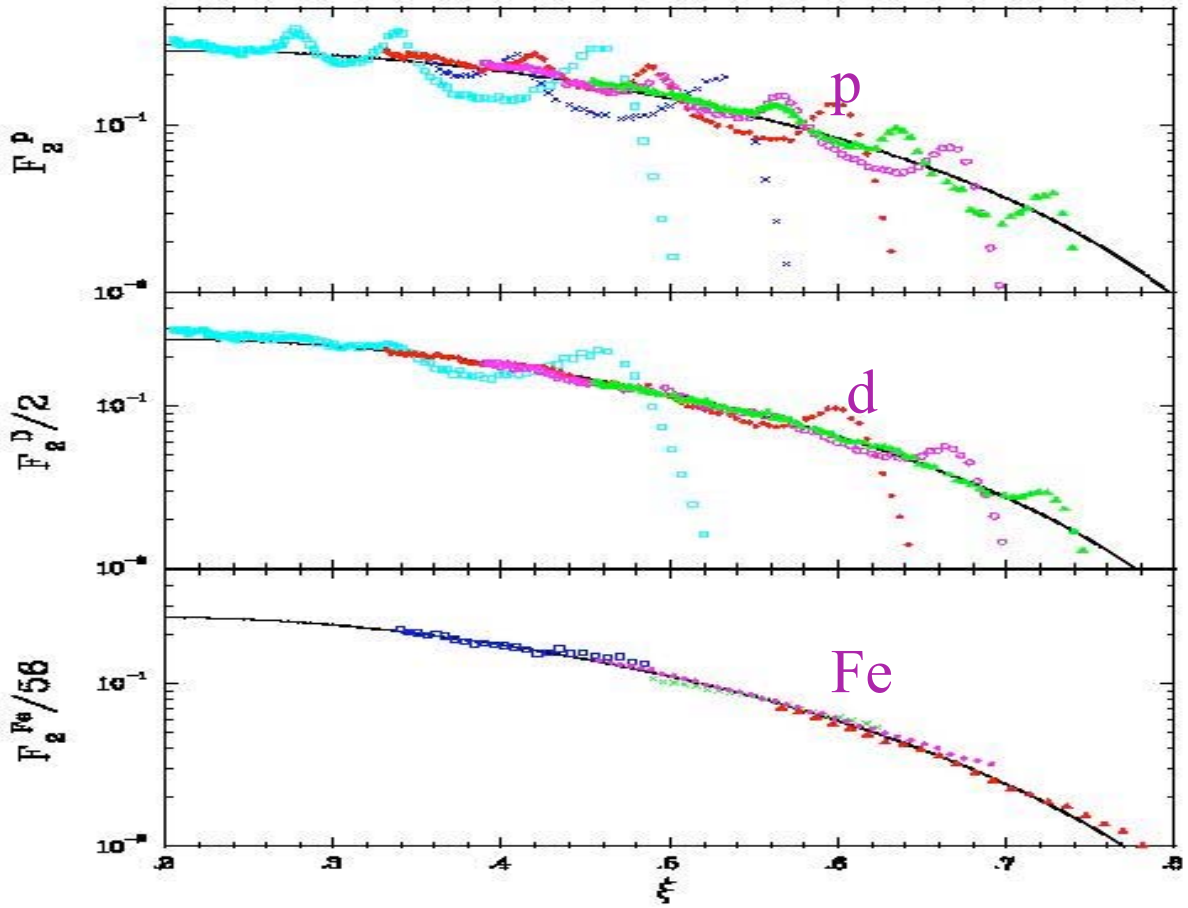
- **Data in resonance region, spanning Q^2 range 0.7 - 5 GeV^2**
- **GRV curve**



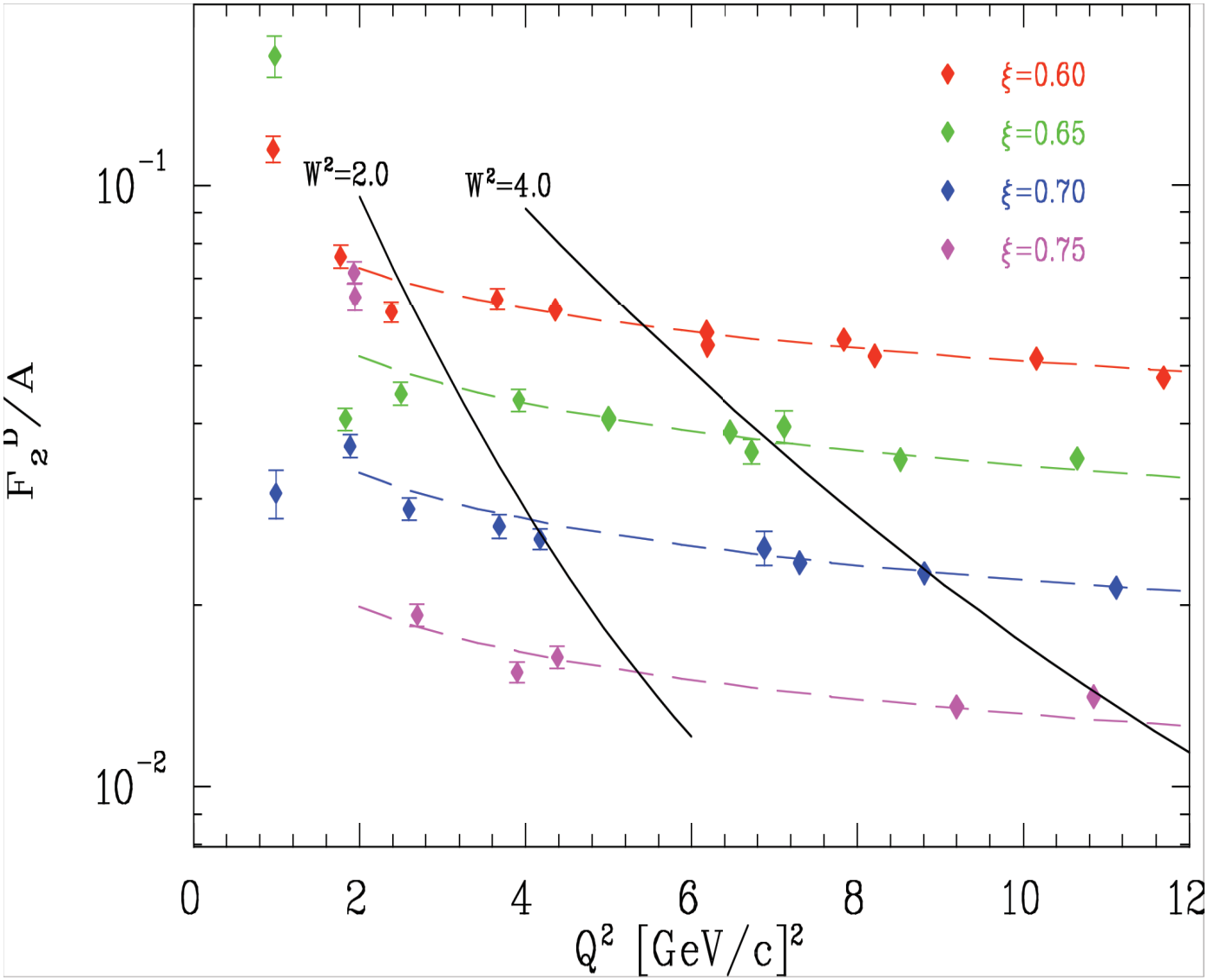
Duality Works in Nuclei, Too! (F_2)

$$\xi = 2x\left[1 + (1 + 4M^2x^2/Q^2)^{1/2}\right]$$

- The nucleus does the averaging
- For larger A, resonance region indistinguish able from DIS



