Quark-Hadron Duality

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PAC-25 Mini-Workshop on Nucleon Excited States

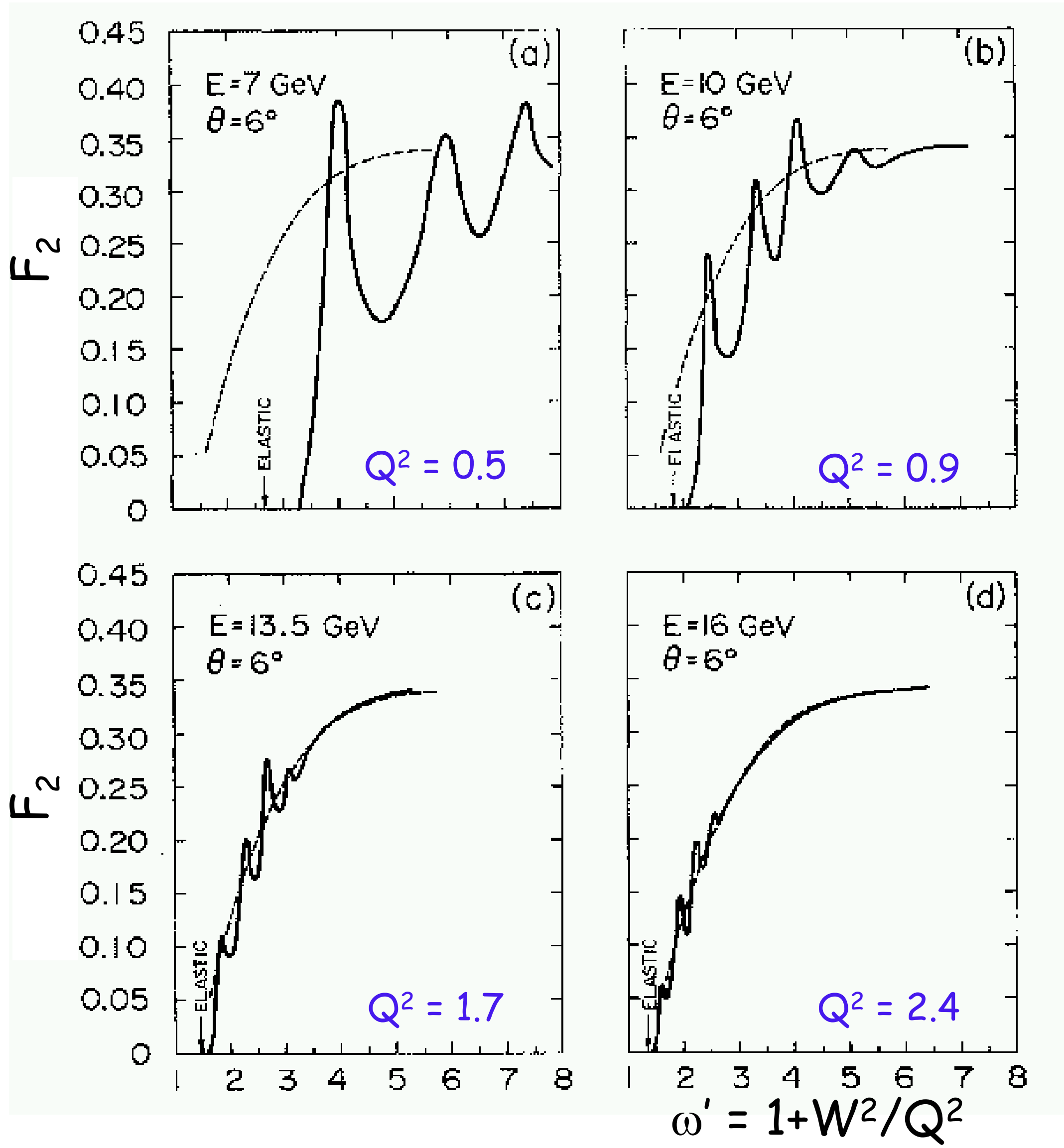
Duality in the F_2 Structure Function

First observed ~1970 by Bloom and Gilman at SLAC by comparing resonance production data with deep inelastic scattering data

- *Integrated F_2 strength in Nucleon Resonance region equals strength under scaling curve. Integrated strength (over all ω') is called Bloom-Gilman integral*

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



Duality in the F_2 Structure Function

First observed ~1970 by Bloom and Gilman at SLAC

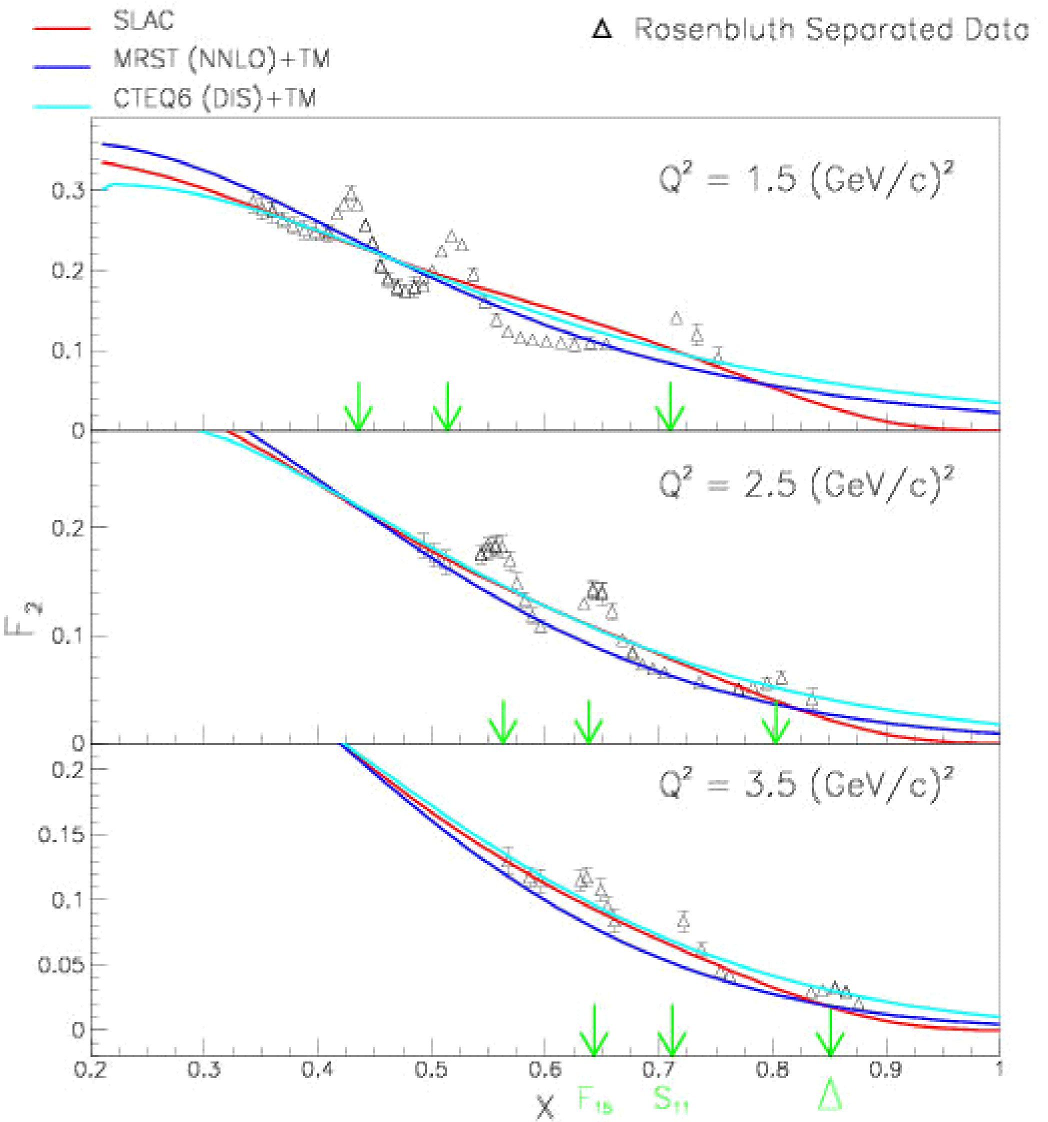
Now can truly obtain F_2 structure function data, and compare with DIS fits or QCD calculations/fits (CTEQ/MRST/GRV)

