Quark-Hadron Duality: New Experimental Results

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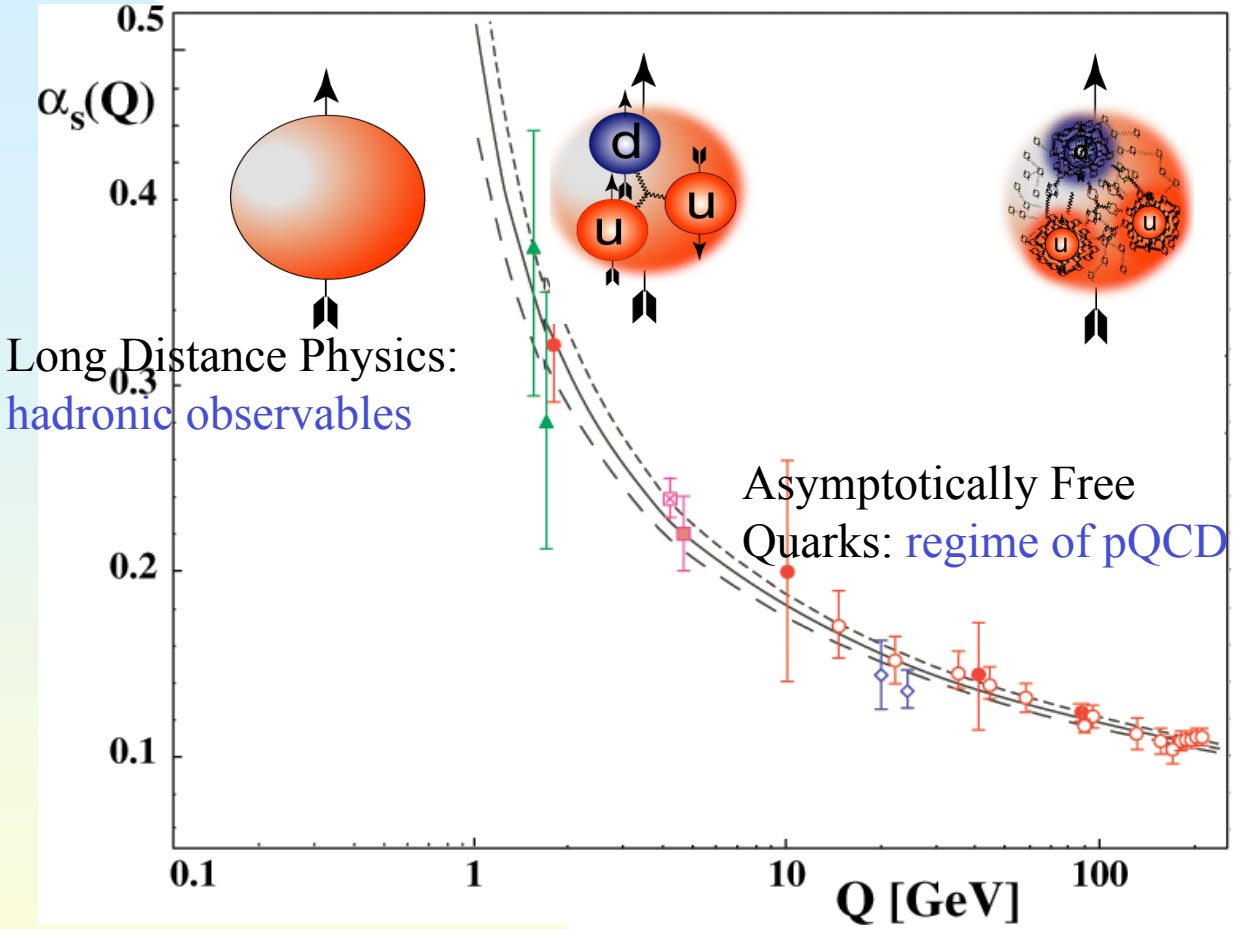
Hampton University / Jefferson Lab

The Partonic Structure of Hadrons

ECT Trento 2005

Duality and the Transition to Perturbative QCD



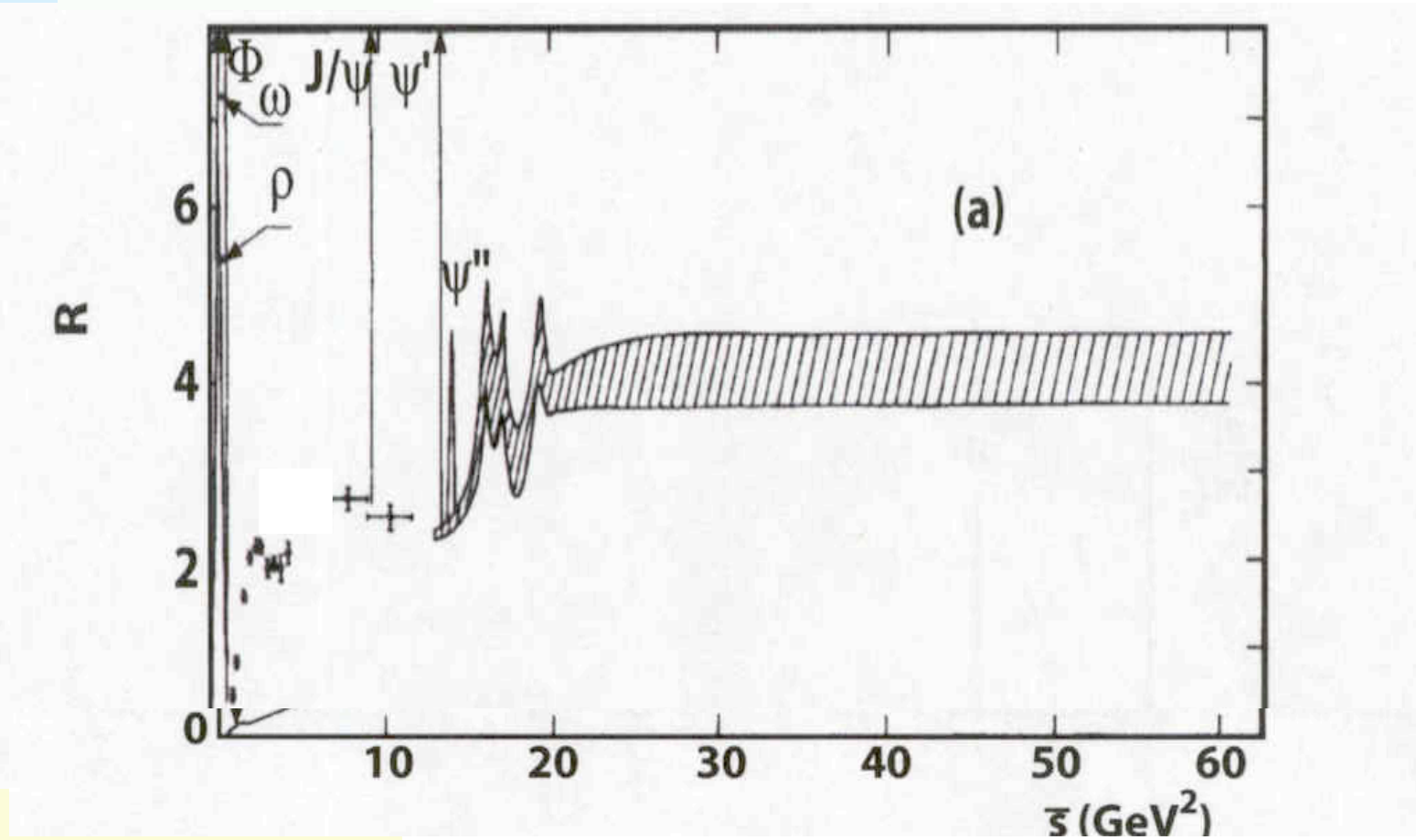
Asymptotically the photon couples to quarks, yet *confinement* ensures that only hadronic final states are observed.

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

Textbook Example: $e^+e^- \longrightarrow$ hadrons

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

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



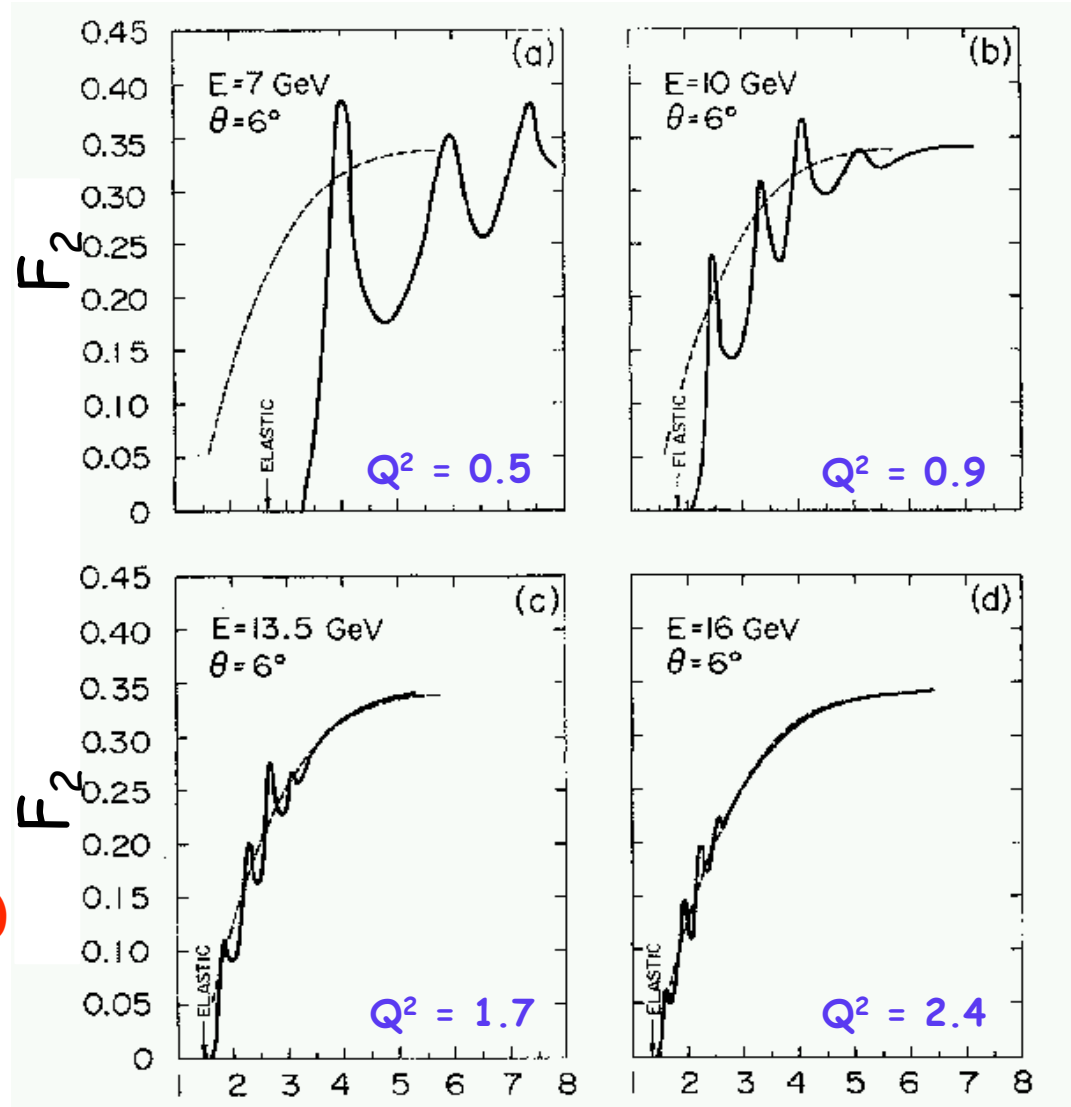
Only evidence of hadrons produced is narrow states oscillating around step function determined by quark color,

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

Shortcomings:

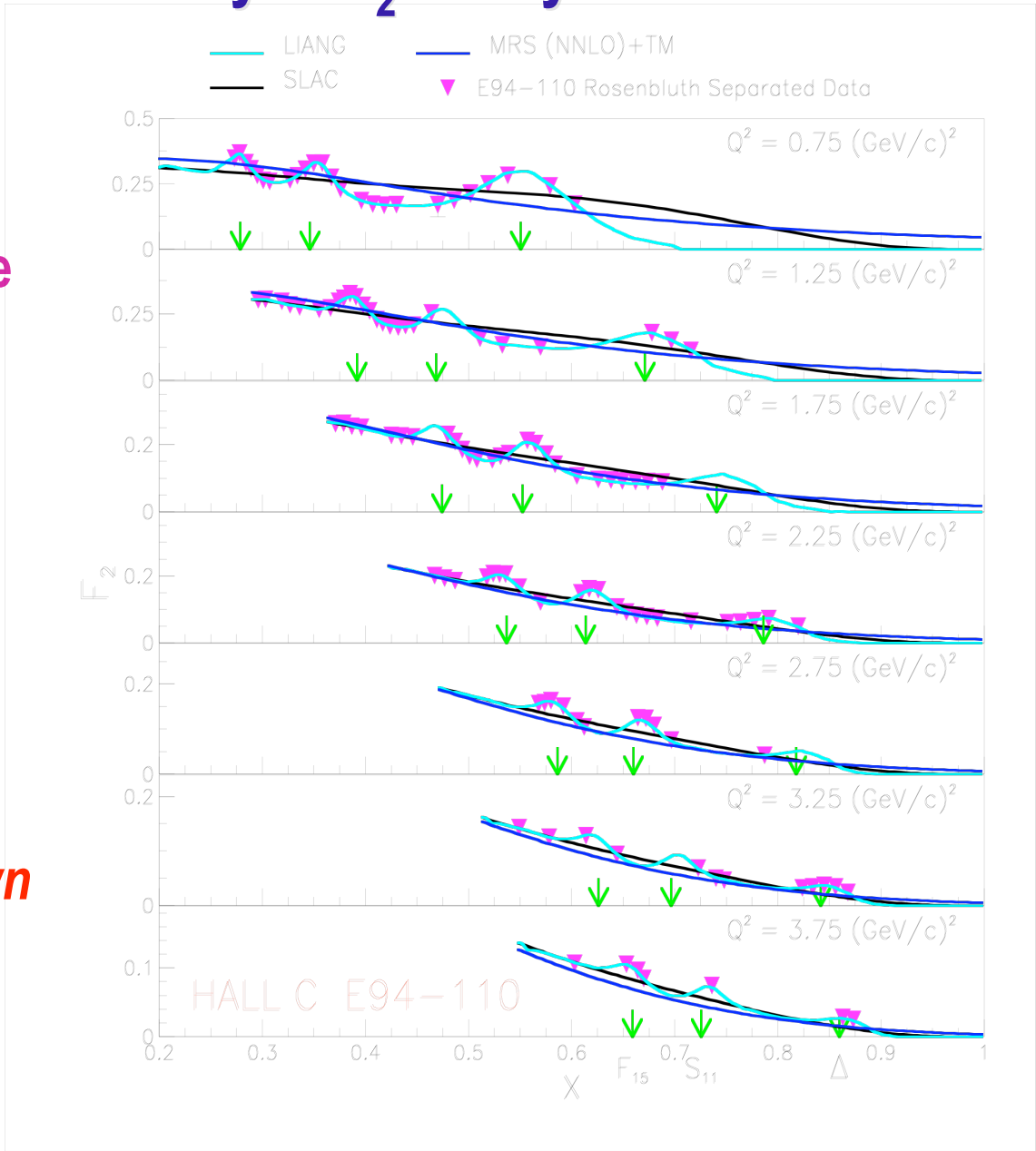
- Only a single scaling curve and no Q^2 evolution (theory inadequate in pre-QCD era)
- No σ_L/σ_T separation → F_2 data depend on assumption of $R = \sigma_L/\sigma_T$
- Only moderate statistics