Duality (F_2) in Deuterium

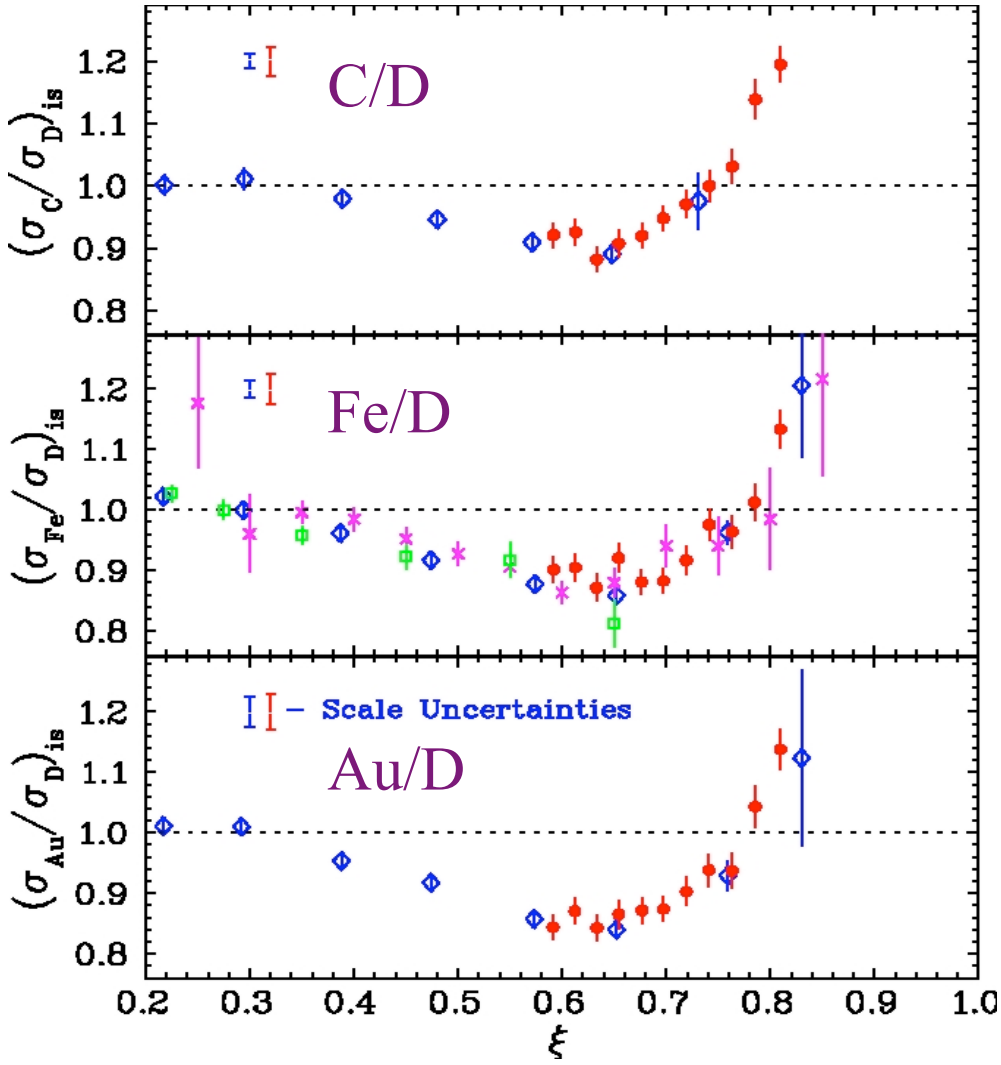


Resonane region and DIS F_2 same, with same Q^2 dependence, other than at smallest W

Duality and the EMC Effect

Medium modifications to the structure functions are the same in the resonance region as in the DIS

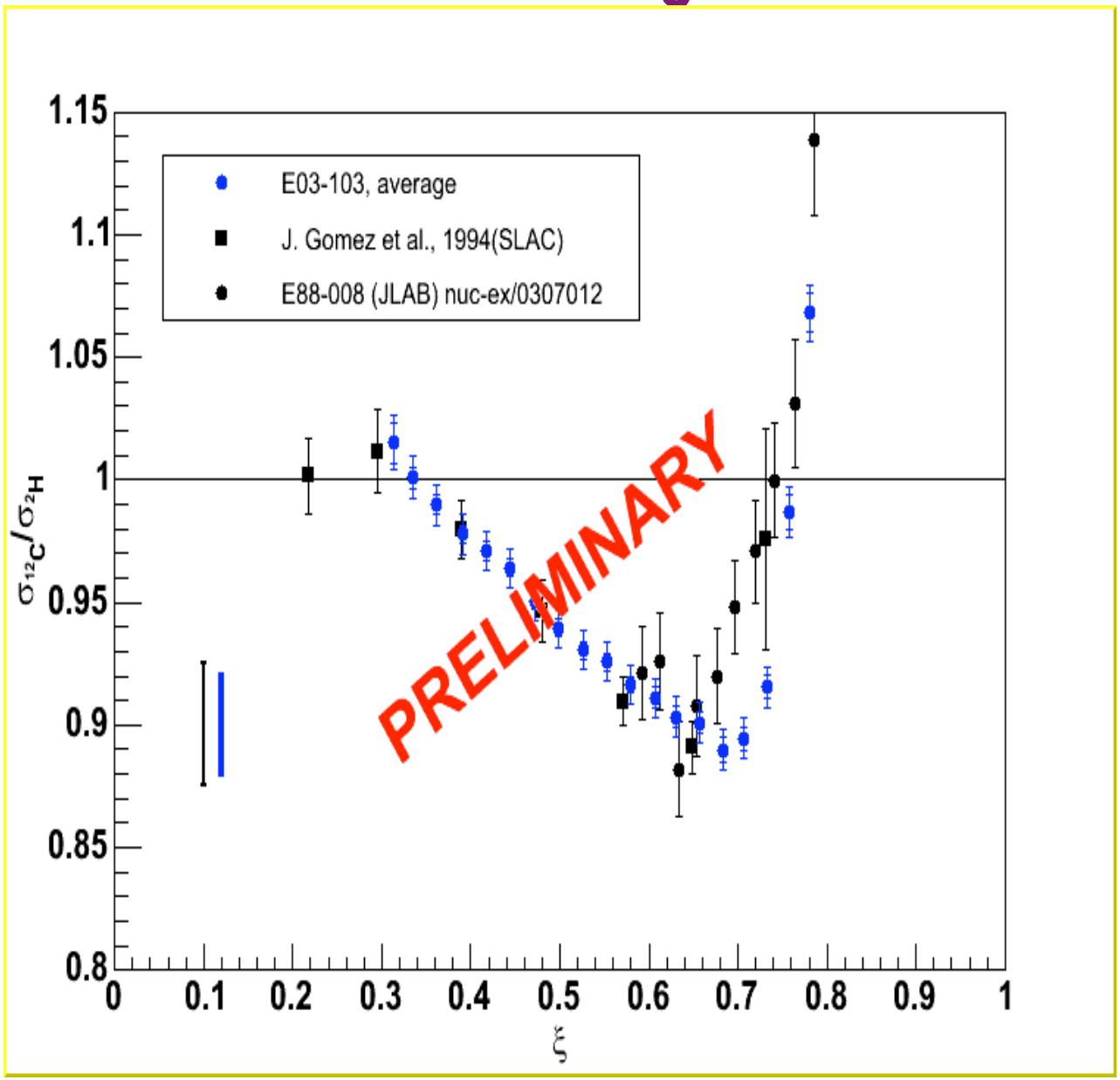
Rather surprising (Deltas in nuclei, etc.)