Use Bjorken x instead of Bloom-Gilman's ω'

- Bjorken Limit: Q^2, $\nu \rightarrow \infty$
- Empirically, DIS region is where logarithmic scaling is observed: $Q^2 > 5$ GeV^2, $W^2 > 4$ GeV^2
- Duality: Averaged over W, logarithmic scaling observed to work also for $Q^2 > 0.5$ GeV^2, $W^2 < 4$ GeV^2, resonance regime

(note: $x = Q^2/(W^2-M^2+Q^2)$)

- JLab results: Works quantitatively to better than 10% at surprisingly low Q^2



Quark-Hadron Duality

complementarity between quark and hadron descriptions of observables

At high enough energy:

Hadronic Cross Sections

averaged over appropriate energy range

Perturbative

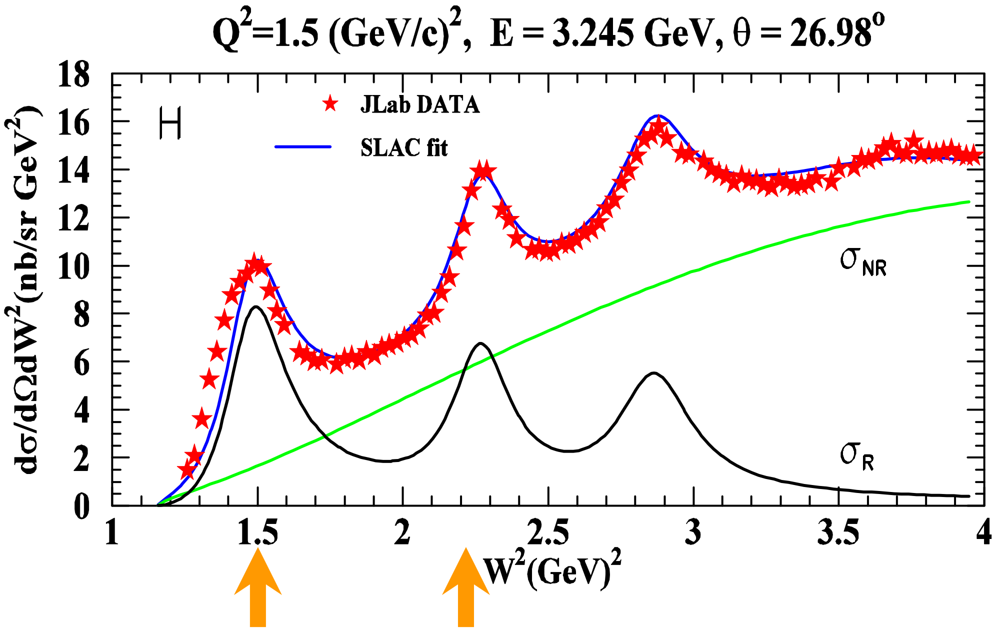
Quark-Gluon Theory

$$\sum_{\text{hadrons}} = \sum_{\text{quarks+gluons}}$$

Can use either set of complete basis states to describe physical phenomena

But why also in limited local energy ranges?

If one integrates over all resonant and non-resonant states, quark-hadron duality should be shown by any model. This is simply unitarity.
However, quark-hadron duality works also, for $Q^2 > 0.5$ (1.0) GeV^2, to better than 10 (5) % for the F_2 structure function in both the N-Δ region and the N-S_{11} region!



One resonance + non-resonant background

Few resonances + non-resonant background

Why does local quark-hadron duality work so well, at such low energies?
~ quark-hadron transition

Confinement is local ….

QCD and the Operator-Product Expansion

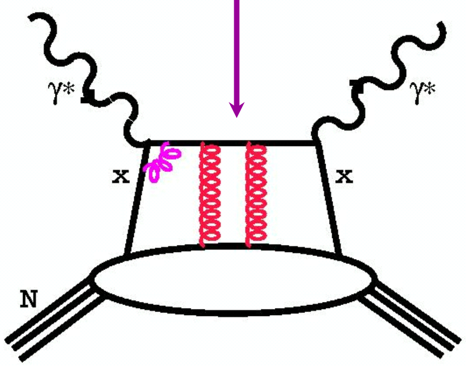
- Moments of the Structure Function $M_n(Q^2) = \int_0^1 dx\ x^{n-2} F(x,Q^2)$

  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



- Duality is described in the Operator Product Expansion

  as higher twist effects being small or canceling

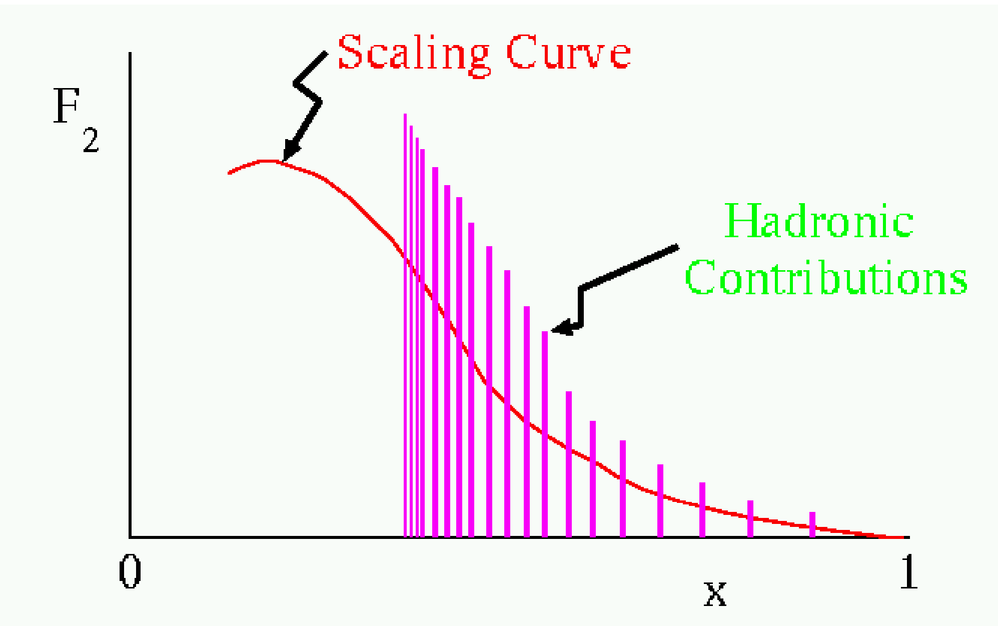
DeRujula, Georgi, Politzer (1977)

Quark-Hadron Duality – Theoretical Efforts

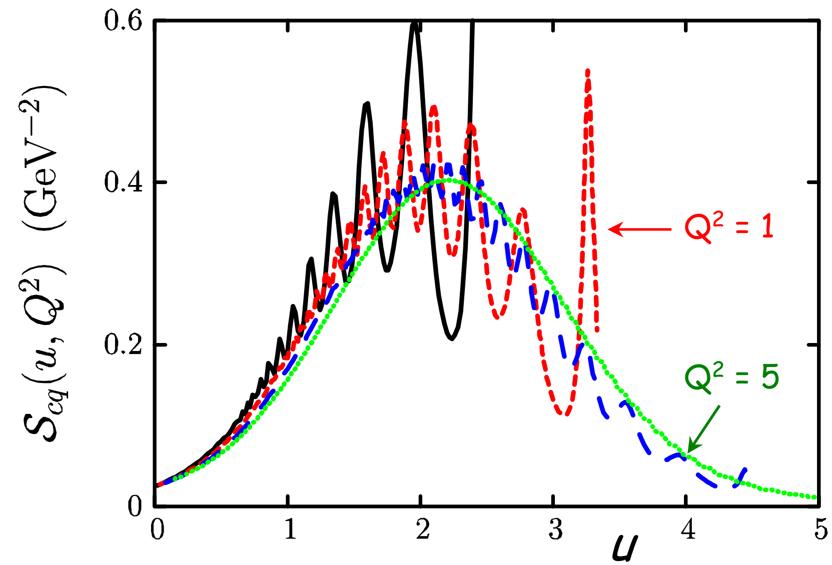
<u>N. Isgur et al : $N_c \to \infty$</u>

qq infinitely narrow resonances

qqq only resonances



One heavy quark, Relativistic HO



Scaling occurs rapidly!