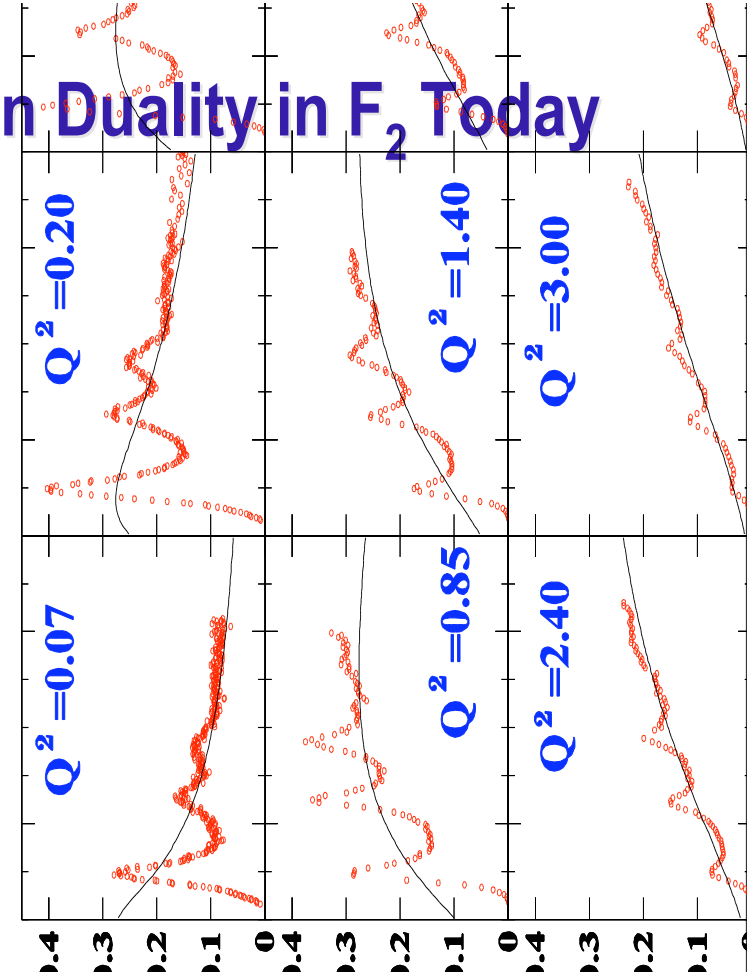
$\omega' = 1+W^2/Q^2$

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
- Duality apparent at all Q^2 values - showing same Q^2 behavior as scaling curves
- Quark-Hadron Duality *shown to hold to better than 5% above Q^2 ~ 0.5 GeV^2*



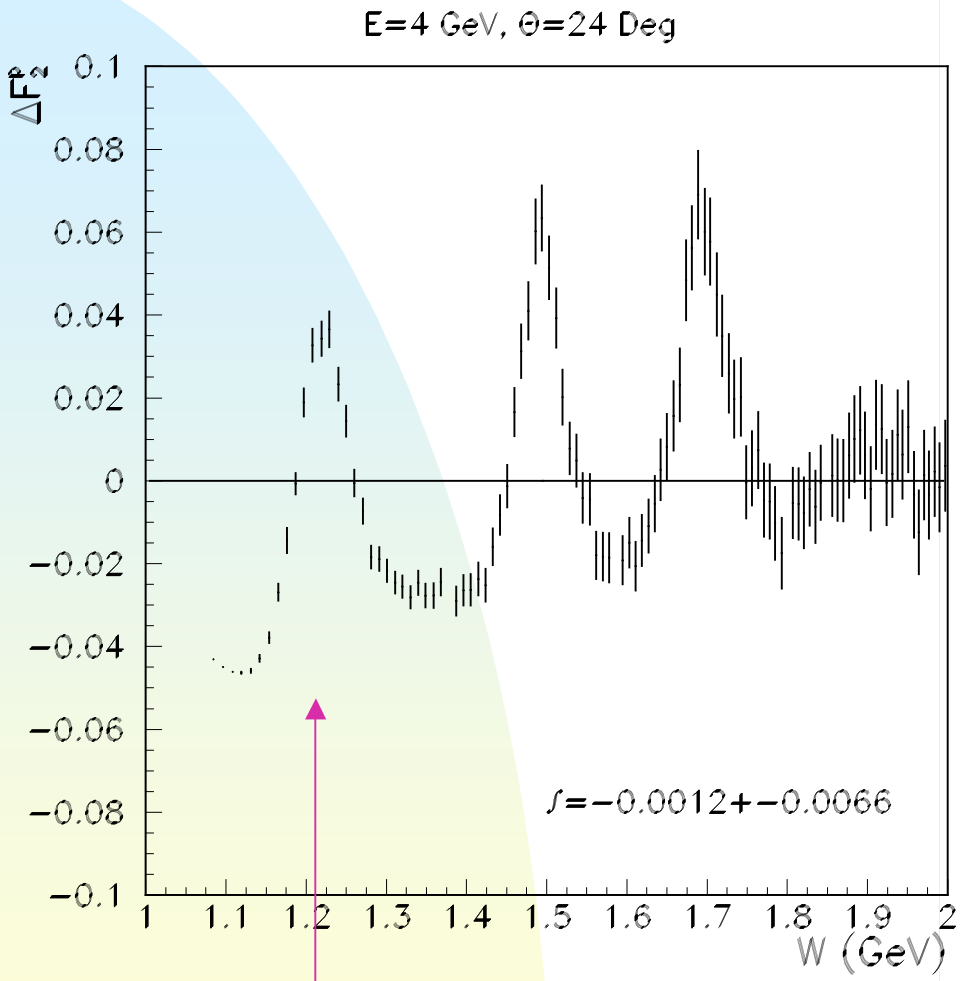
Bloom-Gilman Duality in F_2 Today

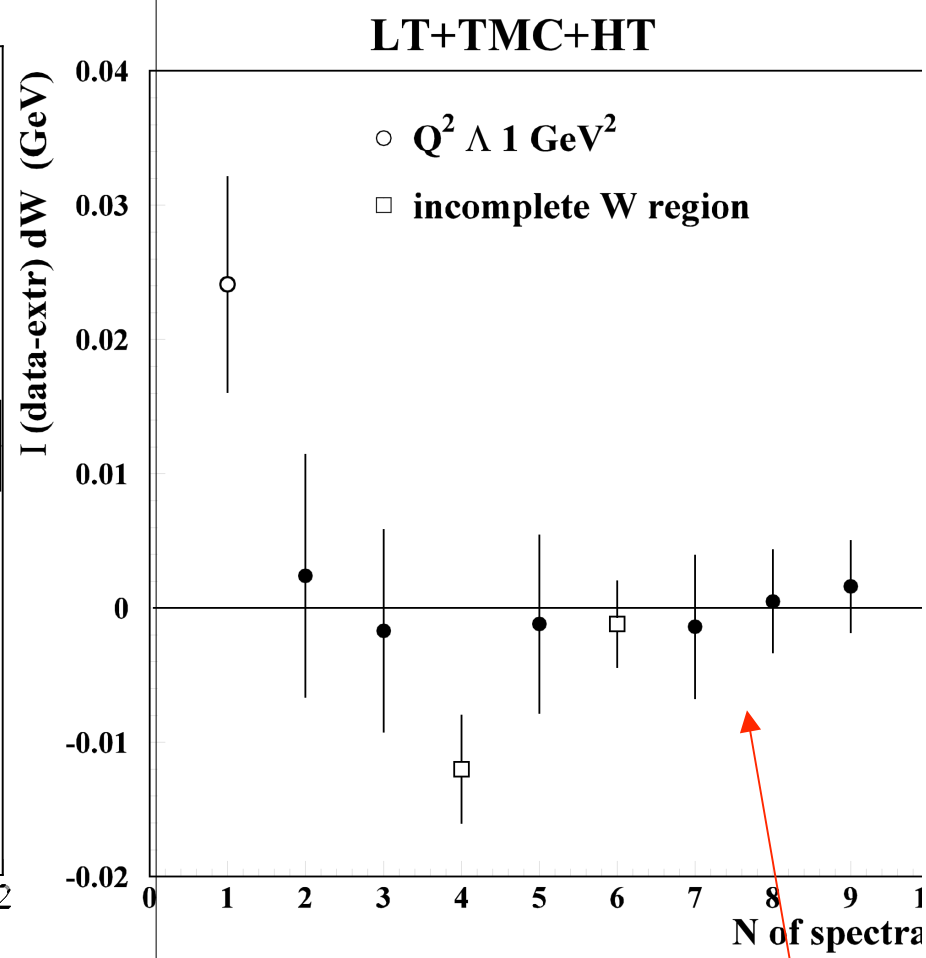


W^2 (GeV^2)

The scaling curve determines the Q^2 behavior of the resonances!

Bloom-Gilman Duality in F_2 Today



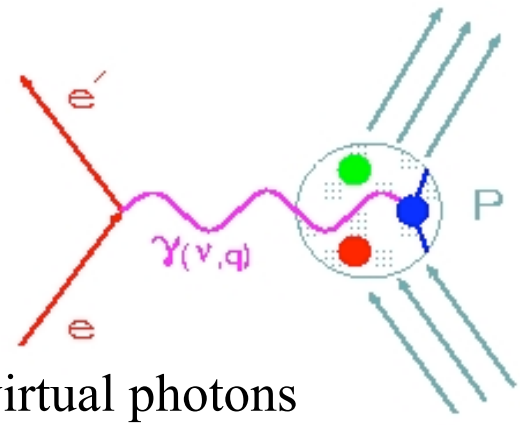


Difference between Alekhin NNLO curve (formed from lepton-nucleon scattering only) and resonance data, *integrated for many spectra*

Inclusive e + p → e + X Scattering

Rosenbluth:

$$\frac{d\sigma}{d\Omega dE'} = \Gamma(\sigma_T + \varepsilon\sigma_L)$$



Where: Γ = flux of transversely polarized virtual photons
ε = relative longitudinal polarization

Alternatively:

$$\frac{d\sigma}{d\Omega dE'} = \sigma_{mott}(F_2/\nu + 2F_1 \tan^2(\theta/2)/M)$$

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{2xF_1}$$

$$F_L = (1 + \frac{4M^2x^2}{Q^2})F_2 - 2xF_1$$

longitudinal

mIxEd

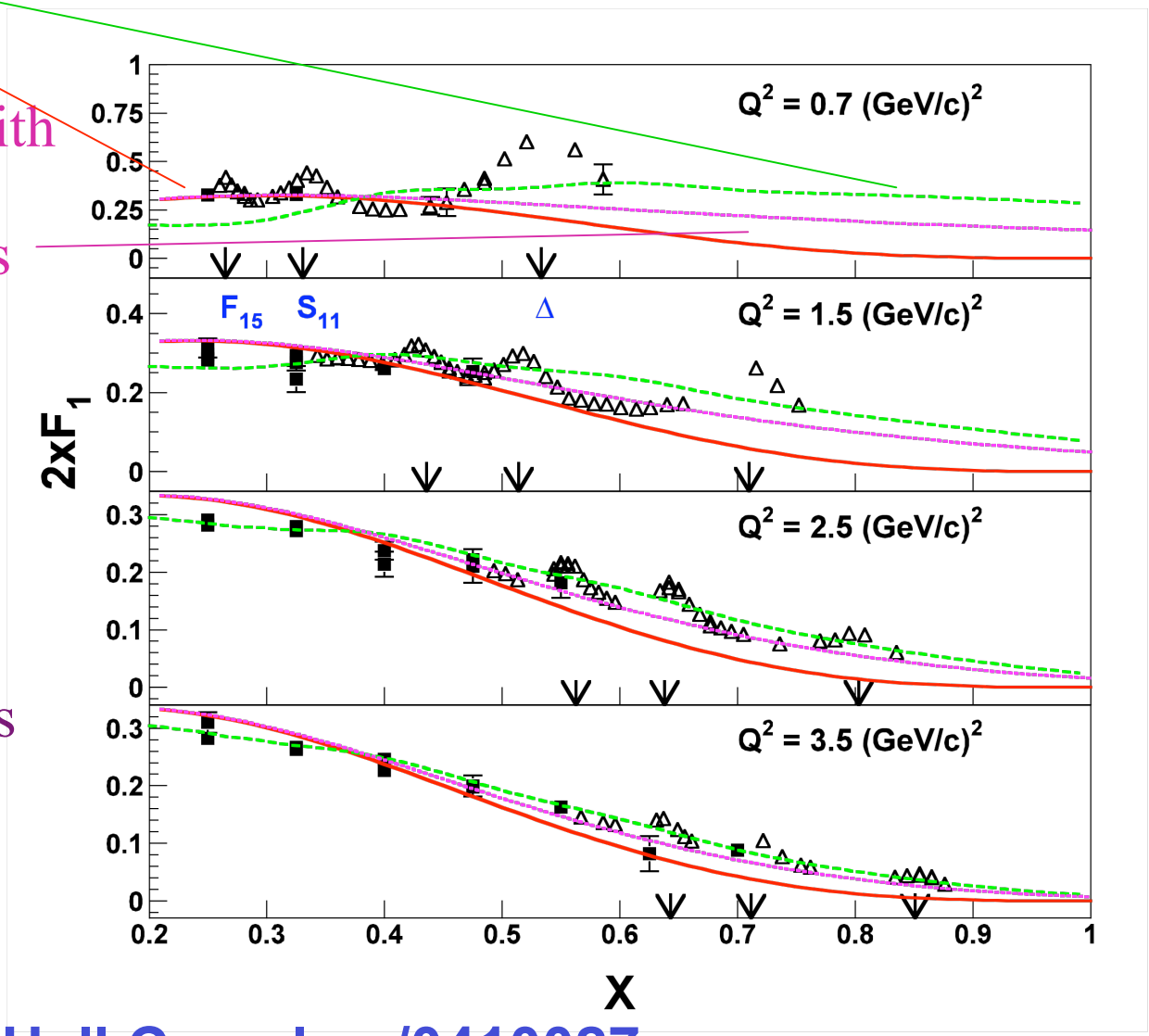
TRANSVERSE

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
- Target mass corrections large and important