J. Arrington, et al., submitted

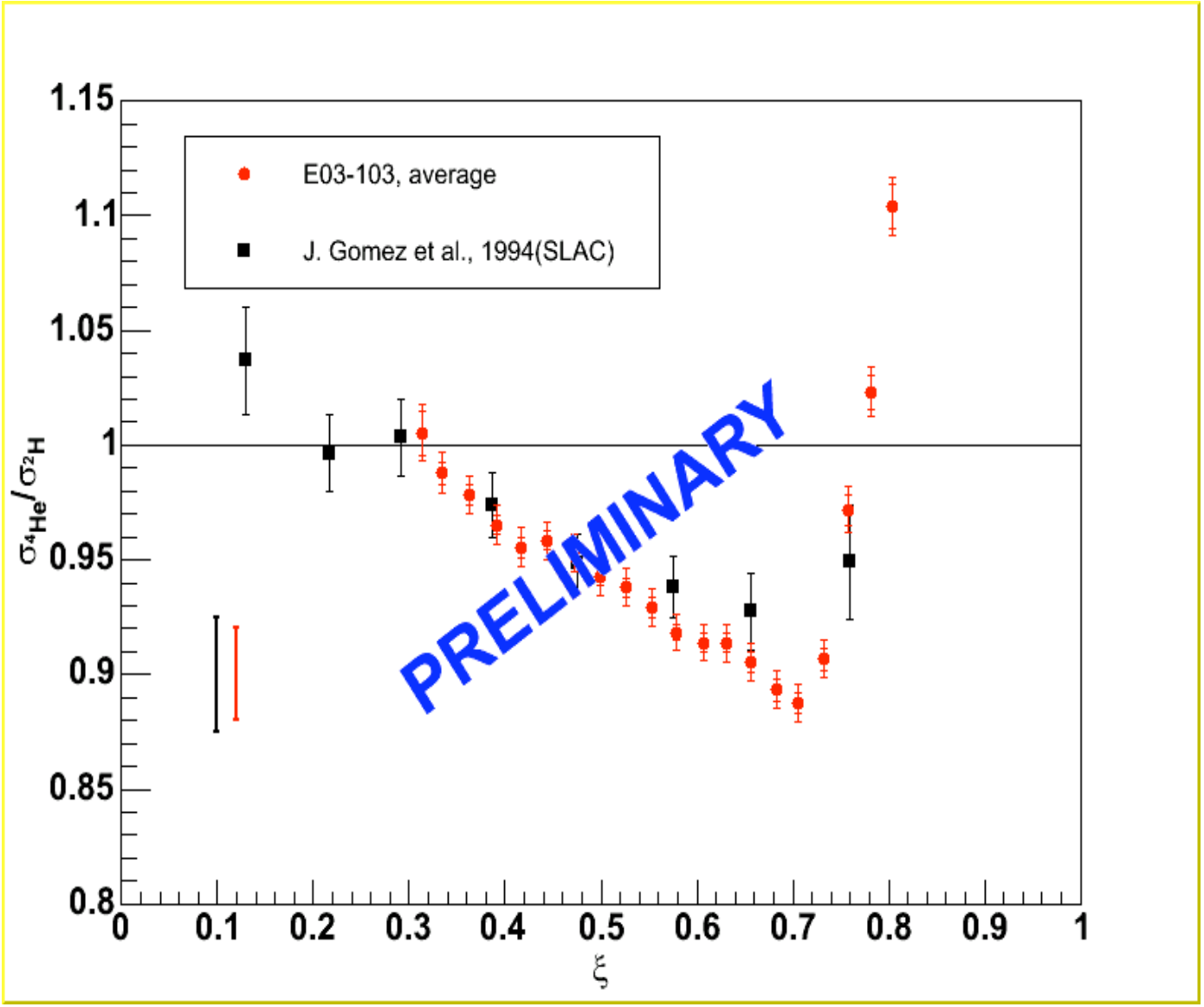
And these results just in…

C/D

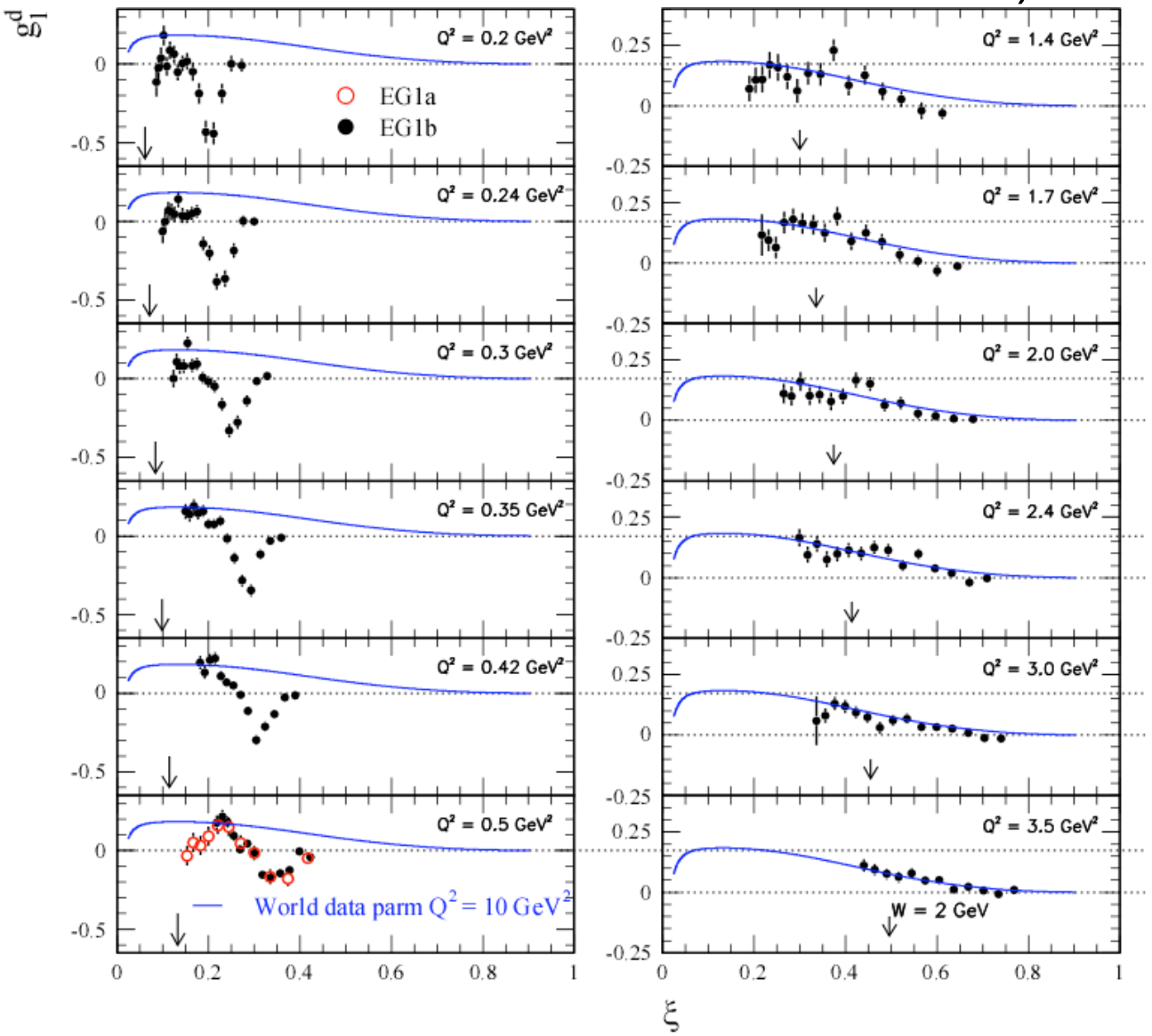