- Distinction between Resonance and Scaling regions is spurious
- Bloom-Gilman Duality must be invoked even in the Bjorken Scaling region
  → Bjorken Duality

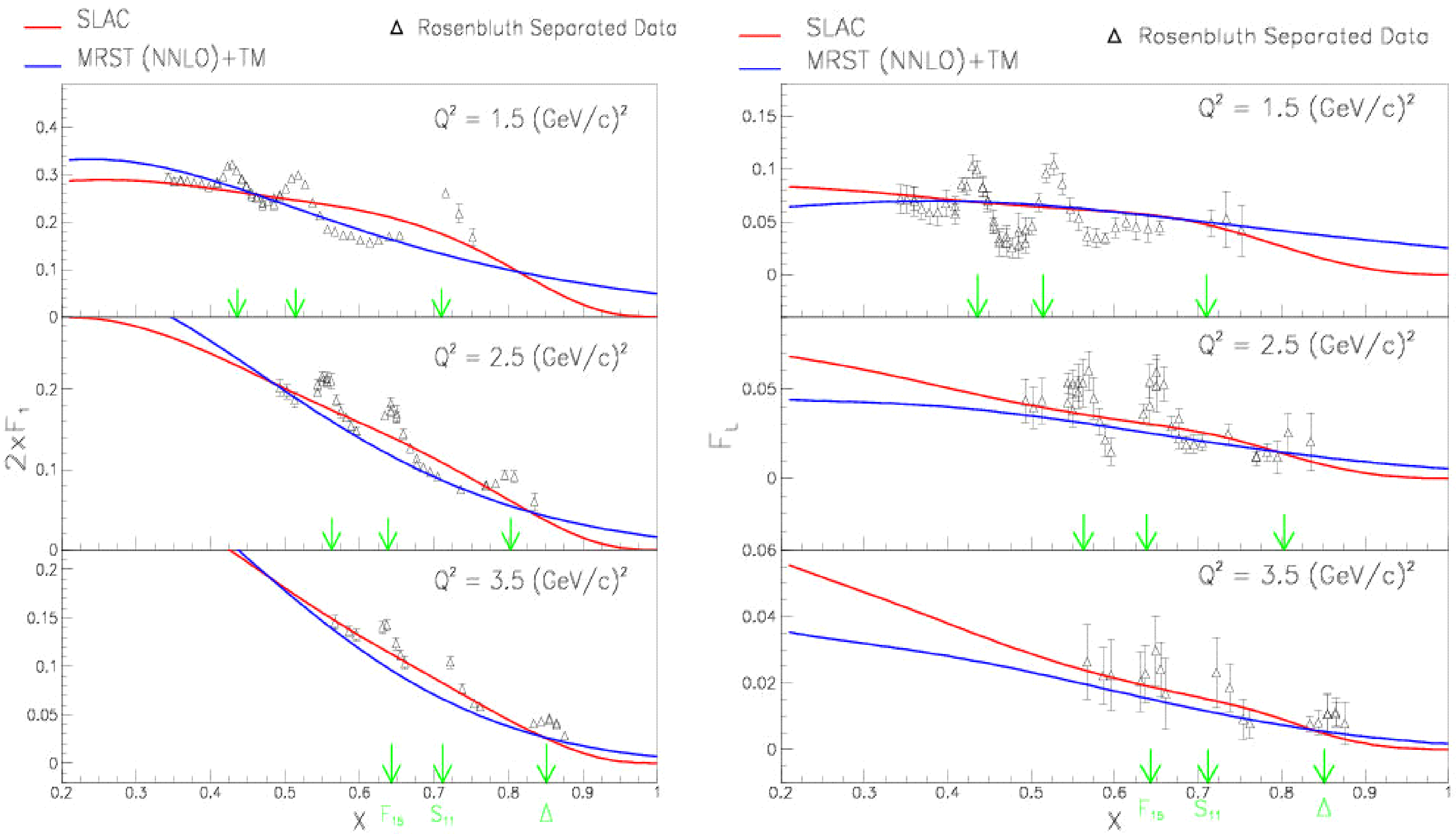
<u>F. Close et al : SU(6) Quark Model</u>

How many resonances does one need to average over to obtain a complete set of states to mimic a parton model?

→<u>56</u> and <u>70</u> states o.k. for closure

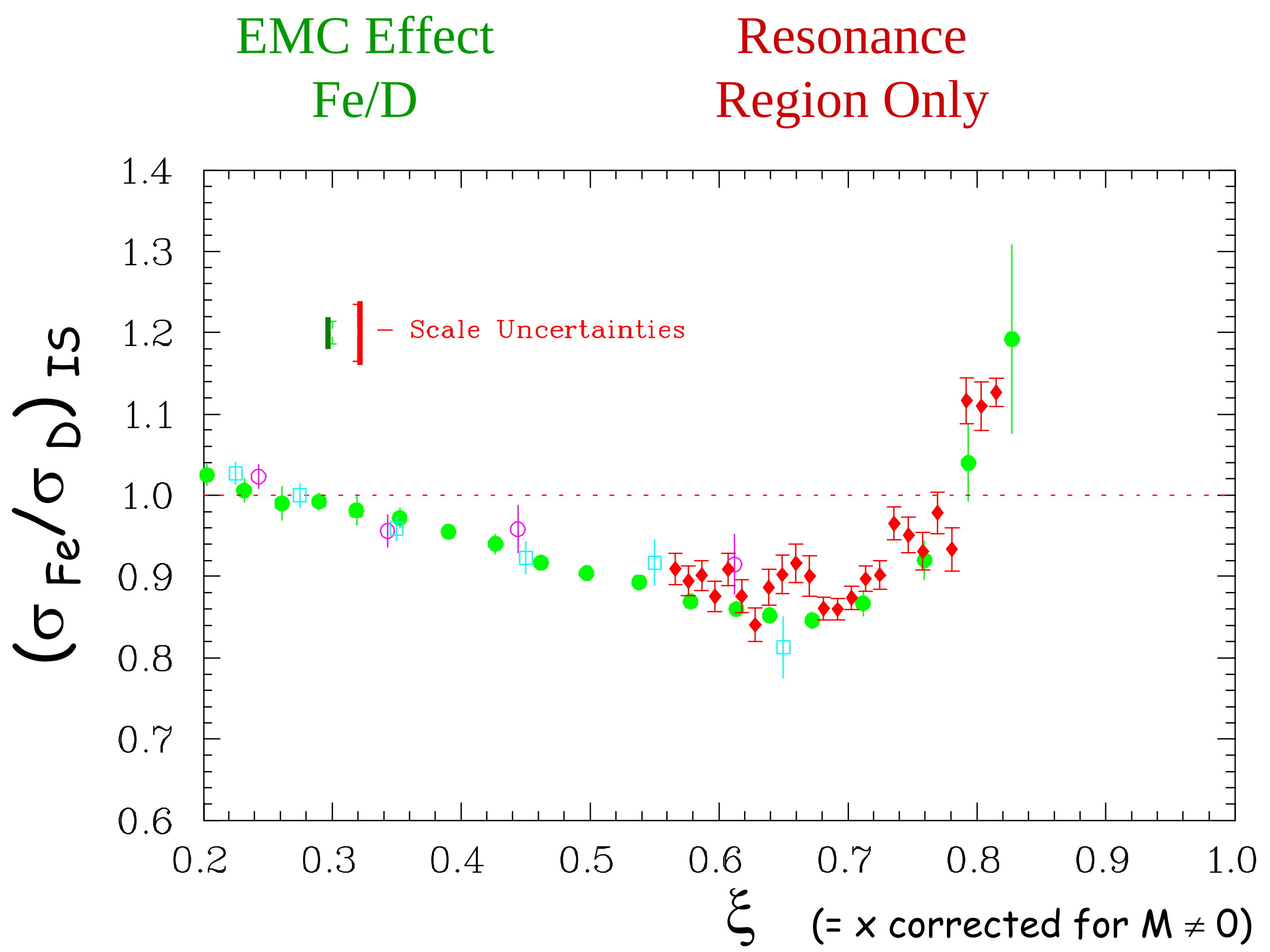
→Similar arguments for e.g. DVCS and semi-inclusive reactions