JLab Hall C nucl-ex/0410027

Experimental Status of L/T Separated Structure Functions: F_L

Alekhin NNLO

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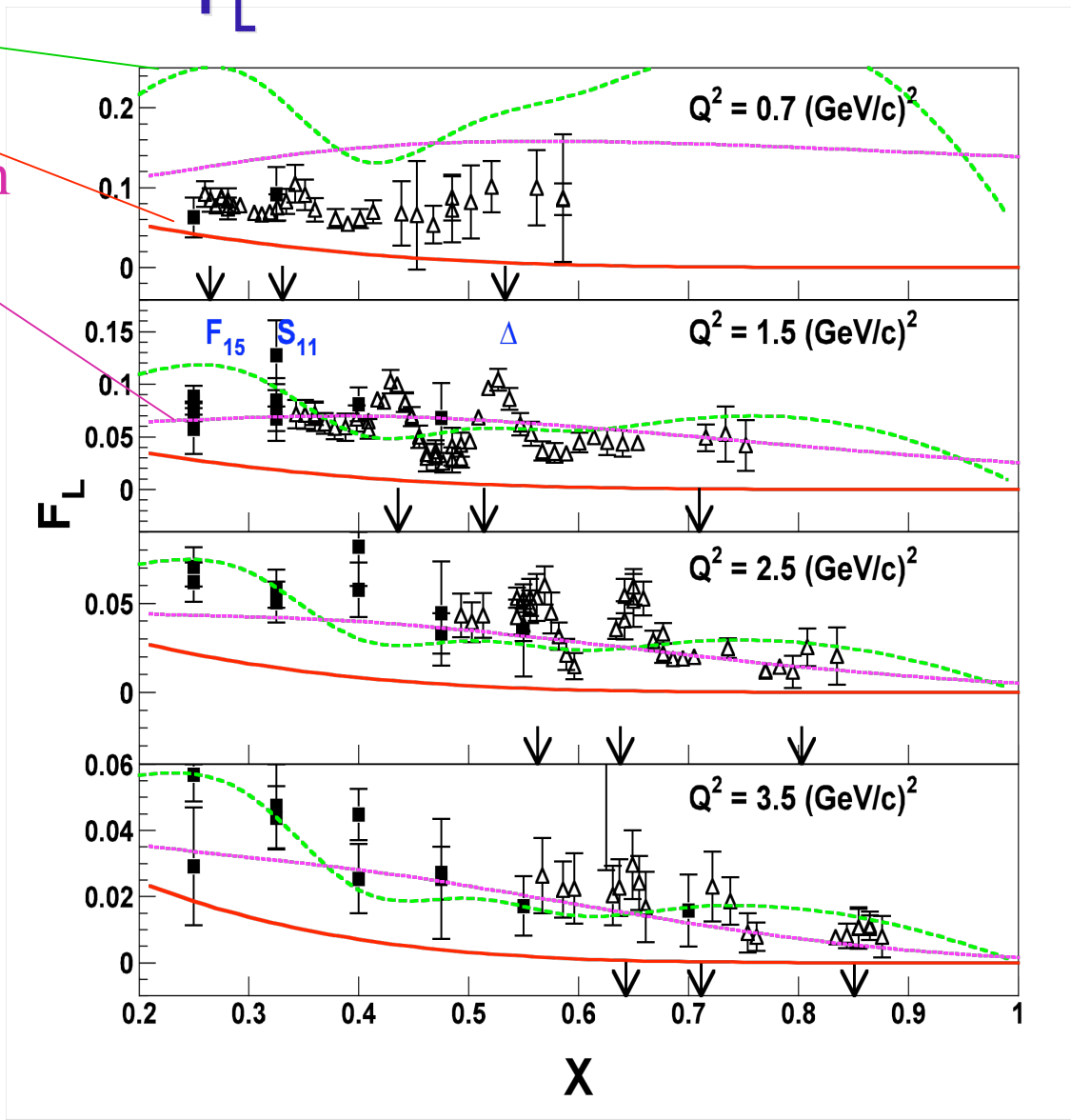

- Smooth transition from DIS (solid squares) to resonance region
- Resonances oscillate about perturbative curves
- Target mass corrections large and important
- Fun side note…what's that mass below the S_{11}?

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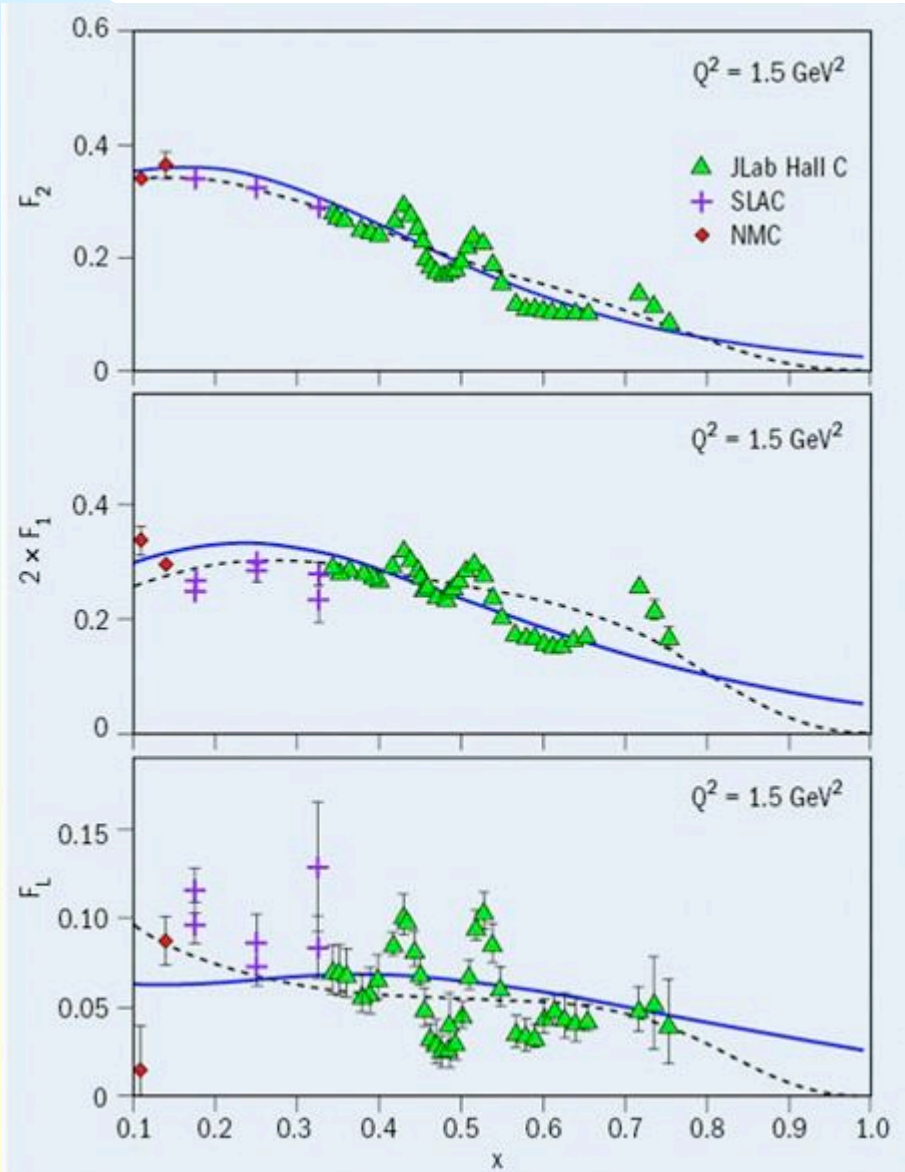
Duality and Large x…..

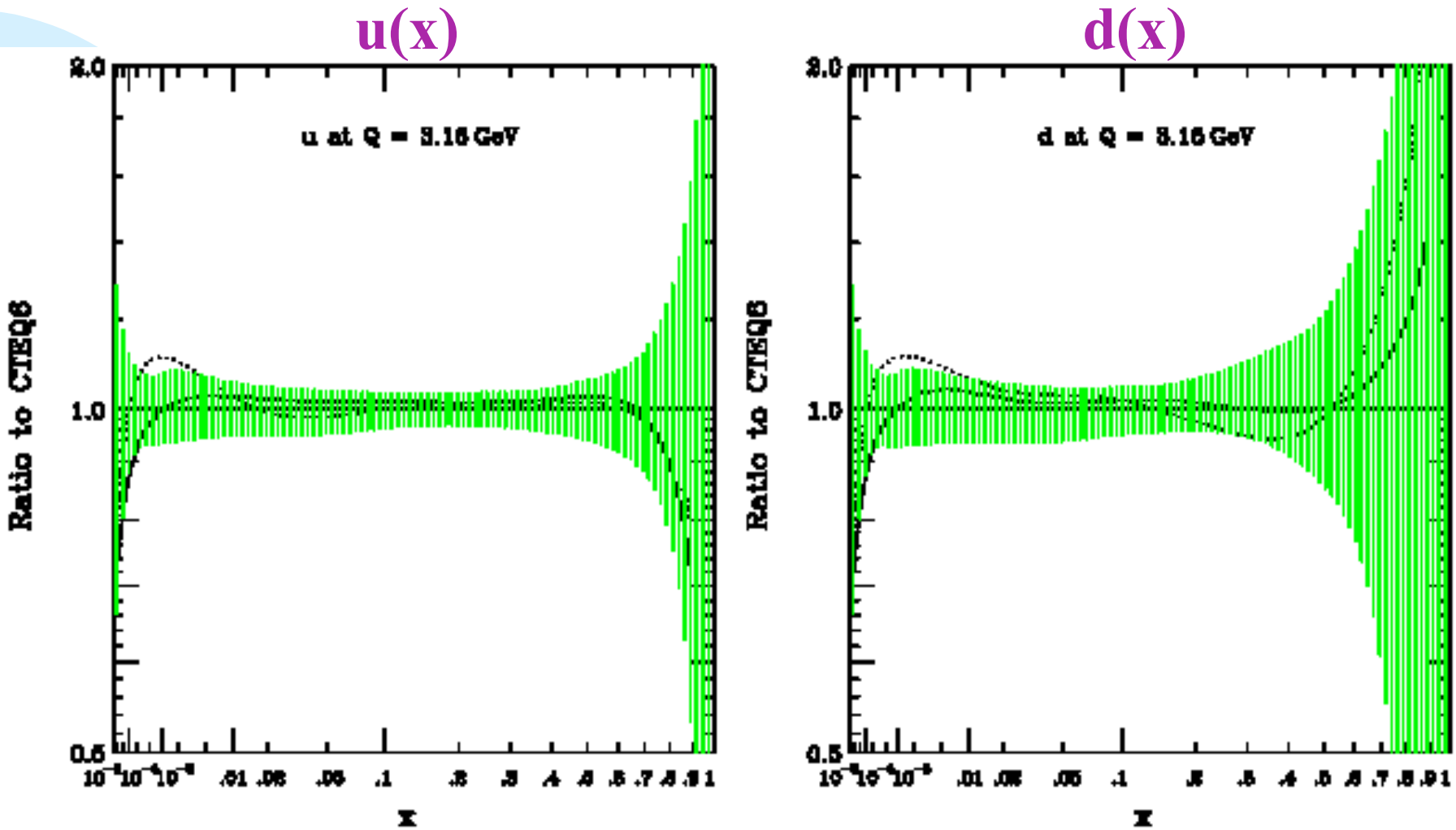


- The resonance region is, on average, well described by NNLO QCD fits.
- This implies that Higher-Twist (FSI) contributions cancel, and are on average small…although Simonetta may disagree… :)
- The result is a smooth transition from Quark Model Excitations to a Parton Model description, or a smooth quark-hadron transition.

"The successful application of duality to extract known quantities suggests that it should also be possible to use it to extract quantities that are otherwise kinematically inaccessible."

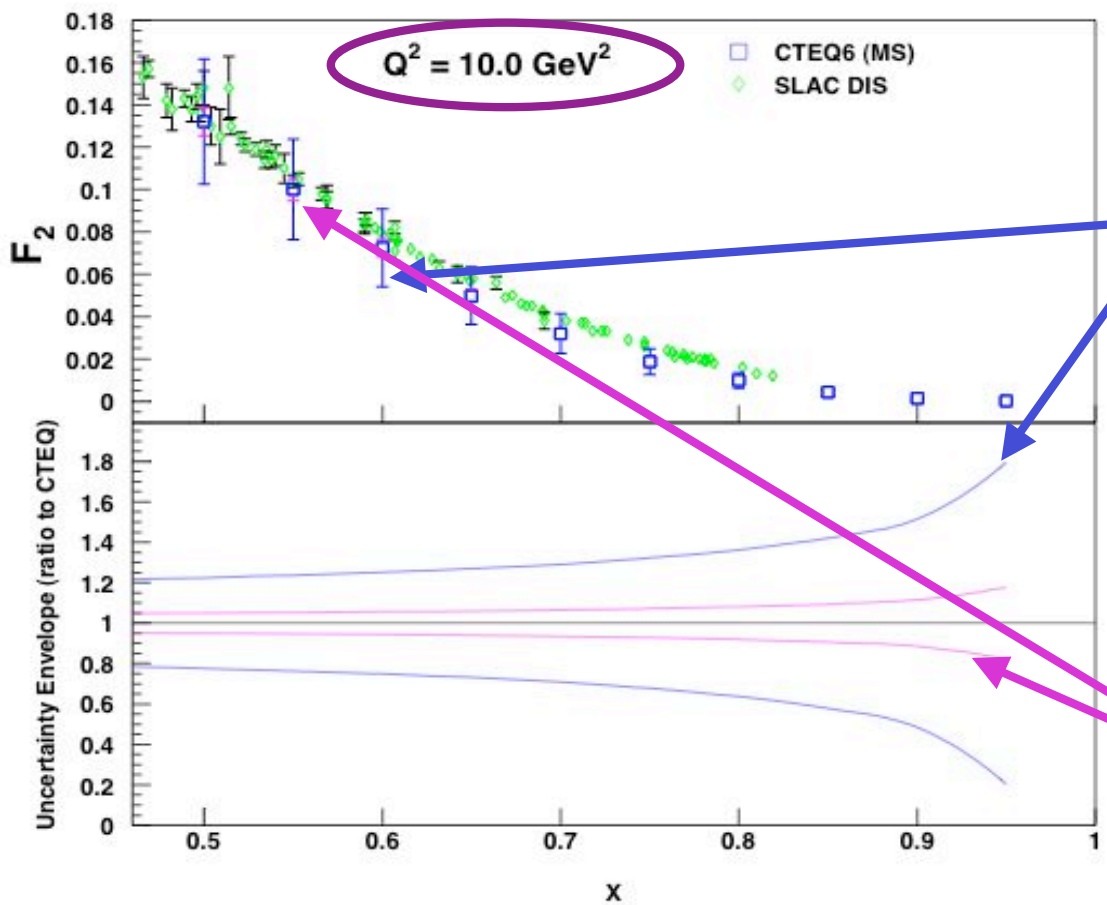
(CERN Courier, December 2004)

Parton Distribution Functions



PDF's by far least well known at large x – poses a problem for duality quantification, ***and an opportunity (USE duality for large x regime!)***

Can the Jlab (SLAC) data help reduce the uncertainties? - another approach



...a work in progress

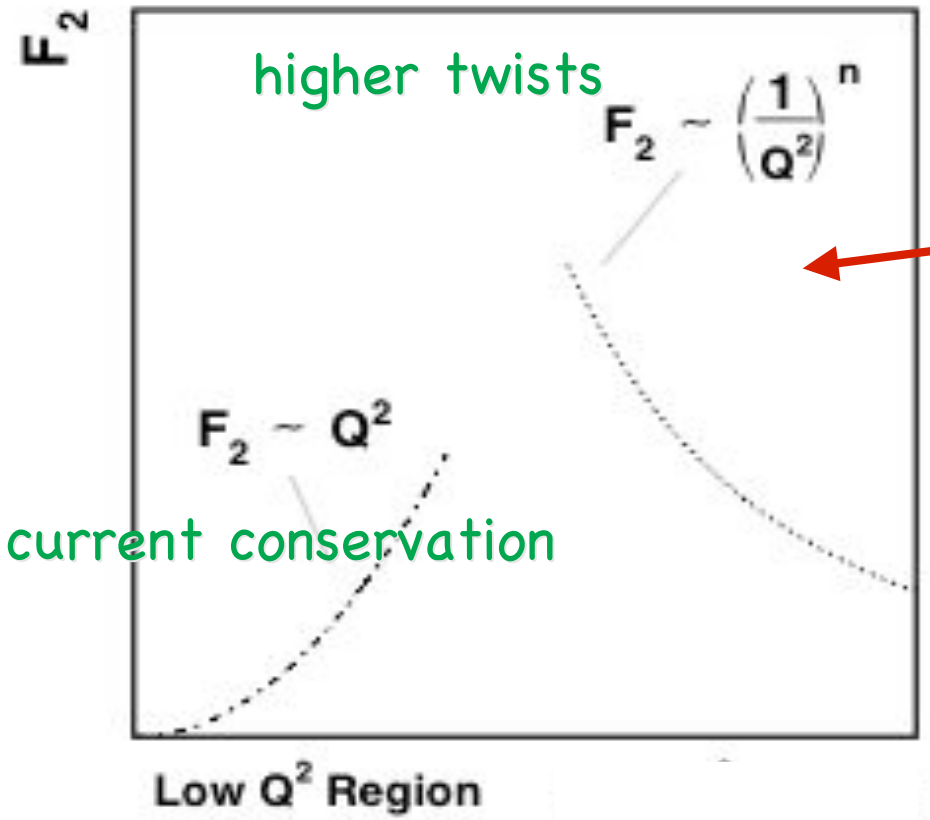
Current cut is W^2 = 10 GeV, Q^2 = 10 GeV^2