And these results just in…

4He/D

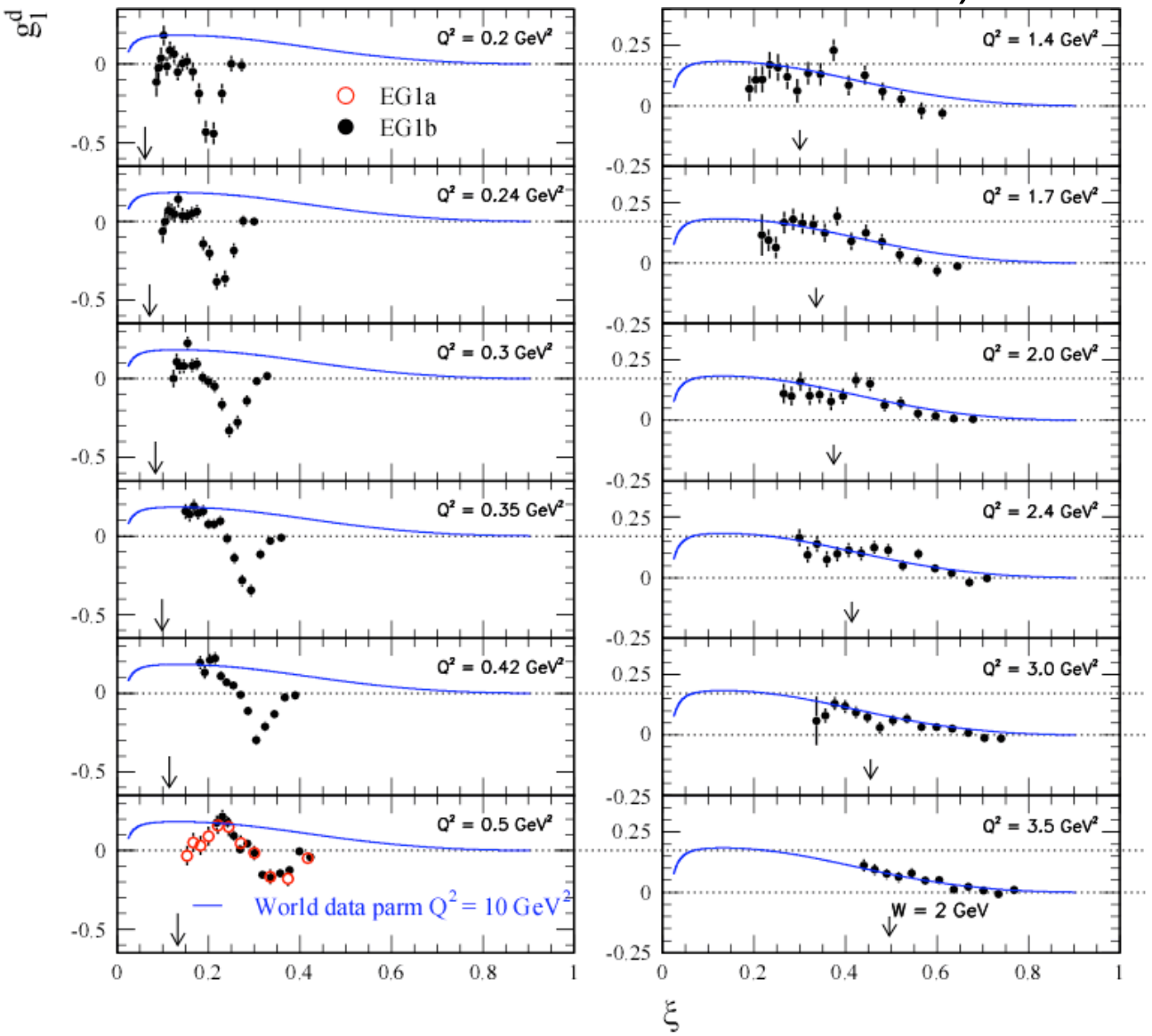


Duality in g_1^d (from T. Forest, P. Bosted et al., Jlab Hall B EG1)