Duality in F_T and F_L Structure Functions



Duality works well for both F_T and F_L above $Q^2 \sim 1.5\ (GeV/c)^2$

Duality "easier" established in Nuclei



Nucleons have Fermi motion in a nucleus

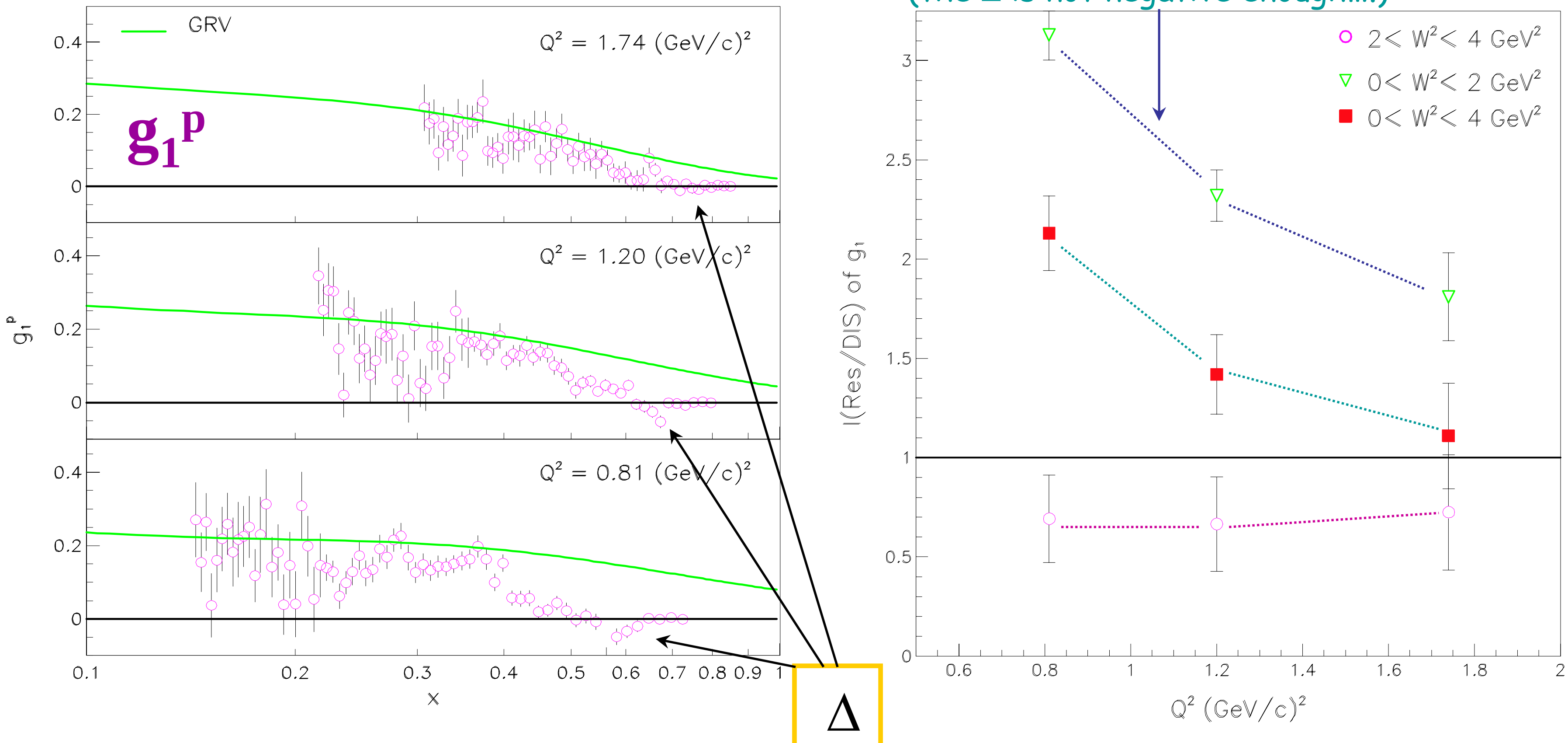
The nucleus does the averaging for you!

... but tougher in Spin Structure Functions

CLAS EG1

Pick up effects of both N and Δ

(the Δ is not negative enough....)



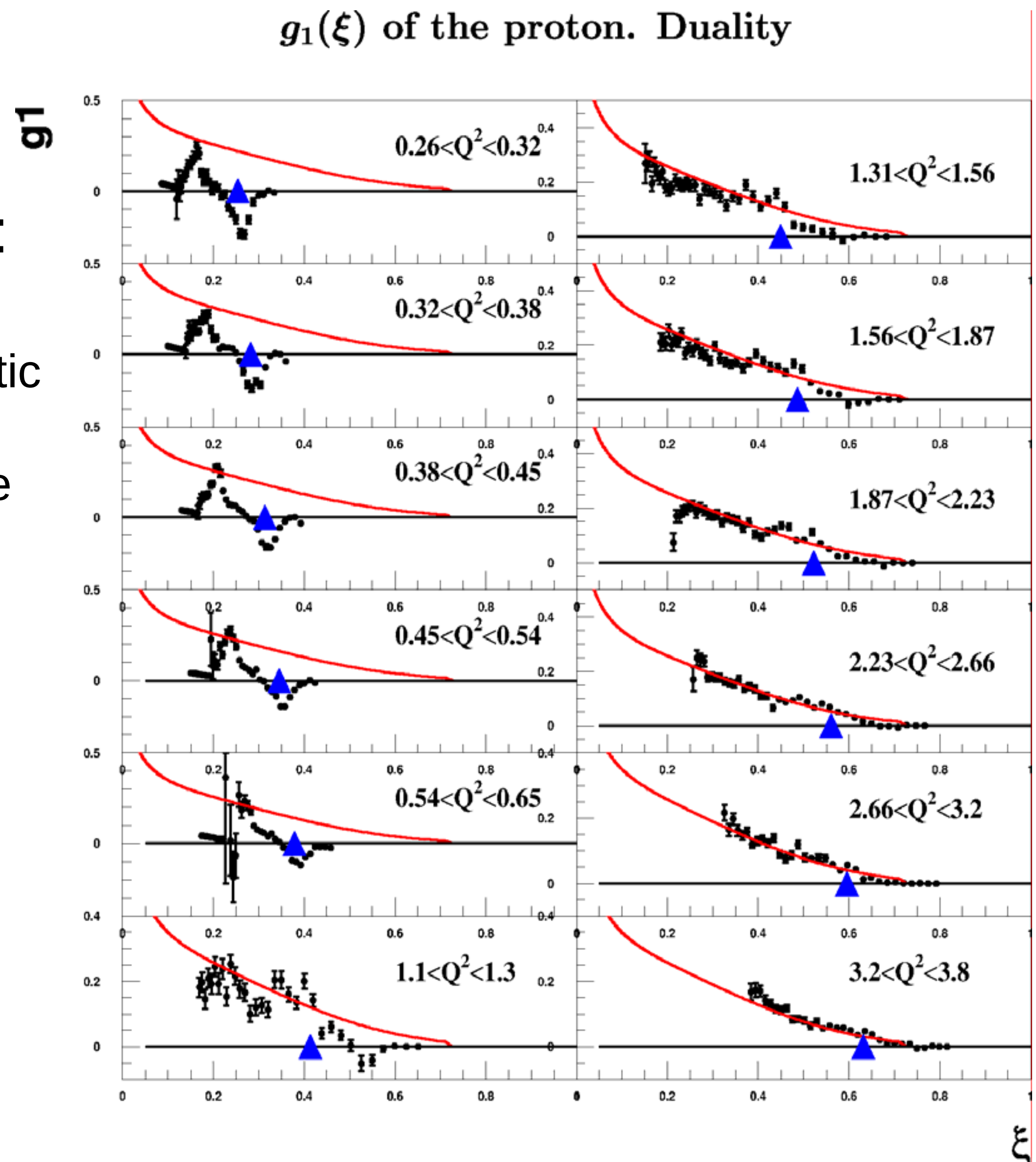
CLAS: N-Δ transition region turns positive at Q^2 = 1.5 (GeV/c)^2