Blue is SF error due to pdf errors (likely an overestimate)

Pink is SF error due to pdf errors, but normalized to x = 0.5 data

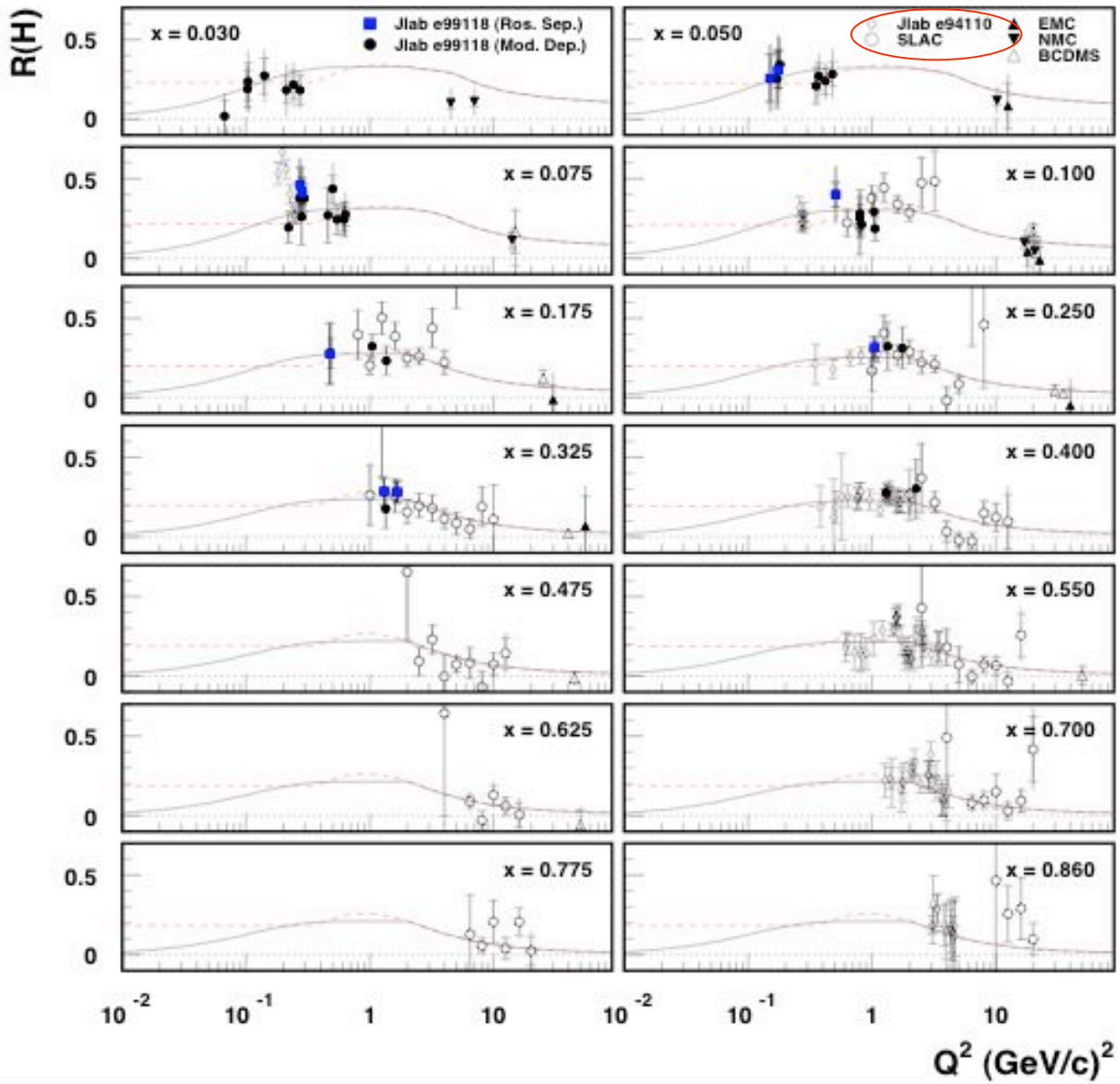
(Bottom plot better shows error at large x)

Challenges / Issues / Physics at Low Q^2



- NEED L/T separations to extract inclusive Structure Functions F_1, F_L, *and* F_2, g_1
- Low Q^2 behavior not well known
- Higher twists suggest increase
- Current conservation suggests a decrease
- *Experimentally,* can determine where each is dominant

Including Jlab Hall C E99-118 (V. Tvaskis thesis, publication in preparation



Note: R still not small at low Q2 as expected!

F_2, g_1, etc. should be revisited

Duality in pQCD

- 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!

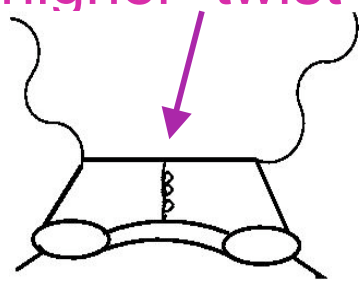
- Operator Product Expansion

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

higher twist

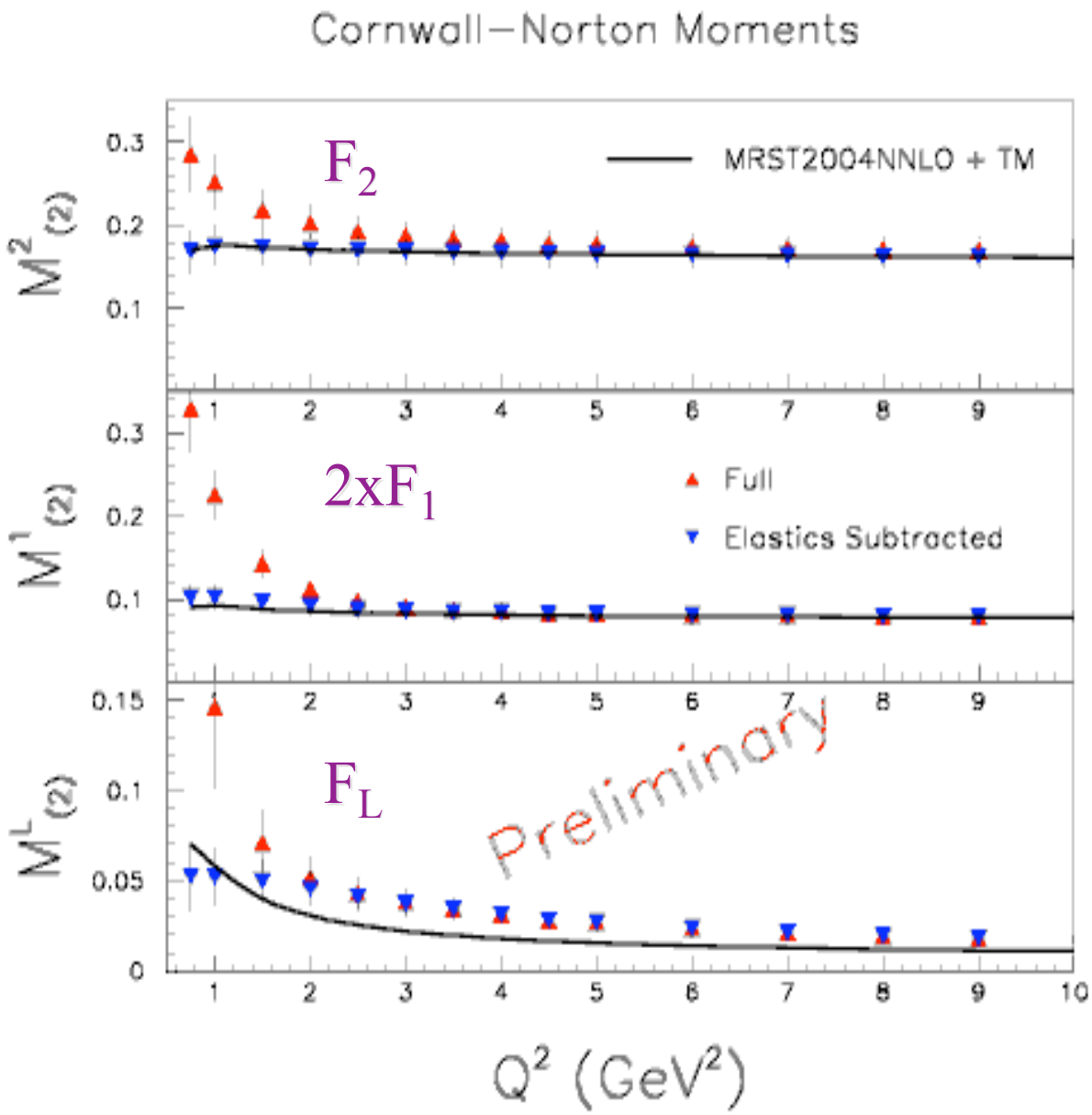
logarithmic dependence

(pQCD)



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

n = 2 Cornwall-Norton Moments



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

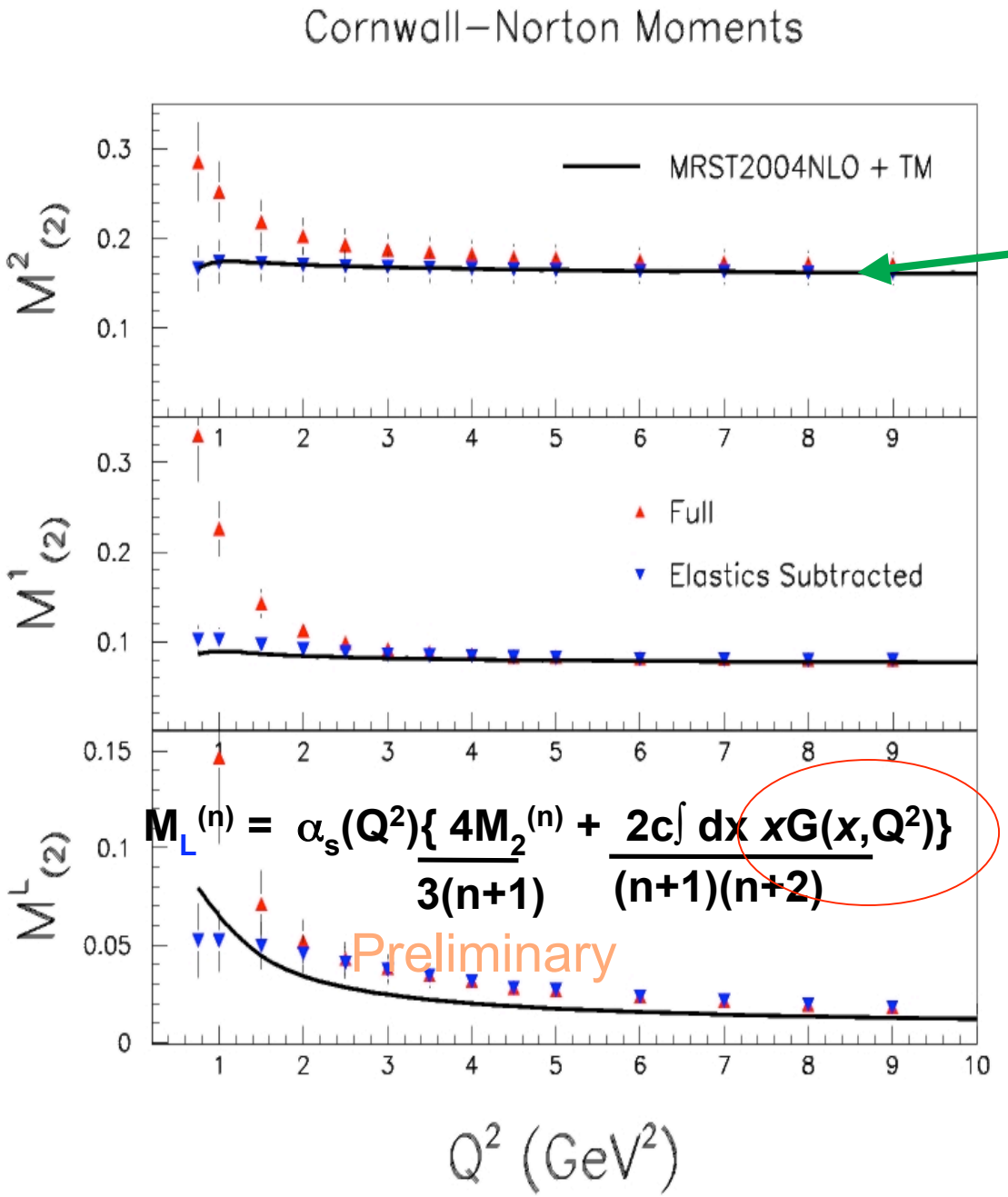
No (or canceling) higher twists

Yet, dominated by large x and resonance region

Remove known HT (a bit novel), the elastic, and there is no more down to $Q^2 = 0.5$ GeV2

The case looks different for F_L (data or curve?)