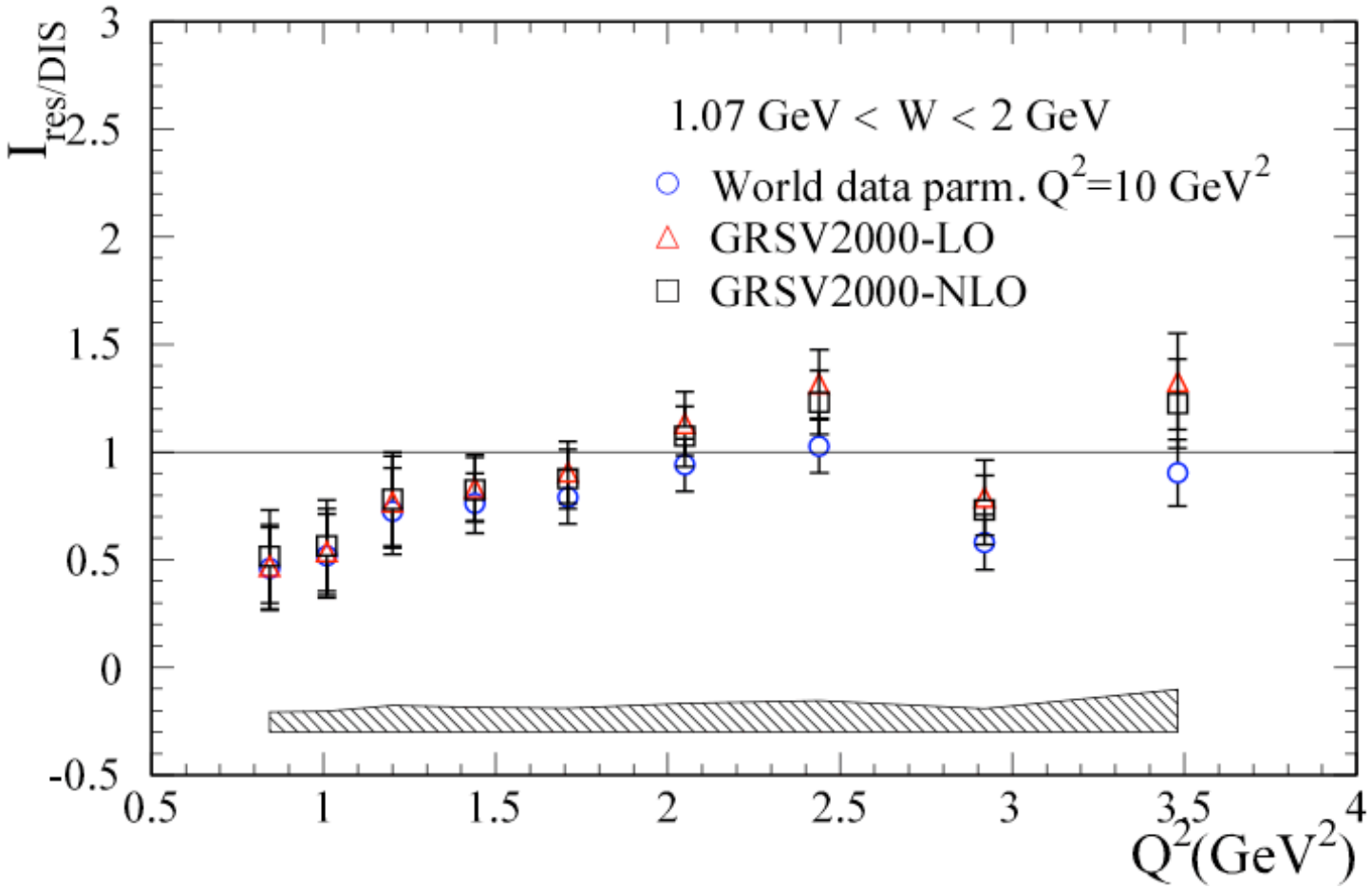
Like F_2, g_1 in the resonance region wiggles around high-Q2 curve curve. But, strong deviation in region of Delta(1232).

Duality in g_1^d (from T. Forest, P. Bosted et al., Hall B EG1)



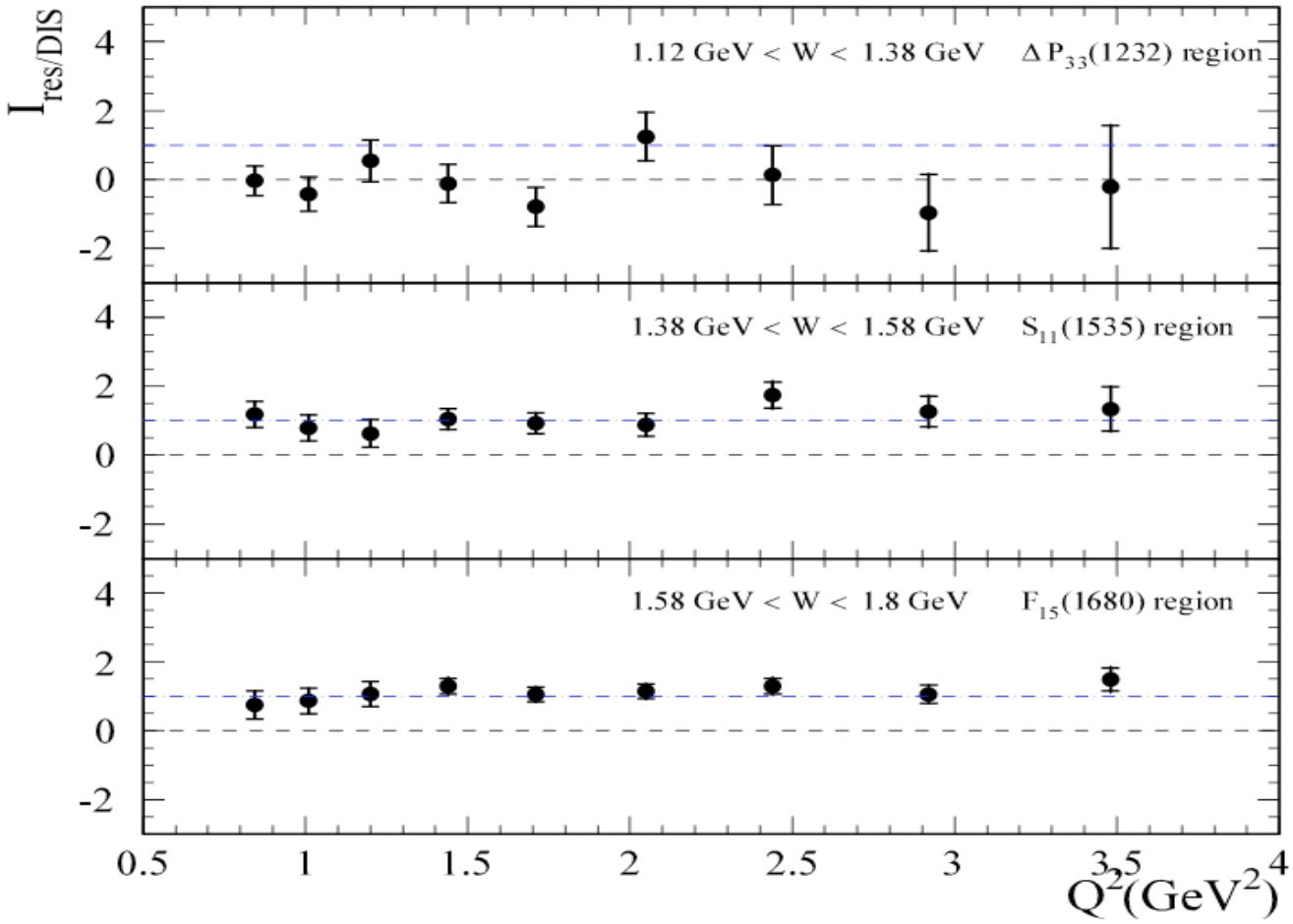
The 2.5 and 4.2 GeV data (still under analysis) will clarify the intermediate Q^2 range

Spin Structure Functions, g_1^d (continued)



Global duality established down to ~1.5 GeV^2.