Elastic and N-Δ transition cause most of the higher twist effects

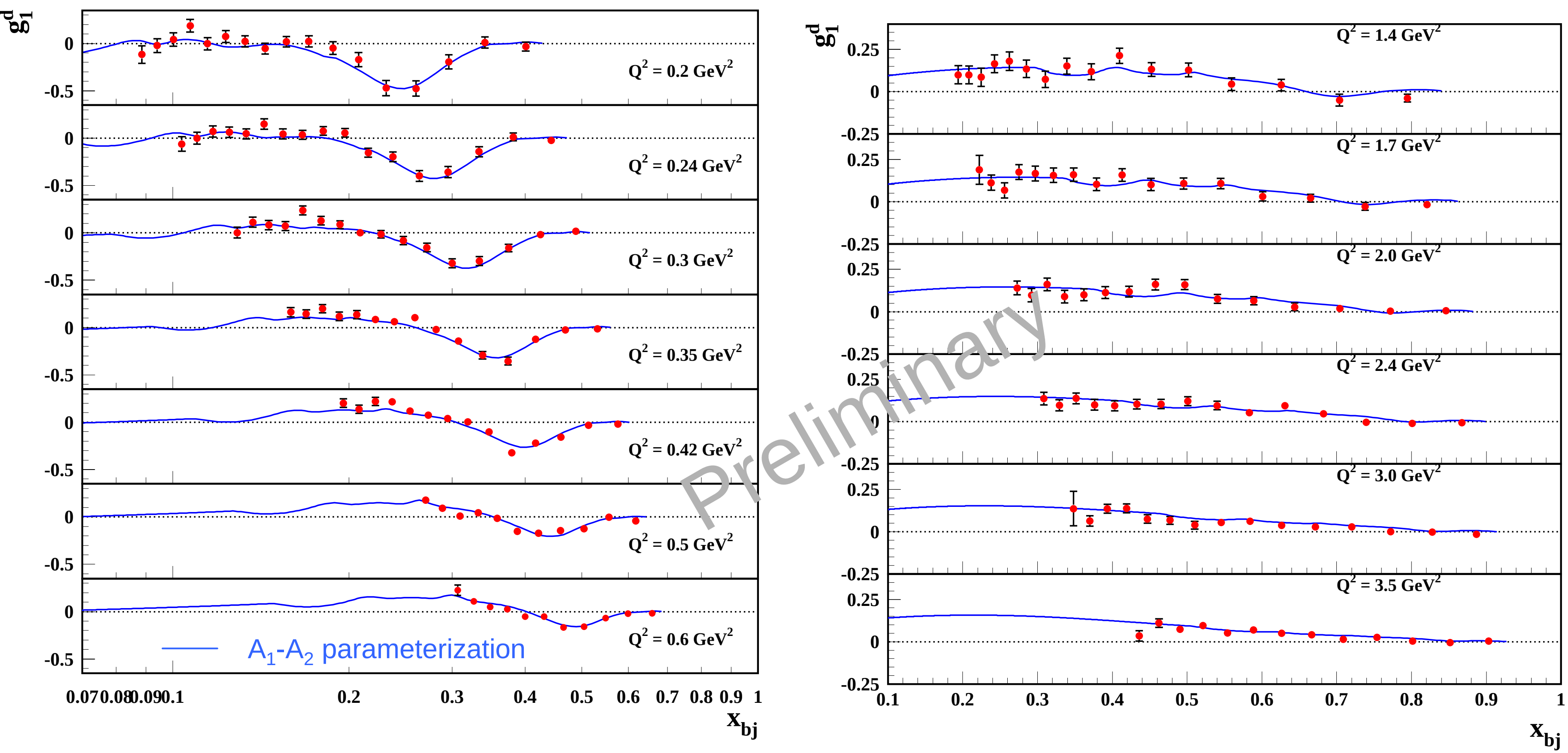
CLAS – Spin Structure Function $g_{1p}(\xi,Q^2)$

Test of Local Spin Duality:

- The presence of a strong magnetic dipole transition in the Δ(1232) region, and other higher resonance effects shift the onset of LSD to $Q^2 > 1.5$ GeV^2.