Momentum Sum Rule



$$M_L^{(n)} = \alpha_s(Q^2)\left\{ \frac{4M_2^{(n)}}{3(n+1)} + \frac{2c\int dx\, xG(x,Q^2)}{(n+1)(n+2)} \right\}$$

For F_2, QPM gives:
$(1/3)^2(0.17) + (2/3)^2(0.34)$
$= 0.17$

~50% of momentum carried by quarks – the rest, assumably, by the glue

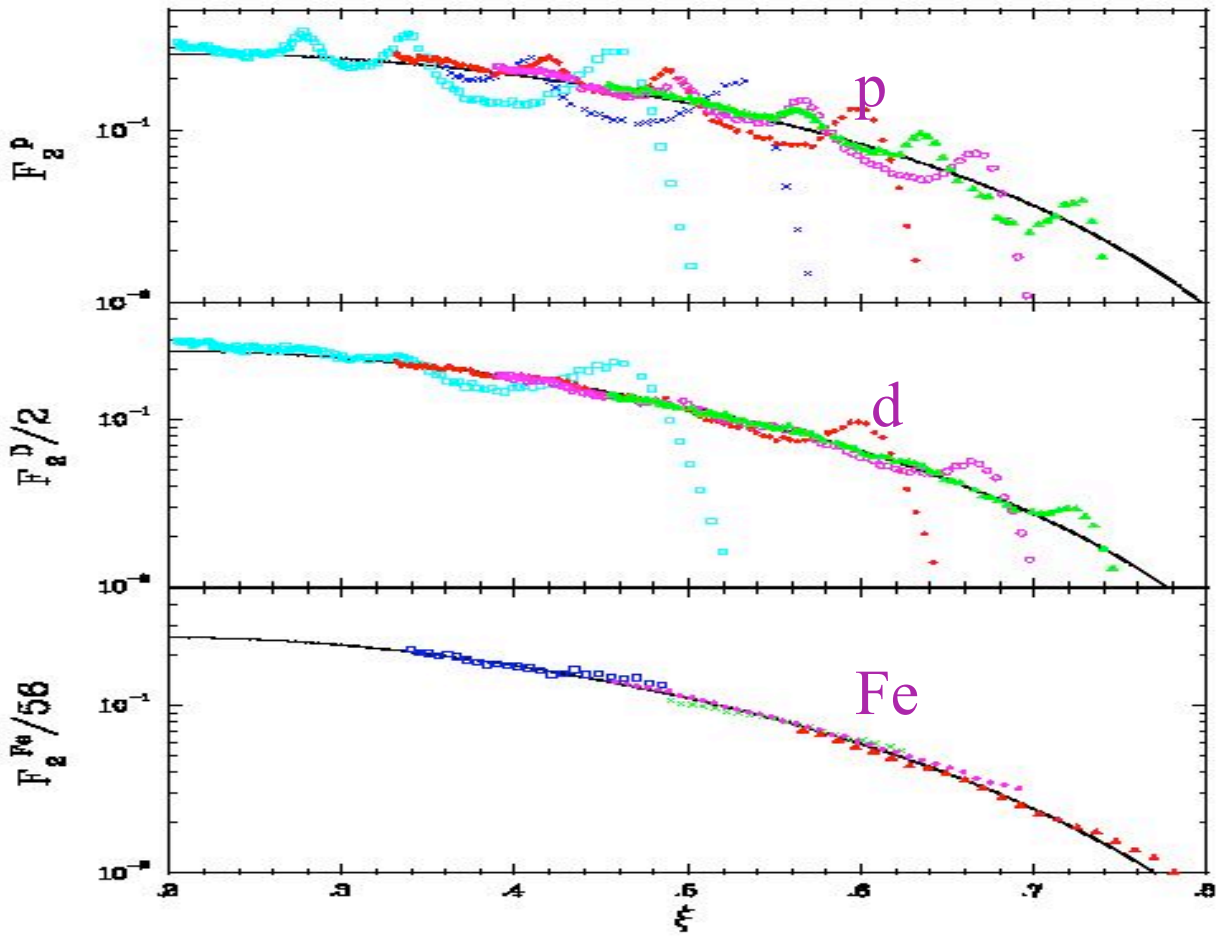
F_L gives a direct measurement of the glue

But, we get 0.70 (preliminary) – also different from pdfs

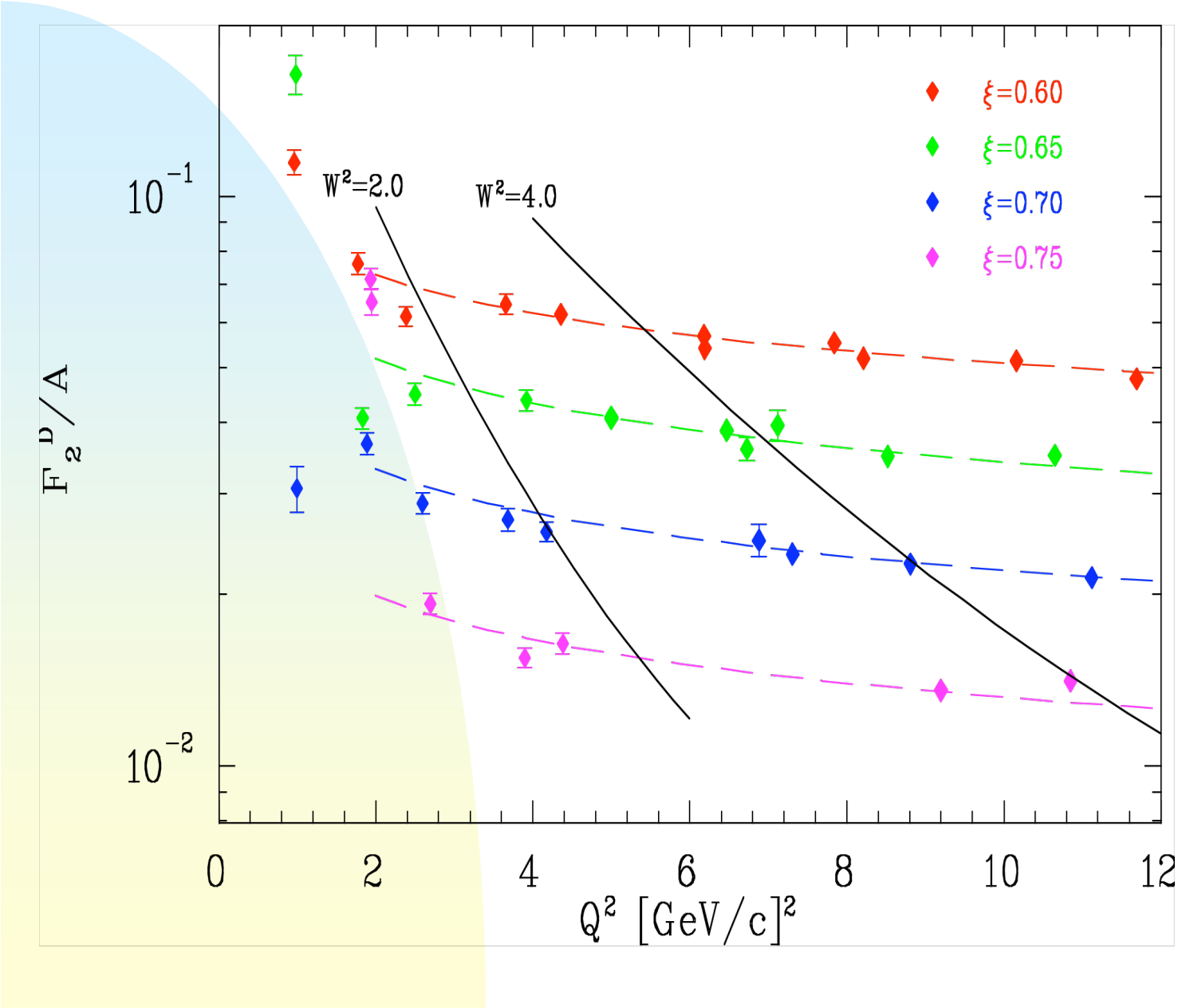
Duality in Nuclei, Too! (F_2)

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

- Data in resonance region, spanning Q^2 range 0.7 - 5 GeV^2
- GRV curve
- The nucleus does the averaging
- For larger A, resonance region indistinguishable from DIS



Duality (F_2) in Deuterium

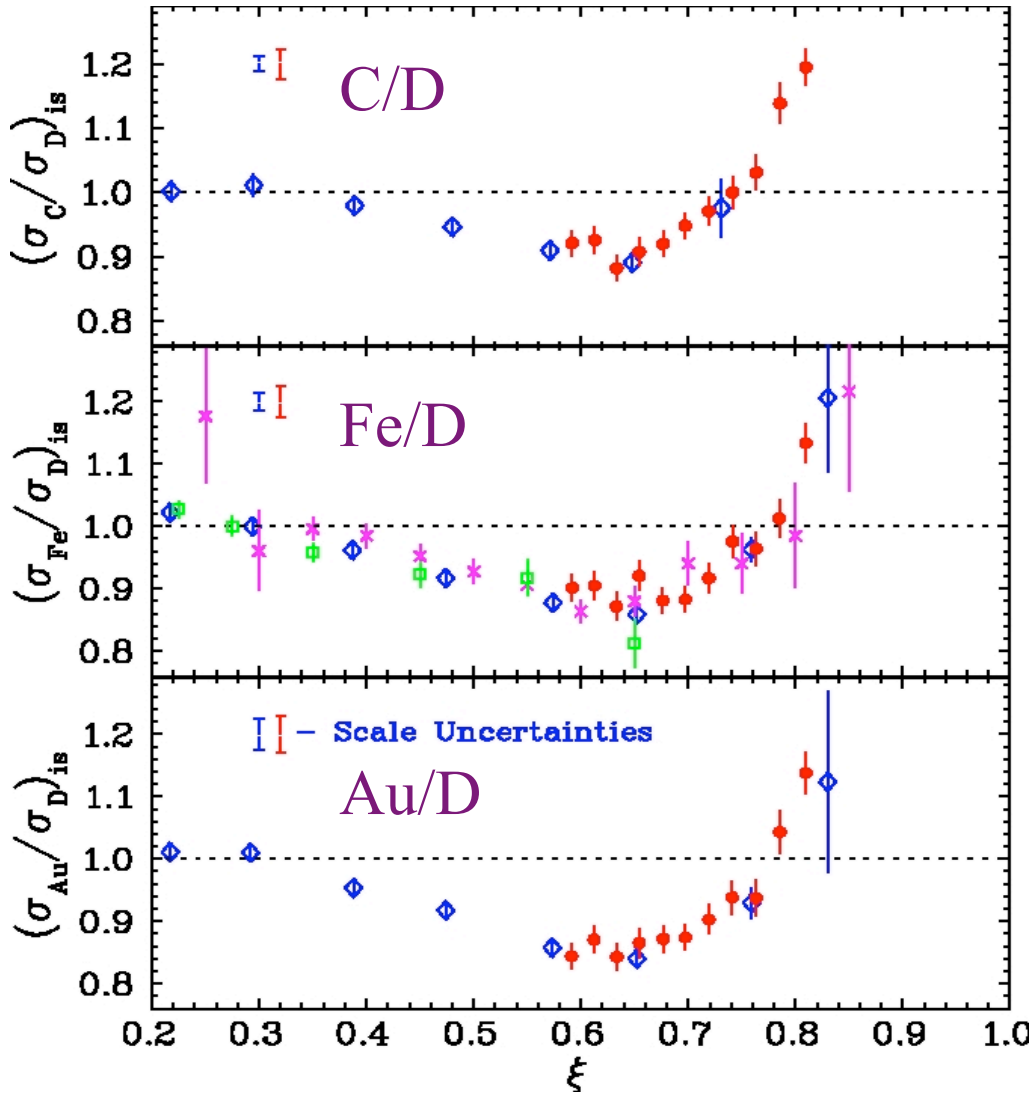


Resonance region and DIS F_2 same, with same Q^2 dependence, other than at smallest W

Duality and the EMC Effect

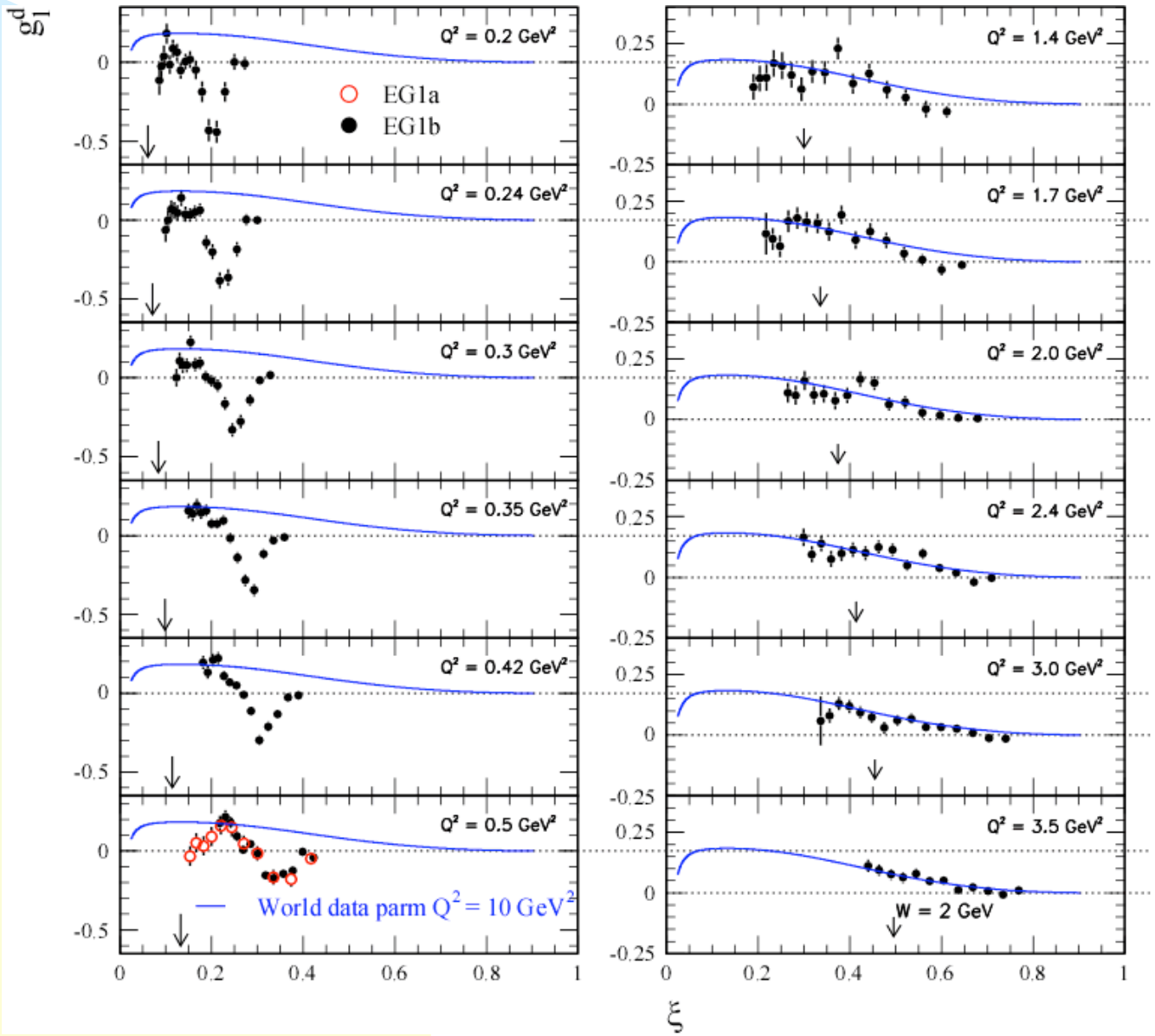
Medium modifications to the structure functions are the same in the resonance region as in the DIS

Rather surprising (deltas in nuclei, etc.)