Spin Structure Functions, g_1^d (continued)

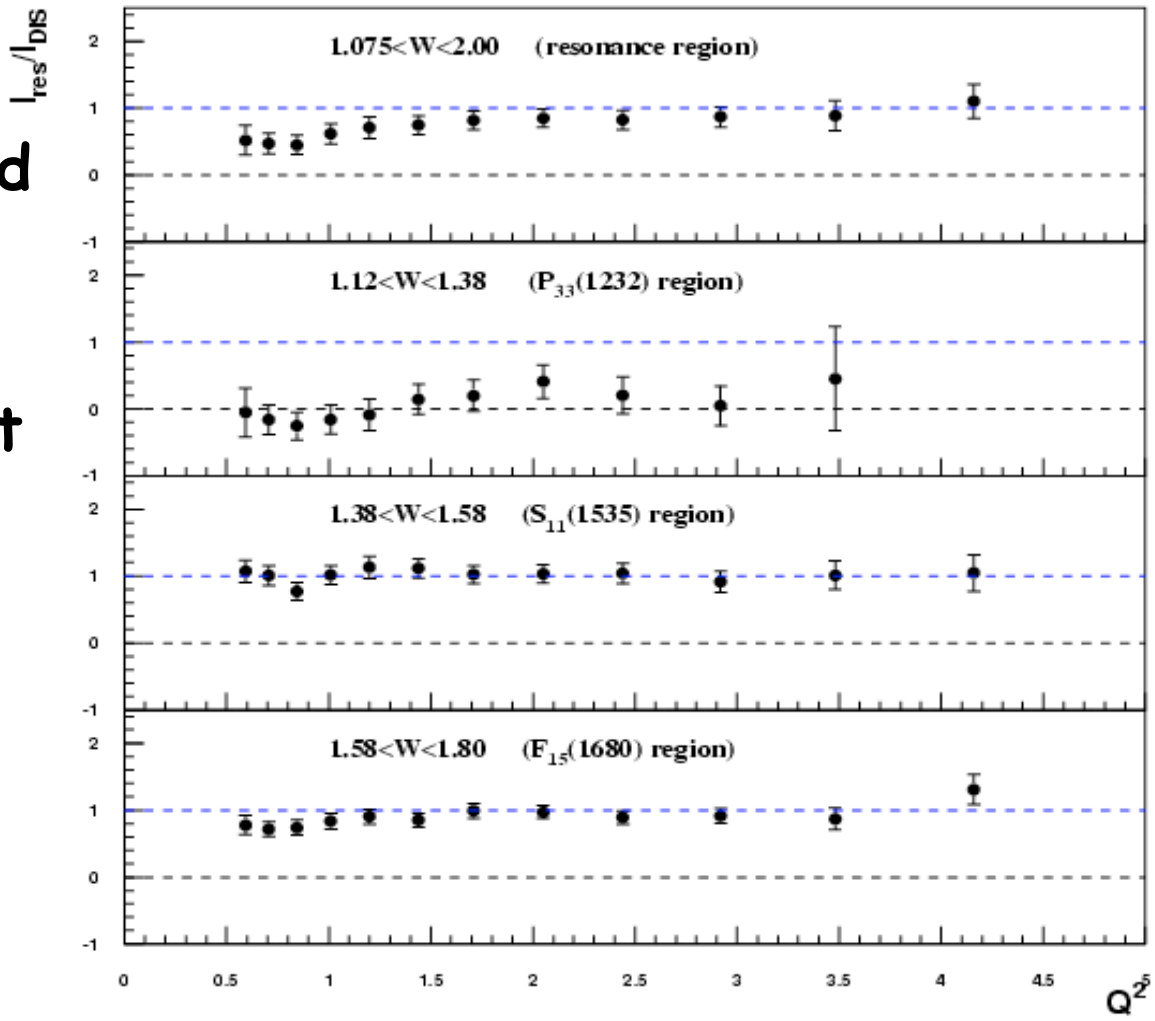


Local duality holds for second and third resonance region down to low Q^2.

Spin Duality for the Proton

Eg1b very preliminary

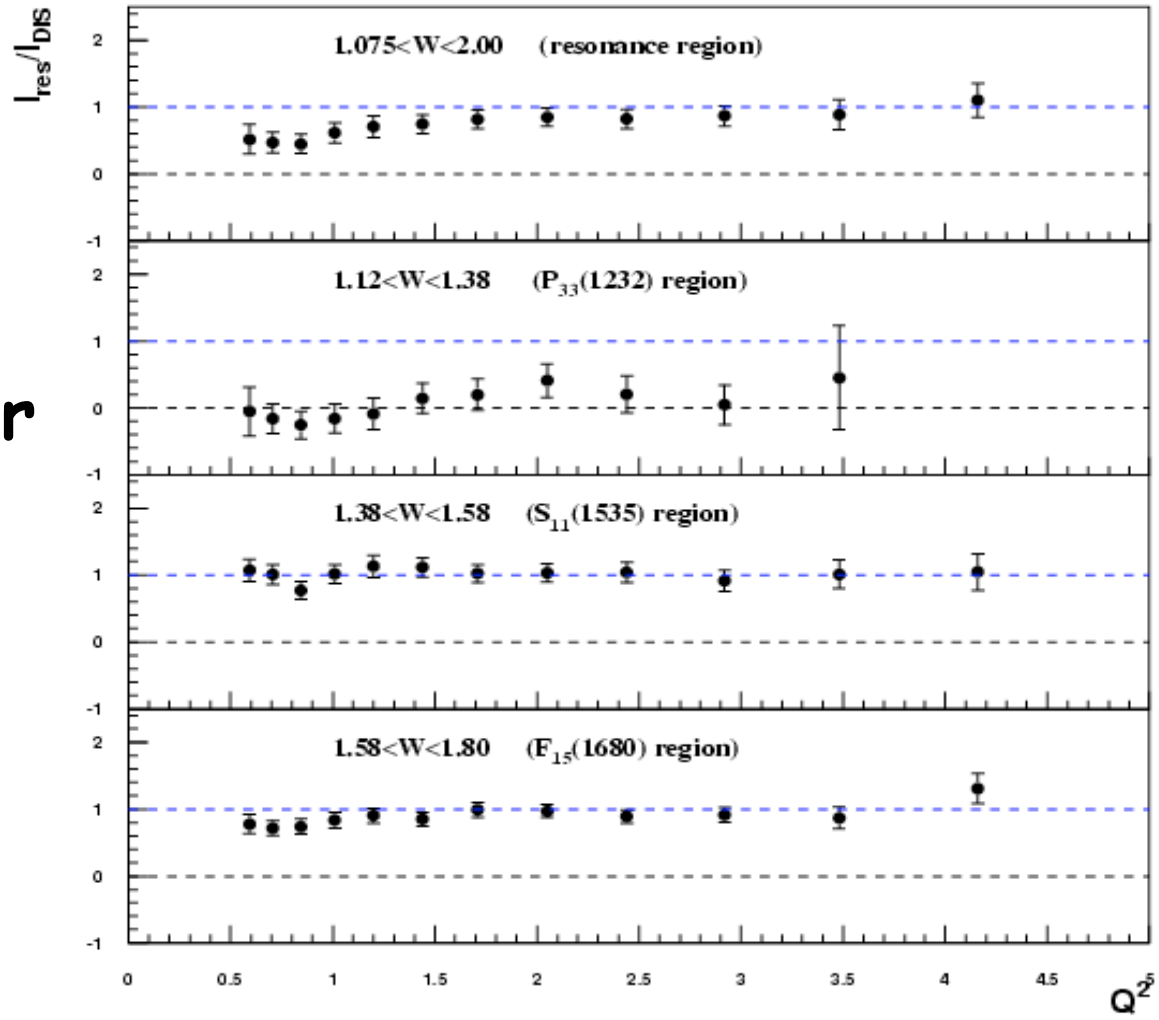
As for deuteron, local duality works very well for 2nd and 3rd resonance regions, down to quite low Q^2. Doesn't work for the Delta(1232) region, although trend is towards unity at higher Q^2 .