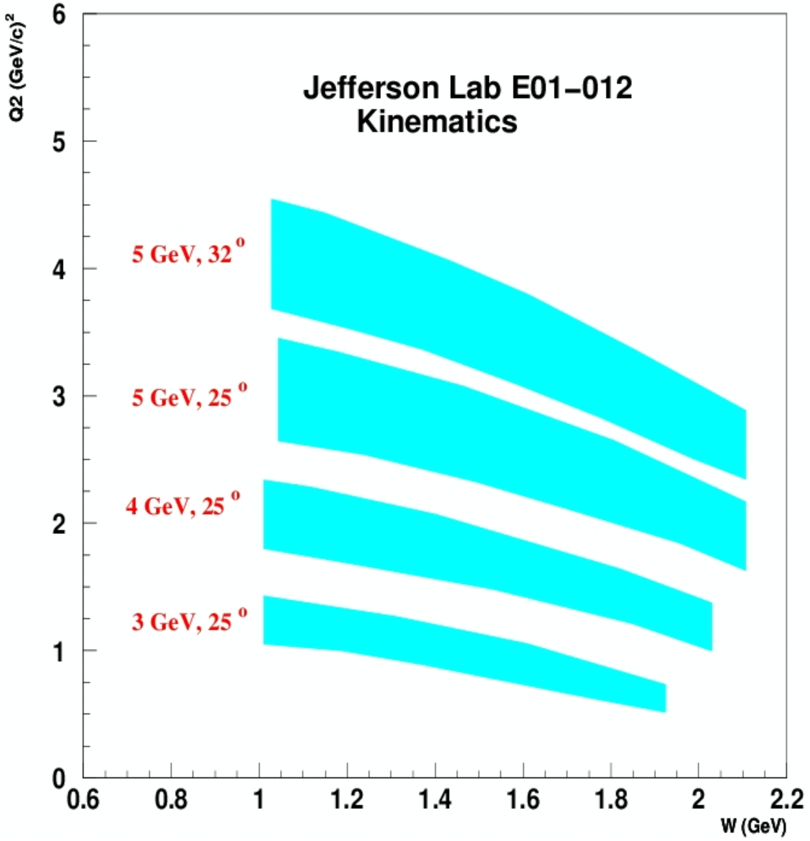
CLAS - $g_1(x,Q^2)$ for the deuteron

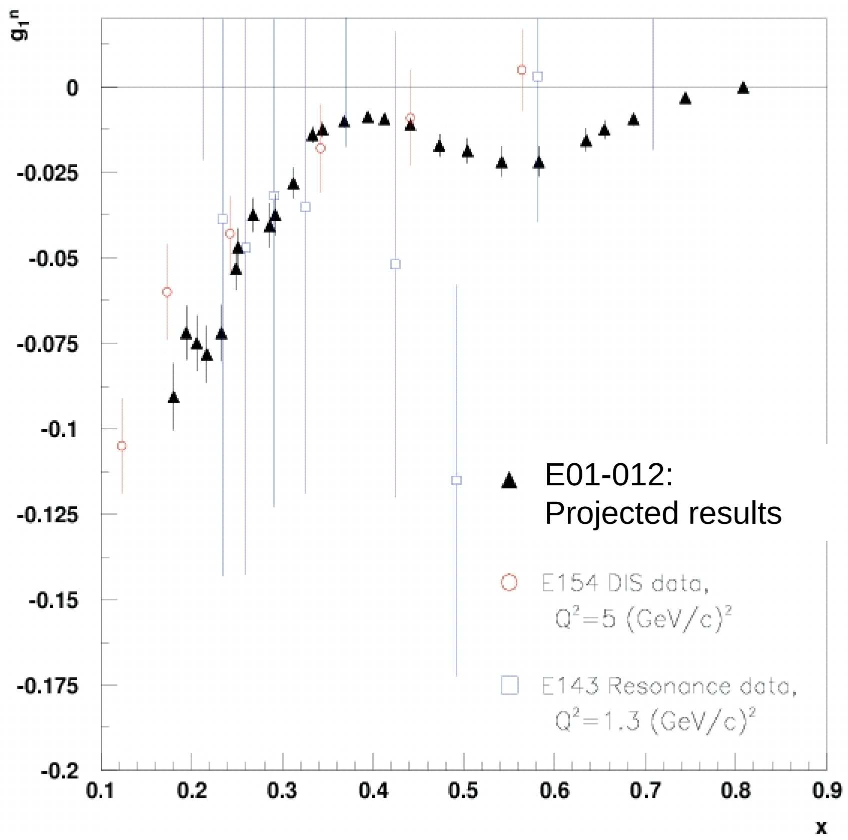


Hall A E01-012: Measurement of neutron (^3He) spin structure functions in the resonance region

- Ran in January and February, 2003.
- **Data analysis in progress**
- **Preliminary results expected this Spring.**

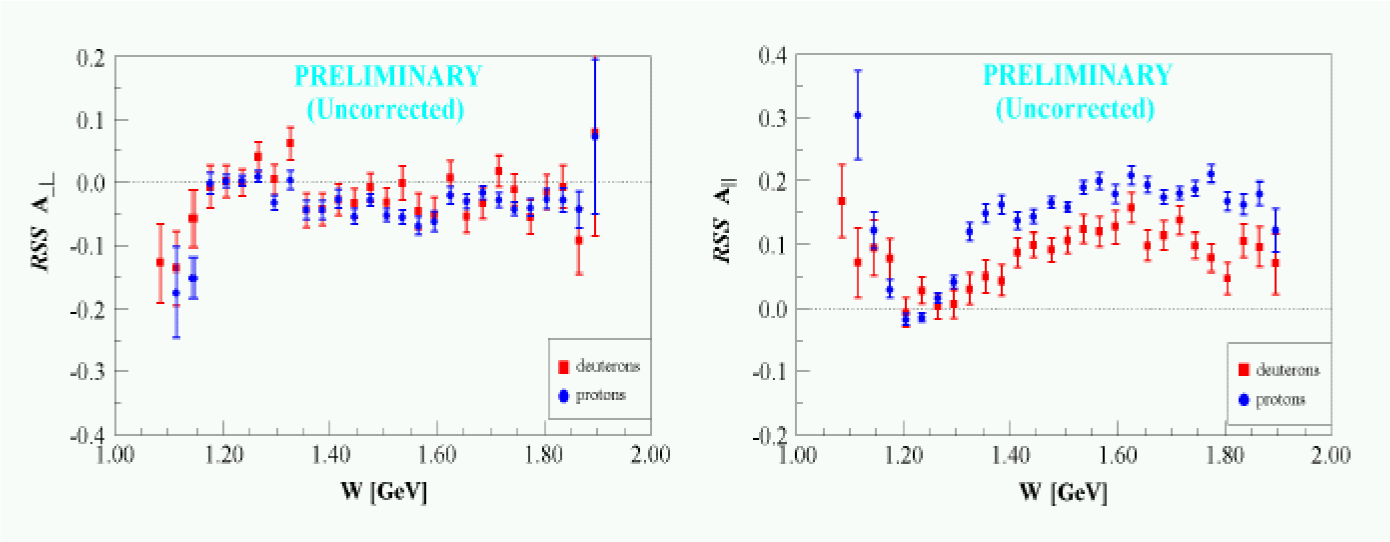
Projected results shown here (black triangles), compared to published resonance data (blue squares) and DIS data (red circles), are from one of the 4 kinematic settings of the experiment.





Hall C E01-006: Precision Measurement of the Nucleon Spin Structure Functions in the Region of the Nucleon Resonances

Measure proton and deuteron spin asymmetries $A_1(W,Q^2)$ and $A_2(W,Q^2)$ at Q^2 = 1.3 GeV^2



Equivalently, using F_2 and R, one can determine $g_1(x,Q^2)$ and $g_2(x,Q^2)$

Hall C E03-109: Spin Asymmetries on the Nucleon Experiment

Similar measurements (but using a non-magnetic detector) at Q^2 ~ 4 GeV^2

Close and Isgur Approach to Duality

Phys. Lett. B509, 81 (2001):

$$\sum q = \sum h$$

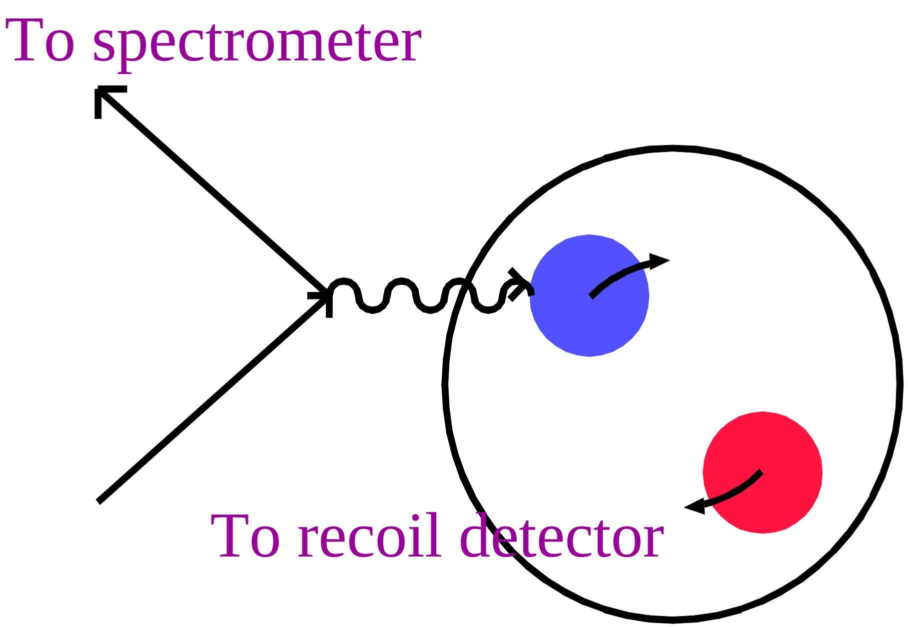
Relative photo/electroproduction strengths in SU(6)

How many states does it take to approximate closure?