J. Arrington, et al., submitted

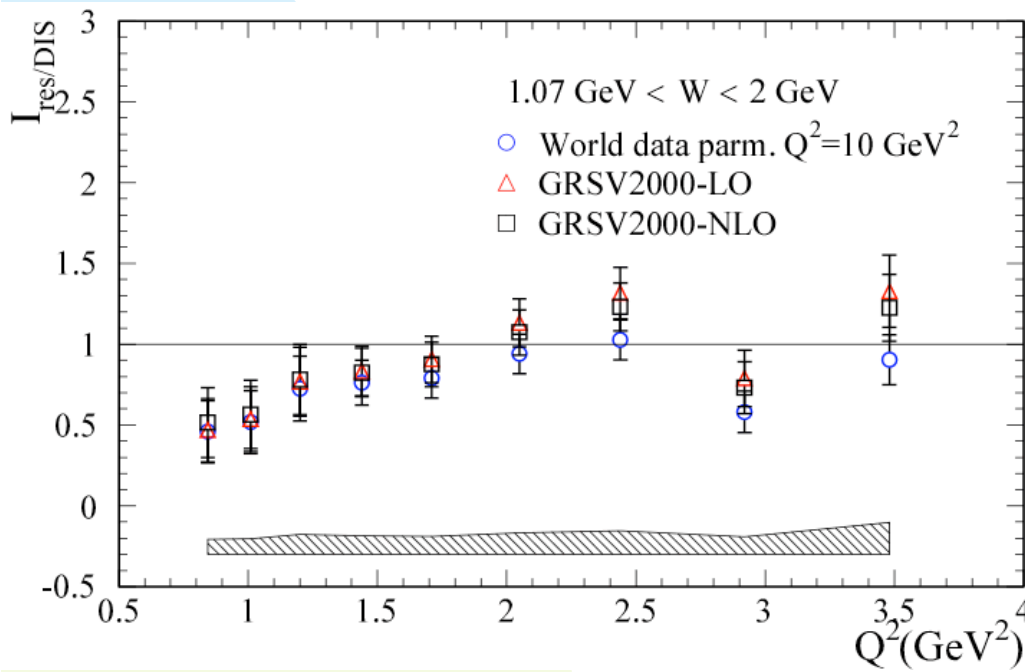
Duality in g_1^d (from T. Forest et al., Hall B EG1)

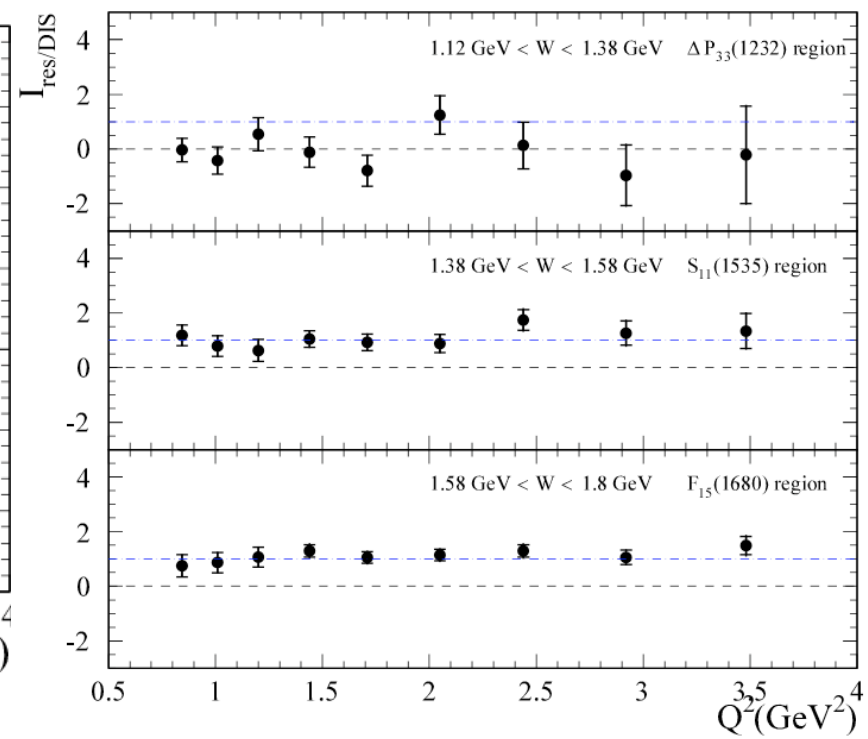


Like F2, g1 in the resonance region wiggles around high-Q2 curve curve. Strong deviation in region of Delta(1232).

The 2.5 and 4.2 GeV data will clarify the intermediate Q^2 range

Spin Structure Functions, g_1^d (continued)





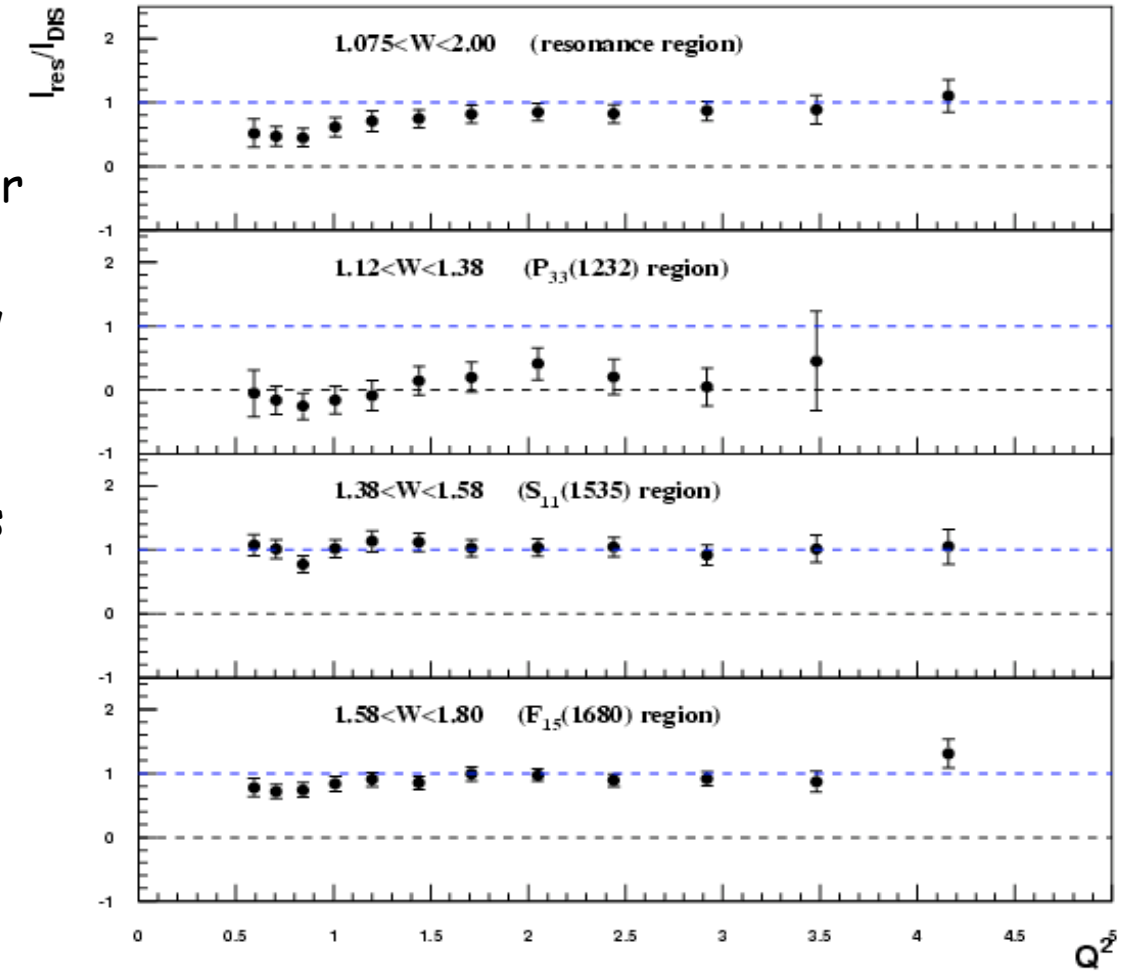
Global duality established down to ~1.5 GeV^2.

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

Spin Duality for the Proton

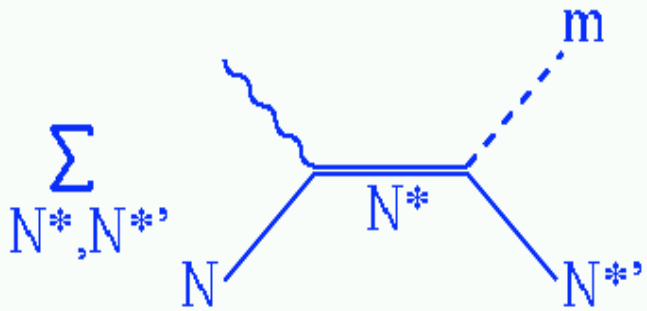
Eg1b very preliminary

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



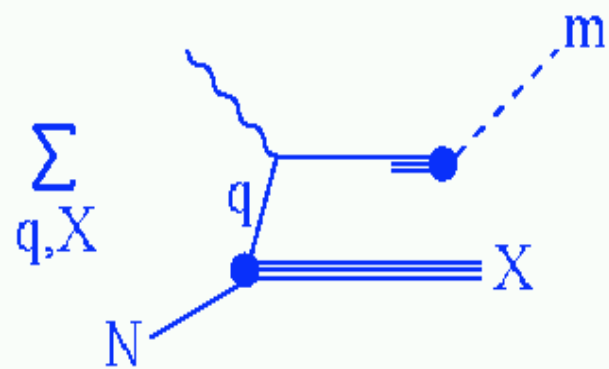
Duality in Meson Electroproduction

hadronic description



$\sim$

quark-gluon description



$$\sum_{N'^*} \left| \sum_{N^*} F_{\gamma^* N \to N^*}(Q^2, W^2)\, \mathcal{D}_{N^* \to N'^* M}(W^2, W'^2) \right|^2$$

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

Transition Form Factor

Decay Amplitude

Fragmentation Function

Requires non-trivial cancellations of decay angular distributions

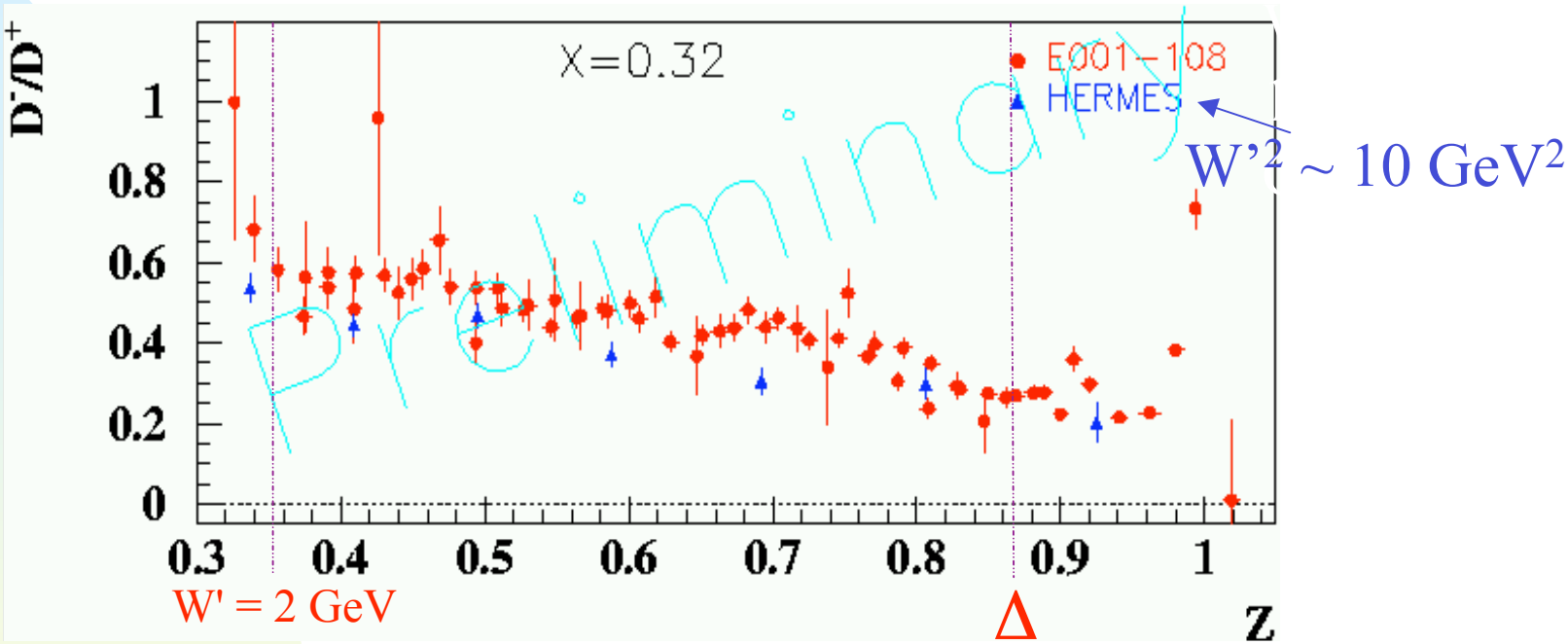
If duality is not observed, factorization is questionable

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

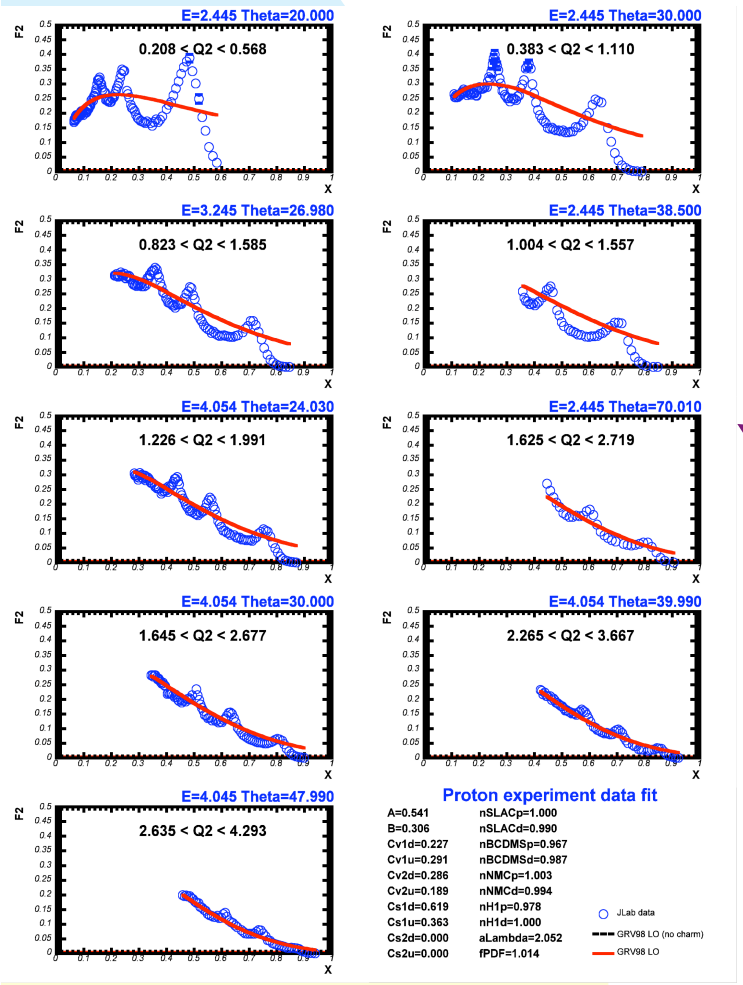


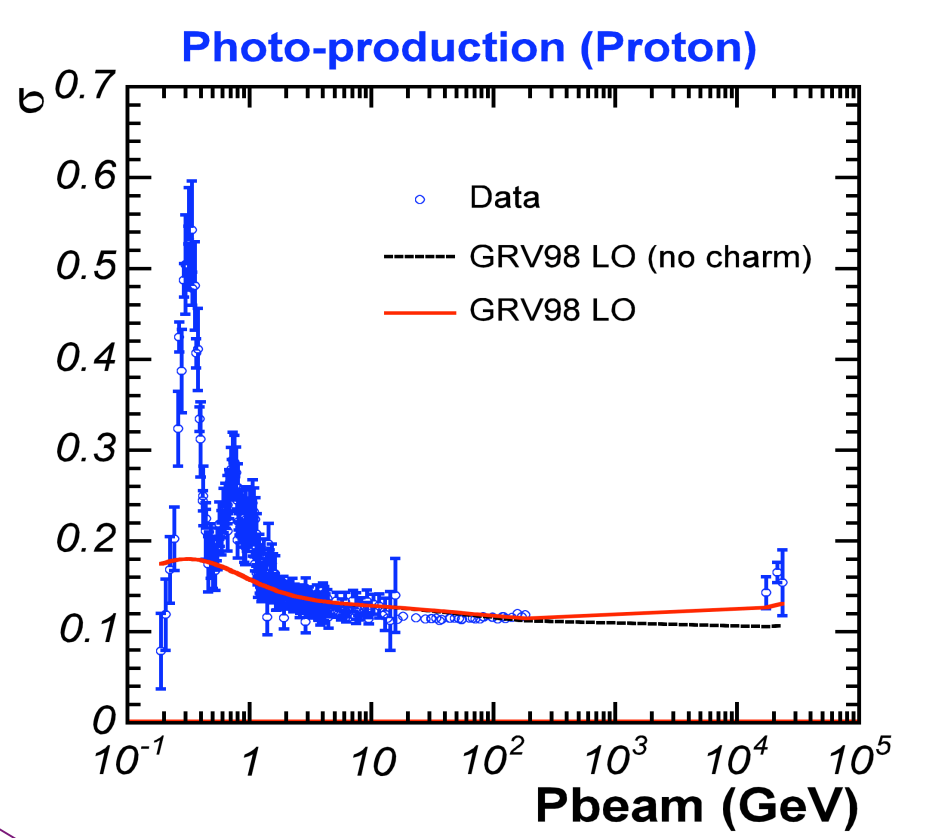
Data predominantly in "resonance region" ... What happened to the resonances?