Spin Duality for the Proton

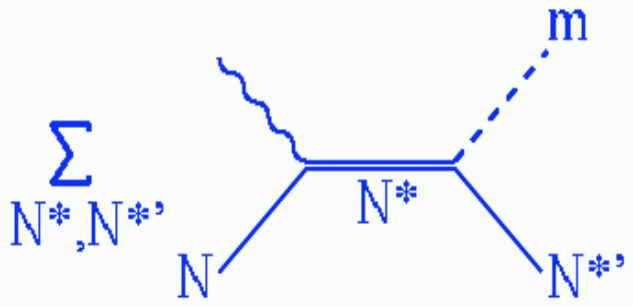
Eg1b very preliminary

If paired with elastic, approaches unity from above rather than from below (work in progress)..

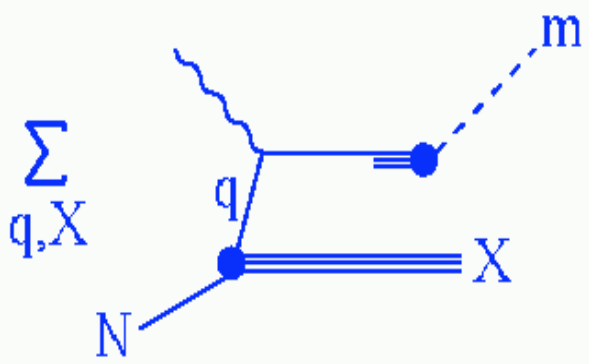


Duality in Meson Electroproduction

hadronic description



quark-gluon description



$$\sum_{N'^*} \left| \sum_{N^*} F_{\gamma^* N \to N^*}(Q^2, W^2)\, \mathcal{D}_{N^* \to N'^* M}(W^2, W'^2) \right|^2 \qquad \sum_q e_q^2\, q(x)\, D_{q \to M}(z)$$

Transition Form Factor | Decay Amplitude | Fragmentation Function

Requires non-trivial cancellations of decay angular distributions

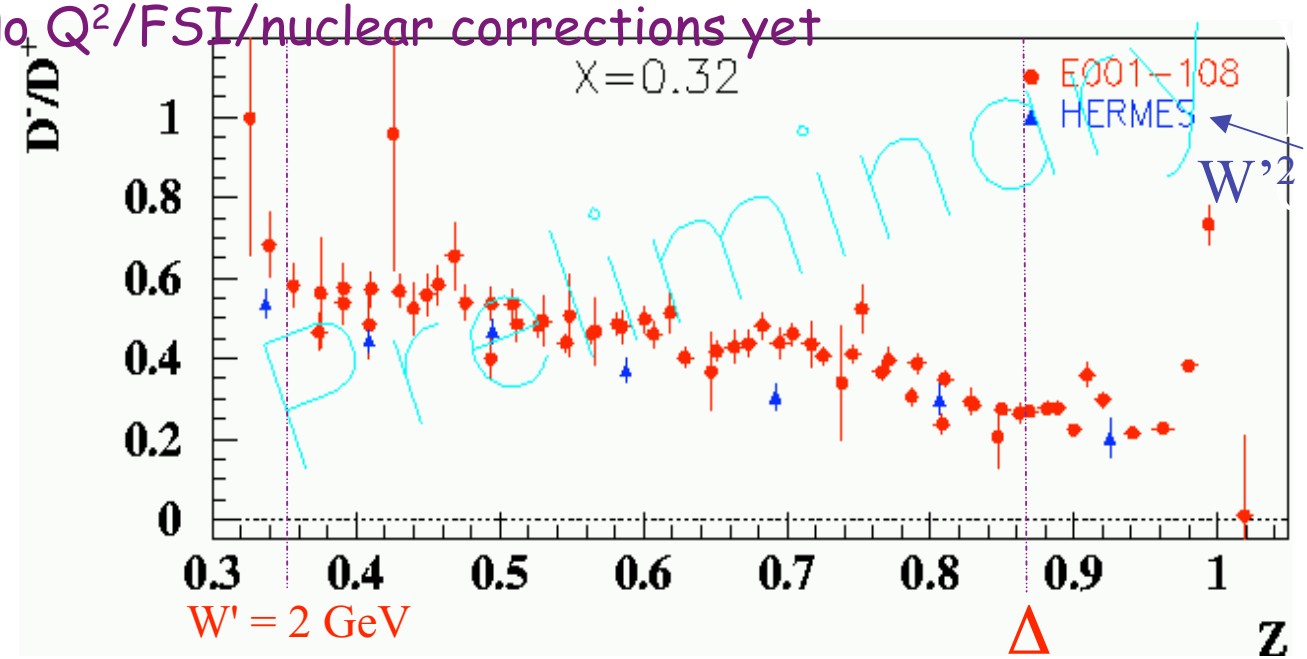
If duality is not observed, factorization is questionable

Duality and factorization possible for $Q^2, W^2 \leq 3$ GeV^2

(Close and Isgur, Phys. Lett. B509, 81 (2001))

JLab Hall C Experiment E01-108 ran in August 2003

- Only first-pass data analysis
- No Q^2/FSI/nuclear corrections yet



$W'^2 \sim 10$ GeV^2

Data predominantly in"resonance region" … What happened to the resonances?

From deuterium data: $D^-/D^+ = (4 - N_{\pi^+}/N_{\pi^-})/(4N_{\pi^+}/N_{\pi^-} - 1)$

Looks promising for duality and factorization measurements at JLab energies…..