Proton W~1.5

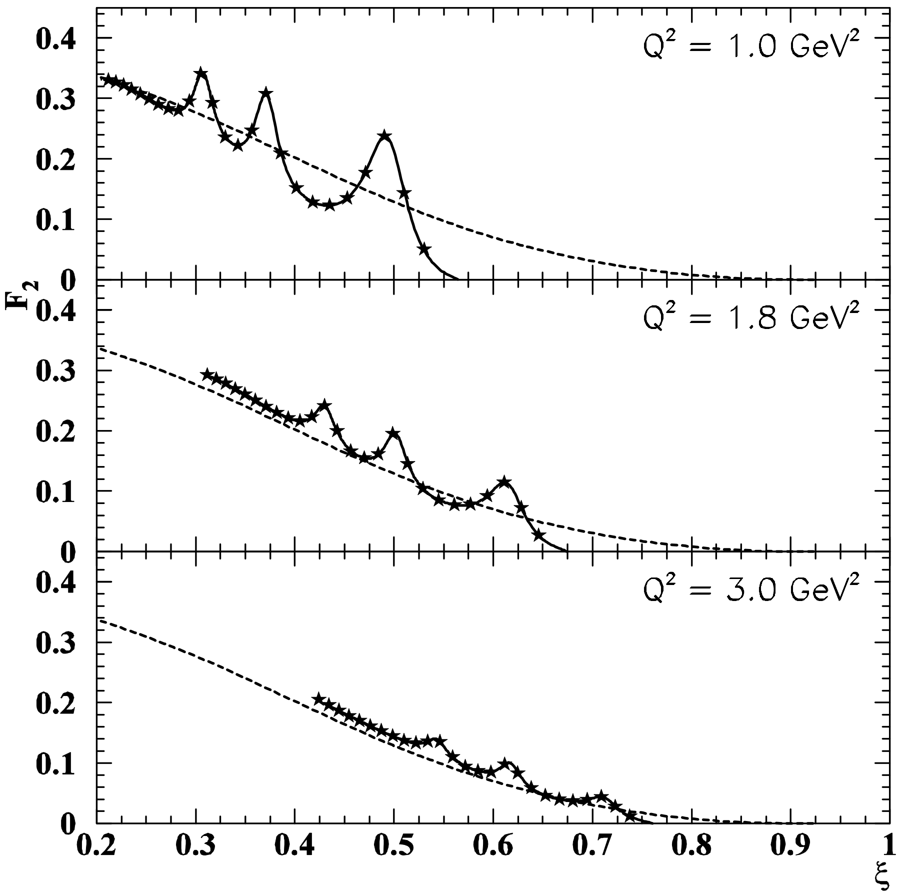
Neutron W~1.7

"The proton – neutron difference is the acid test for quark-hadron duality."



The BONUS experiment will measure neutron structure functions…….

Neutron Quark-Hadron Duality – Projected Results (CLAS/BONUS)



- 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

Systematics ~5%

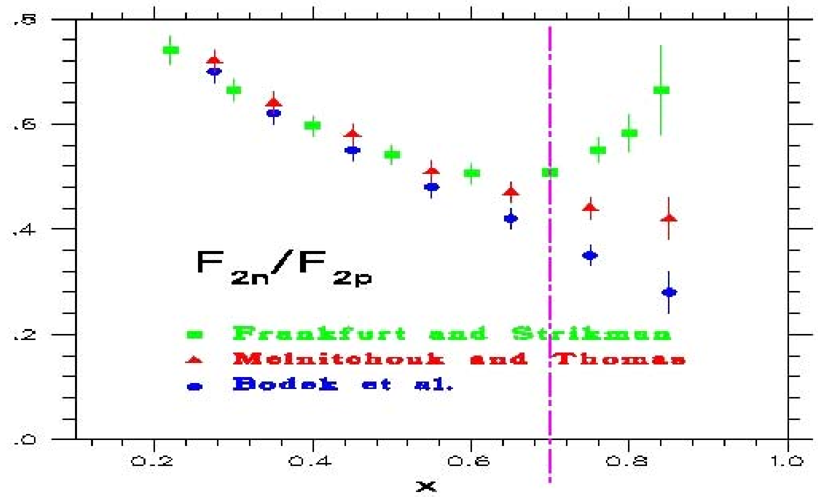
Needs R

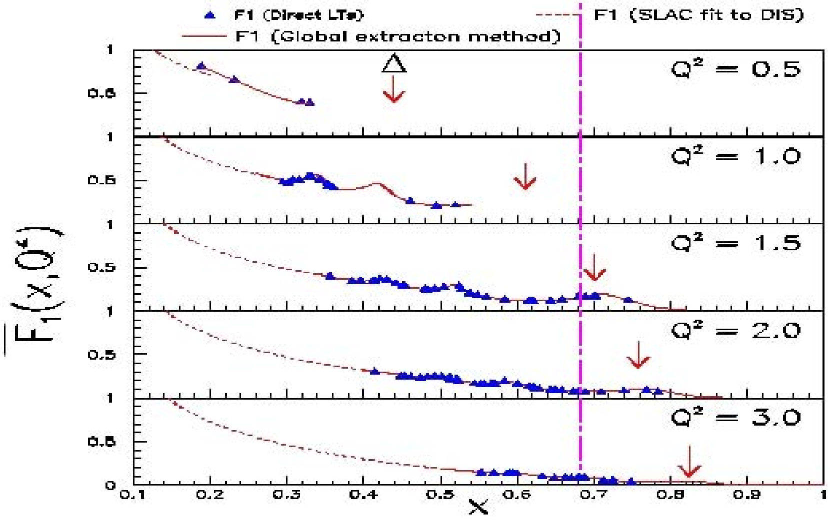
Resonance Structure Functions in Deuterium

Hall C experiment E02-109
will measure R = σ_L/σ_T in deuterium and separate the deuterium Structure Functions in the Resonance Region

Ë also allows for extraction of
low Q^2 neutron moments

Combine with existing proton data to extract valence moments which are calculated on the lattice at Q^2 = 4 GeV^2

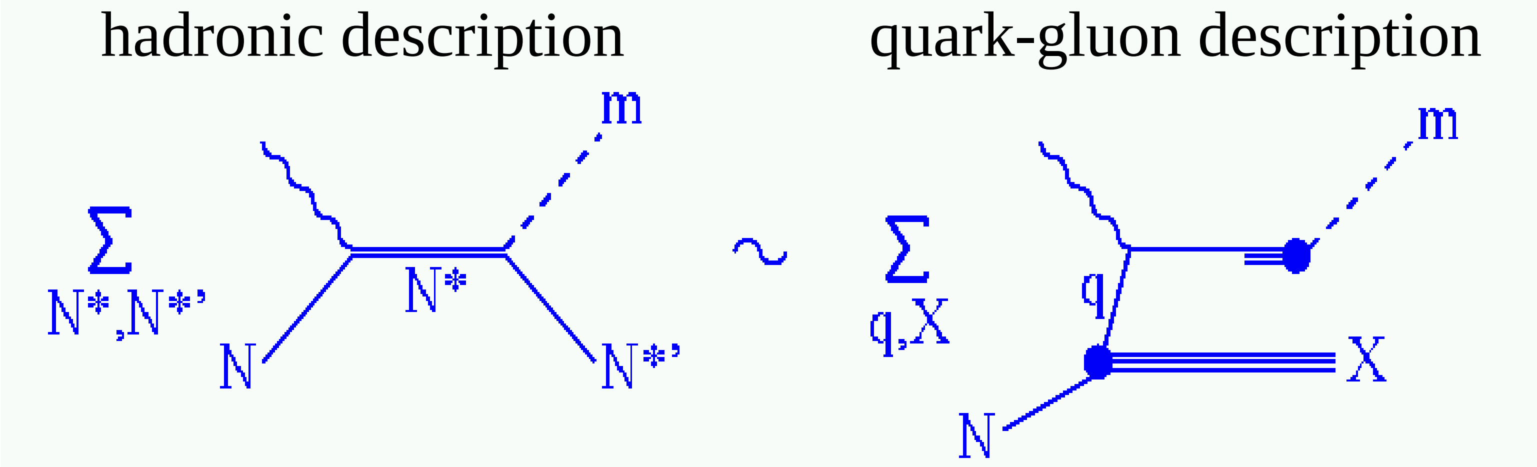




Duality in Meson Electroproduction

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

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



Requires non-trivial cancellations of decay angular distributions

If duality is not observed, factorization is questionable

$$d\sigma/dz \simeq \Sigma_i e_i^2 [q_i(x,Q^2) D_{q_i}^m(z,Q^2) + \bar{q}_i(x,Q^2) D_{\bar{q}_i}^m(z,Q^2)]$$