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…..

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
- Duality in semi-inclusive meson production
- Works in photoproduction as well

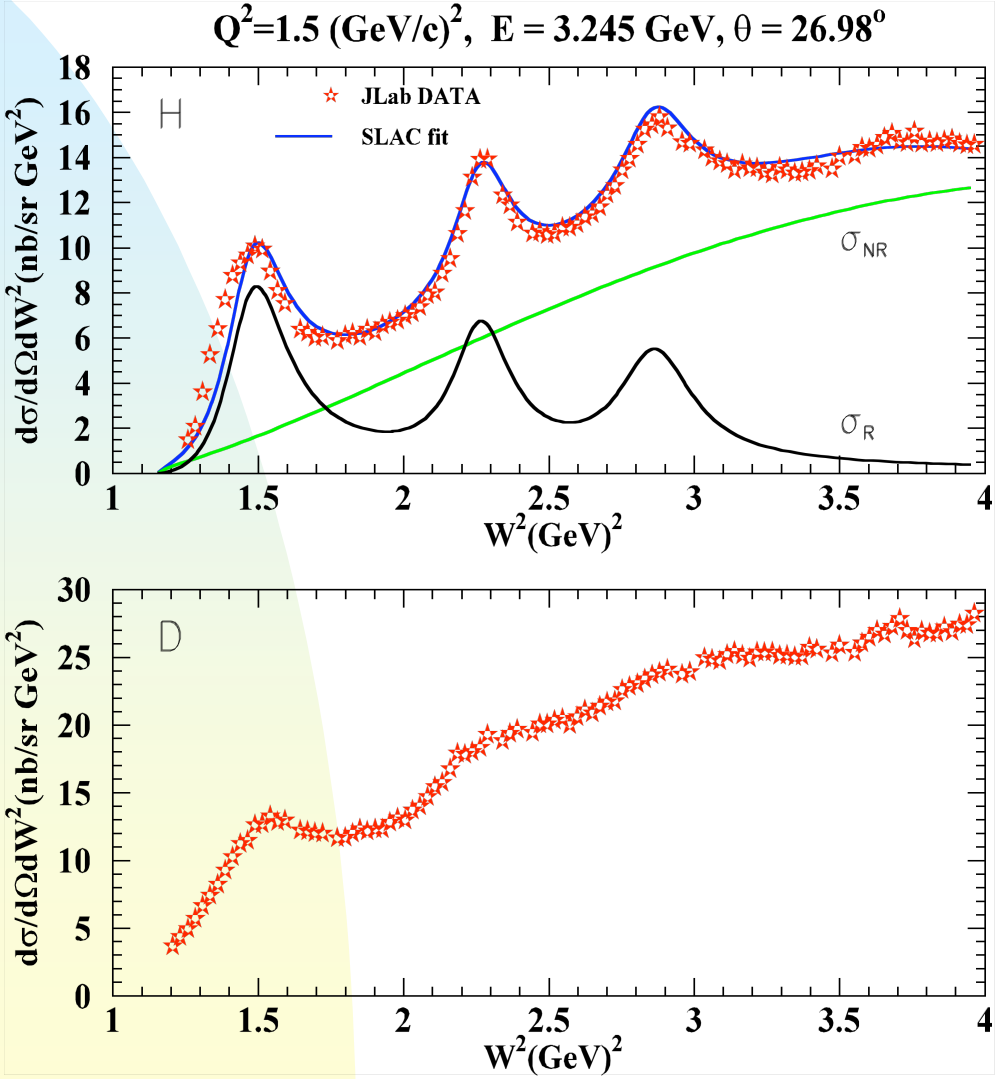
Appears to be a non-trivial property of proton structure!

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

Inclusive Neutron Resonance Electroproduction

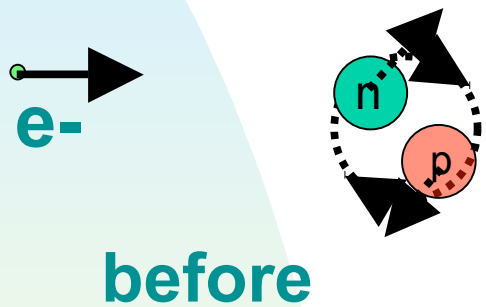


Using a deuterium target, there's a large uncertainty in neutron extraction…..

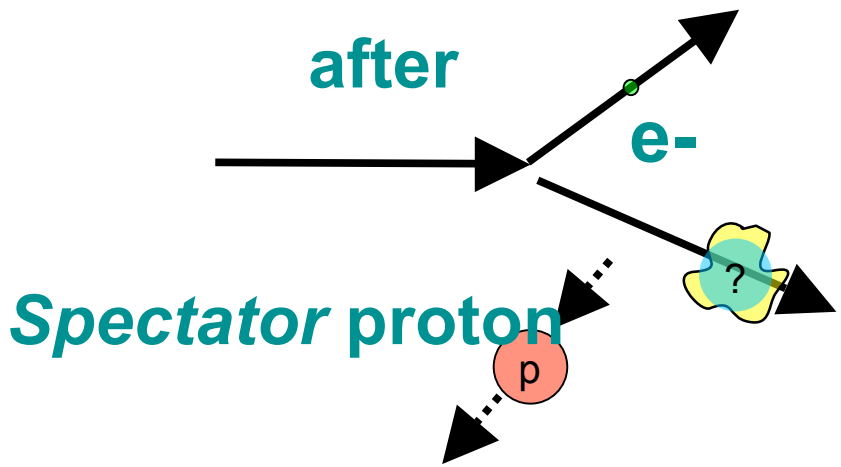
…must consider deuteron wave function, Fermi smearing, off-shell effects, *neutron structure function shape,...*

The BONUS Approach: An Effective Free Neutron Target from Deuterium….

Interaction on Neutron:

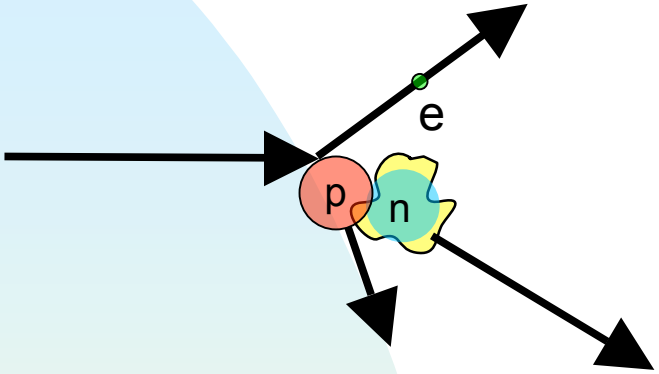


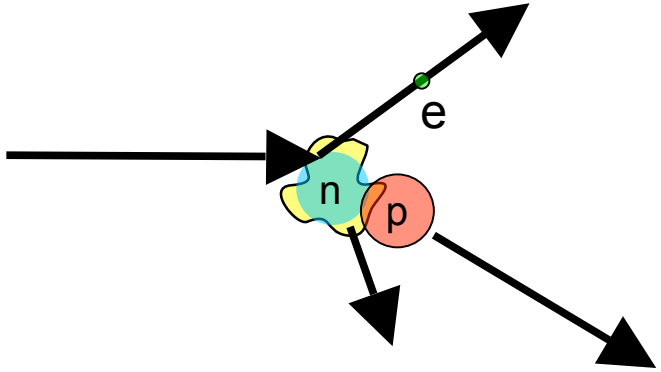
The Proton is left behind.



If the proton is going backwards in the lab frame

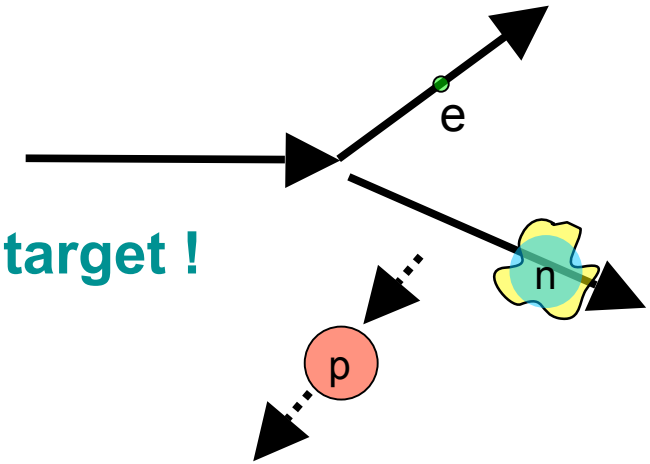
it is almost guaranteed to be only a spectator.



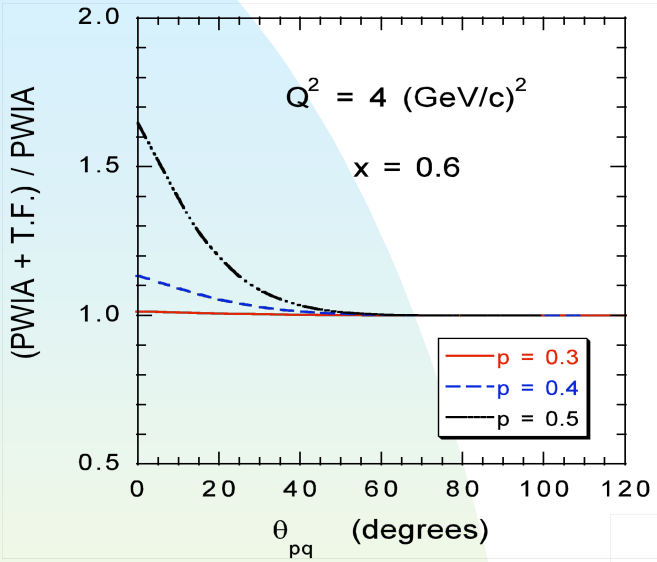


proton target <-- ambiguous --> neutron target

neutron target !

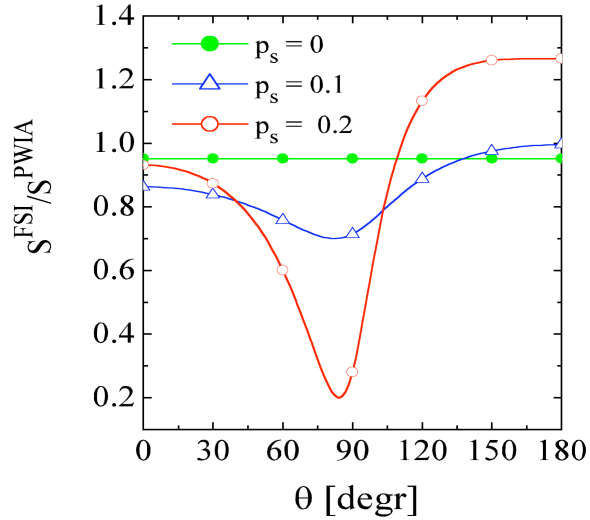


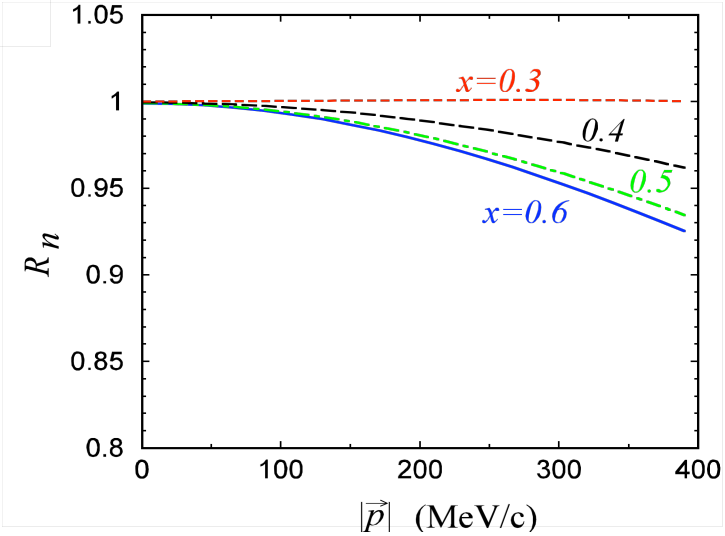
Choice of Spectator Momentum and Angle



Bound / free neutron structure

$\mathcal{O}$(1%)