The Origins of Quark-Hadron Duality – Semi-Inclusive Hadroproduction

F. Close et al : SU(6) Quark Model

How many resonances does one need to average over to obtain a complete set of states to mimic a parton model? →56 and 70 states o.k. for closure

Destructive interference leads to factorization and duality

$$F(\gamma N \to \pi X)(x,z) = \sum_{N^*,N^{*\prime}} F_{\gamma^* N \to N^*}(Q^2,W^2)\, \mathcal{D}_{N^* \to N^{*\prime}\pi}(W^2,W^{\prime 2})$$

$$\sim \sum_q e_q^2\, q(x)\, D_{q\to\pi}(z)$$

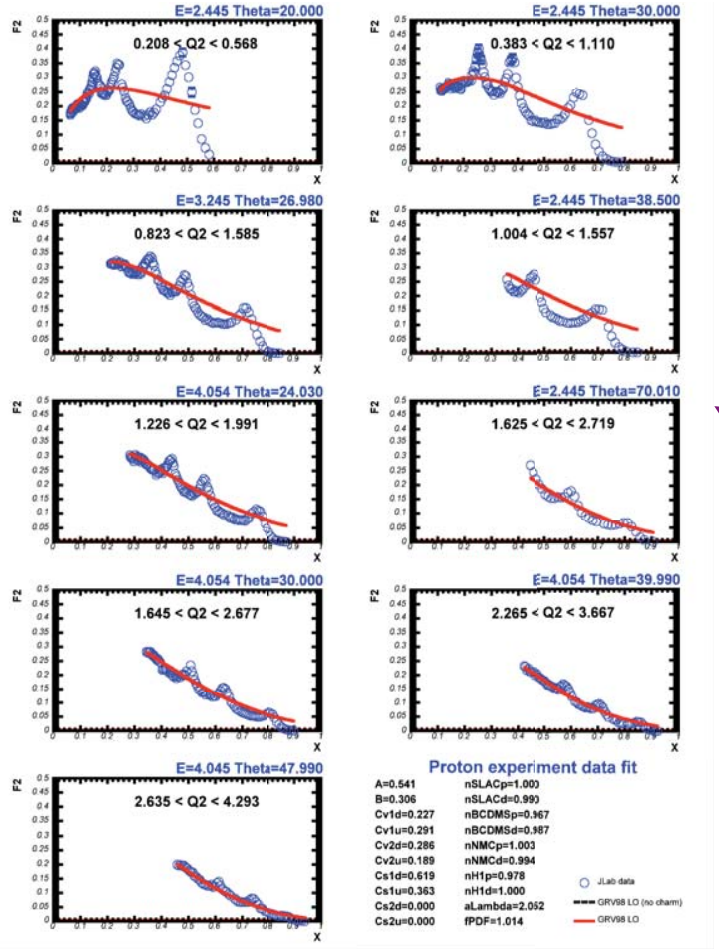
$SU(6)$ and $SU(3) \times SU(2)$ Multiplet Contributions to $\pi^{\pm}$ Photoproduction

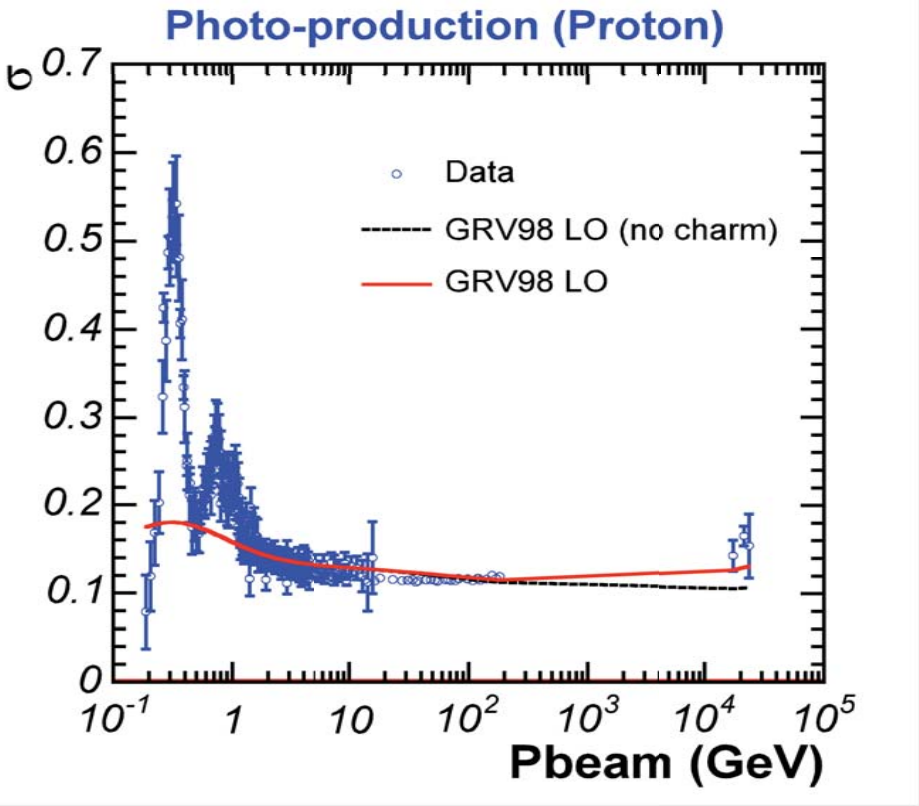
W'	$p(\gamma,\pi^+)W'$	$p(\gamma,\pi^-)W'$	$n(\gamma,\pi^+)W'$	$n(\gamma,\pi^-)W'$
56;8	100	0	0	25
56;10	32	24	96	8
70;^{2}8	64	0	0	16
70;^{4}8	16	0	0	4
70;^{2}10	4	3	12	1
Total	216	27	108	54

Predictions: Duality obtained by end of second resonance region

Factorization and approximate duality for $Q^2, W^2 < 3$ GeV^2

Extension to Photoproduction





Bodek and Yang duality-based model works at all Q^2 values tested – DIS to photoproduction!

Input for next generation neutrino experiments

Currently….

- **Duality holds for all**
  - **Spin-averaged structure functions**
  - **Tested spin structure functions**
- **Duality observed in Nuclei**
  - **Even displays EMC effect**
- **Duality in semi-inclusive meson production**
- **Works in photoproduction as well**

Appears to be a non-trivial property of proton structure!

What about the future?

- Continue semi-inclusive measurements, include kaon (Hall C E01-108)
- Continue spin structure measurements (results still expected from all JLab halls)
- L/T separated nuclear structure functions (Hall C E02-109, E04-001)
- Test the neutron (BONUS)
- Test in neutrino scattering (FNAL MINERνA)

- Major thrust of the JLab 12 GeV program

"It is fair to say that (short of the full solution of QCD) understanding and controlling the accuracy of quark-hadron duality is one of the most important and challenging problems for QCD practitioners today."

M. Shifman, Handbook of QCD, Volume 3, 1451 (2001)