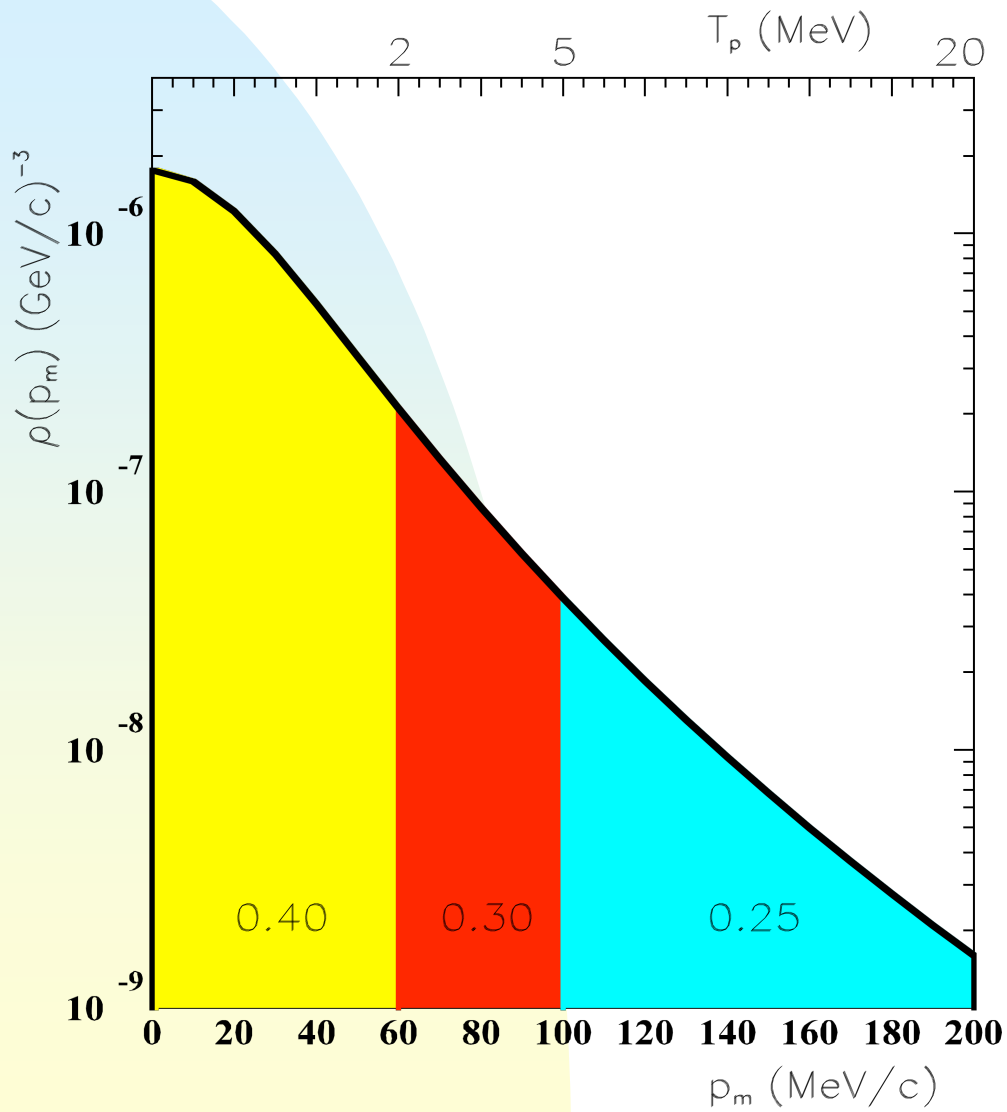
Target fragmentation

negligible

Final state interactions

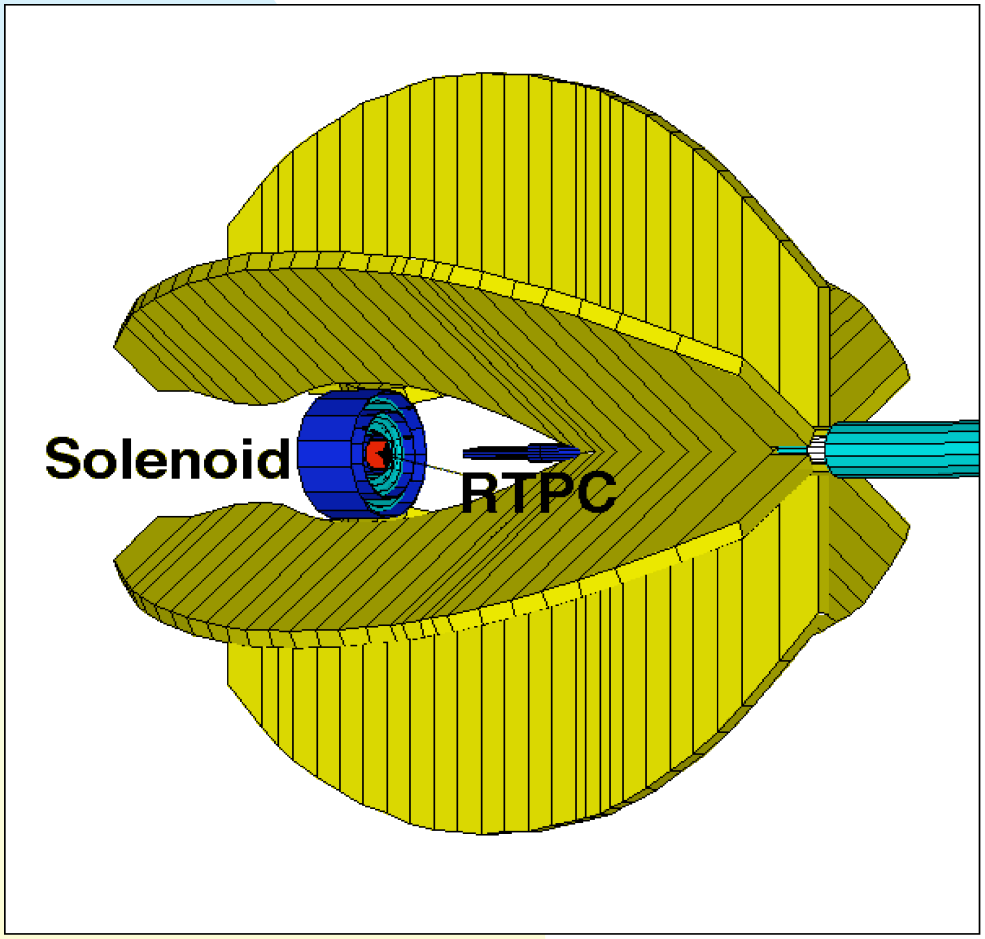
$\mathcal{O}$(5%)

“VIPs”: (Very Important Protons)



- Deuteron ~ free proton + free neutron at small nucleon momenta
- Will target T_p ~ 2 – 5 MeV spectator protons
- 30% of momentum distribution is in chosen p_s range
- T_p > 5 MeV spectators will also be detected

Experimental Setup



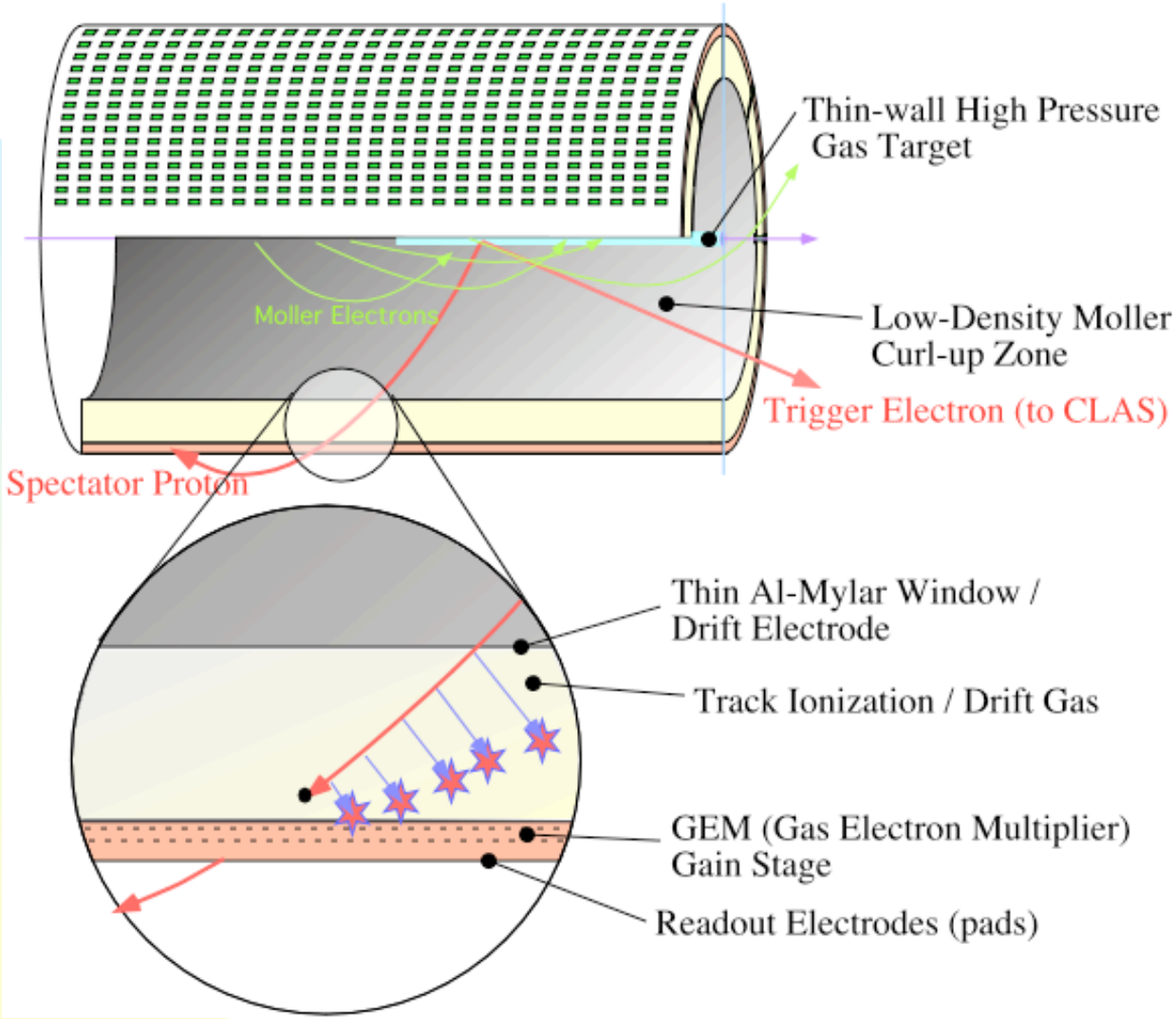
- Hall B CLAS spectrometer for electron detection
- Thin deuterium target (7.5 atm gas)
- Radial Time Projection Chamber (RTPC) for spectator proton detection
- DVCS solenoid to contain Moller background

BONUS RTPC Design

Φ, z from pads

r from time

dE/dx from charge along track (particle ID)

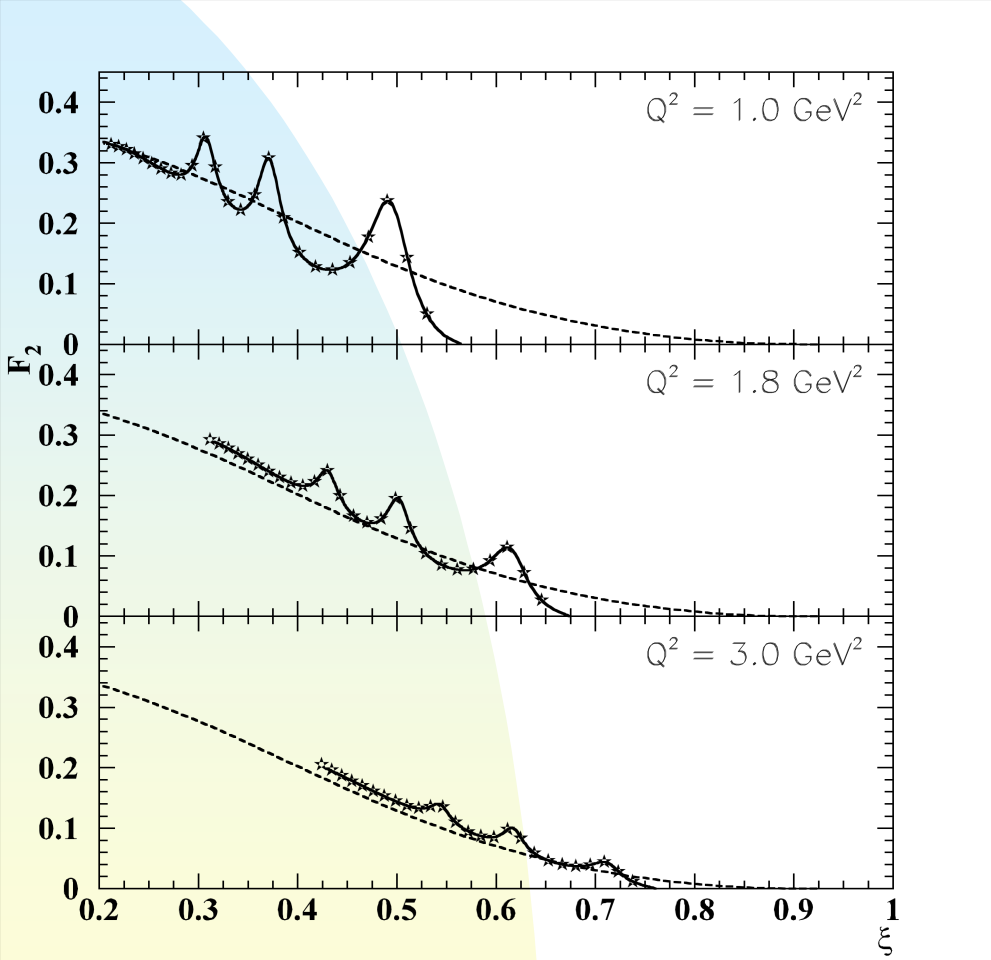


4mm x 10 cm 7.5 atm

4 cm He

neonDME

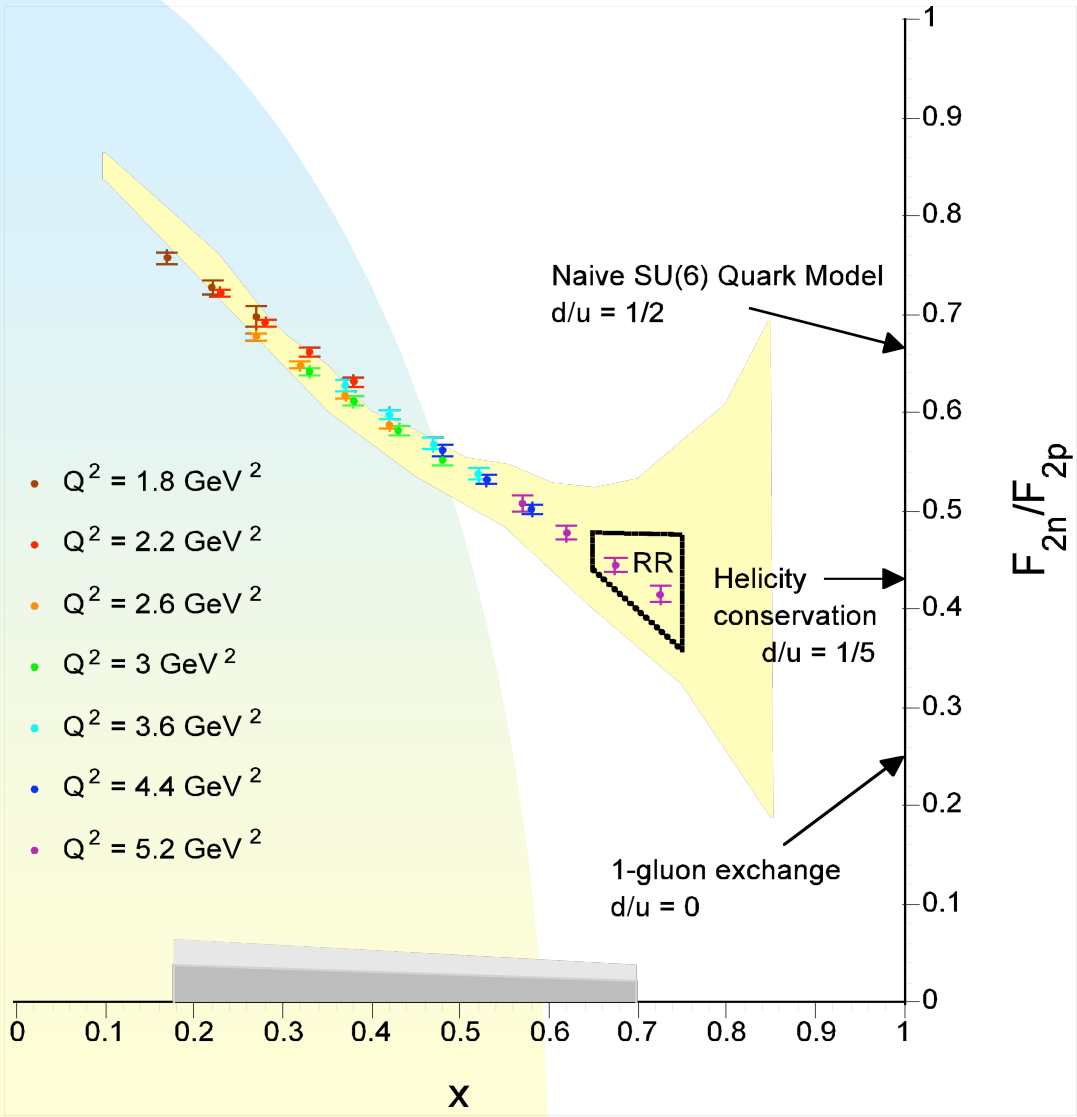
Neutron Quark-Hadron Duality – Projected Results



Systematics ~5%

- **Sample neutron structure function spectra**
- **Plotted on proton structure function model for example only**
- **Neutron resonance structure function essentially unknown**
- **Smooth curve is NMC DIS parameterization**

F_2^n / F_2^p (d/u) Ratio at Large x – Projected Results



- Yellow shaded area represents current theoretical uncertainty
- RR data begin the Resonance Region ($W^2 > 3$ GeV^2, $Q^2 \sim 5$)
- Gray shaded areas represent systematic uncertainty
  - Light = total
  - Dark = normalized, point-to-point

"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)

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

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

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

$SU(6)$ 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