Hall C E00-108 : Duality in Meson Electroproduction

Quark-Hadron Duality in semi-inclusive processes predicted but never observed
Possibly related to low-energy factorization between quark scattering and fragmentation

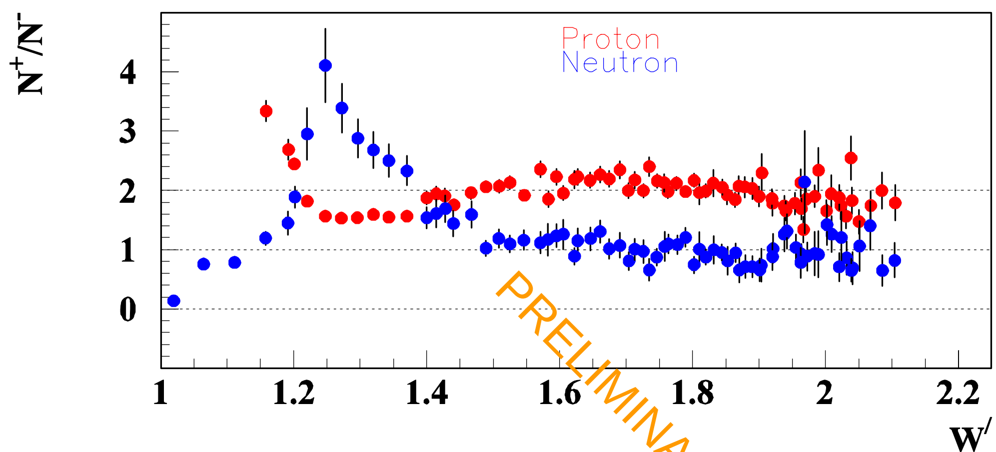
$$d\sigma/dz \cong \Sigma_i e_i^2 [q_i(x,Q^2) D_{q_i}^{m}(z,Q^2) + \bar{q}_i(x,Q^2) D_{\bar{q}_i}^{m}(z,Q^2)]$$

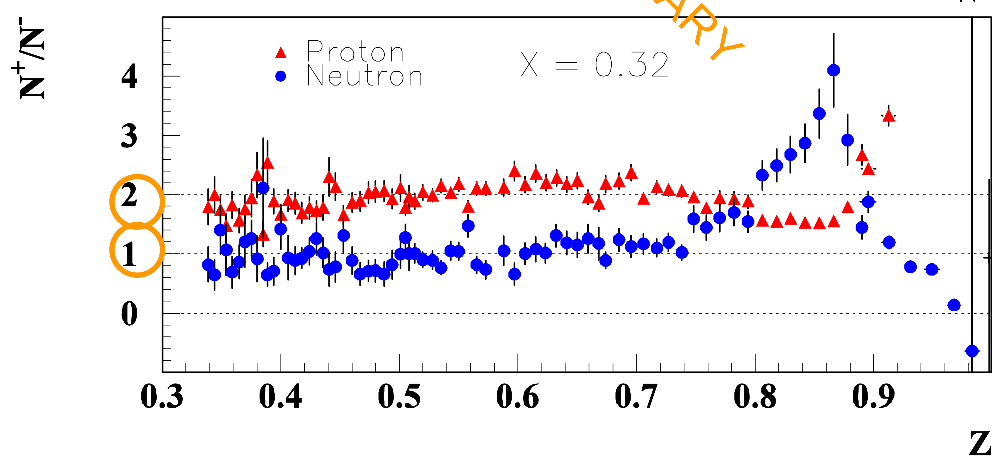
W' is invariant mass of final state in pion electroproduction
$[W'^2 \sim M^2 + Q^2(1/x - 1)(1-z)]$

D is the fragmentation function, z is the fraction of energy transfer carried by the meson

Data were taken for $^1H(e,e.\pi^+)$, $^1H(e,e'\pi^-)$, $^2H(e,e'\pi^+)$, $^2H(e,e'\pi^-)$ in August, 2003

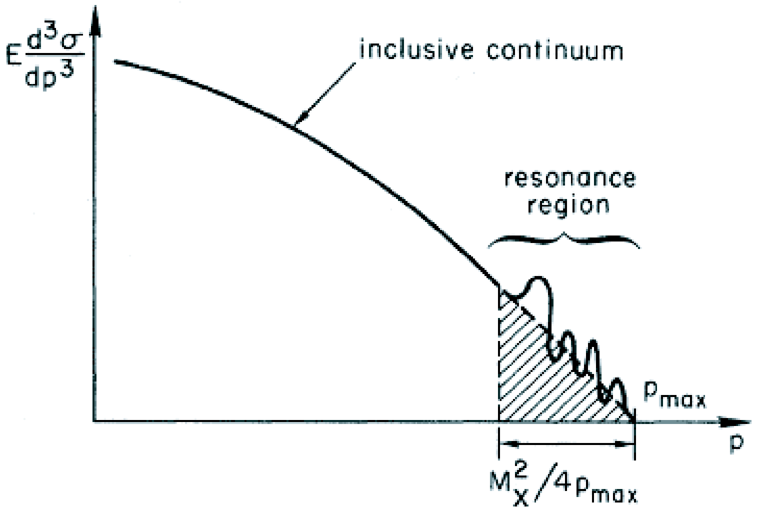
Preliminary results for the ratio of π^+ and π^- (N^+/N^-) yields look encouraging and show little z dependence for fixed *x* beyond the Δ region (z < 0.7). The preliminary ratio is also consistent with the naïve expectation from the quark model and previous data.





Duality in Exclusive Processes

Inclusive-Exclusive connection: Bjorken and Kogut impose "correspondence principle": demanding continuity of the dynamics from one region of kinematics to the other → relates exclusive cross sections at low energy to inclusive production at high energies



Momentum Spectrum of produced hadrons in an inclusive reaction $\gamma^*N \rightarrow MX$

Used to predict the behavior of real Compton Scattering off the proton at large Θ_{cm} and recently by Zhao and Close relating Quark-Hadron Duality to DVCS and to exclusive hard pion photoproduction

Could potentially be addressed by Hall A experiments E99-114 (RCS) and E94-104/E02-010 ($D(\gamma,\pi^{+/-})$) [both not in N* program]

Quark-Hadron Duality - Applications

- CTEQ currently planning to use duality for large x parton distribution modeling
- Neutrino community using duality to predict low energy (~1 GeV) regime
  - Implications for exact neutrino mass
  - Plans to extend JLab data required and to test duality with neutrino beams
- Duality provides extended access to large x regime
- Allows for direct comparison to QCD Moments
  - Lattice QCD Calculations now available for u-d (valence only) moments at $Q^2 = 4\ (GeV/c)^2$
  - Higher Twist not directly comparable with Lattice QCD
  - If Duality holds, comparison with Lattice QCD more robust

Summary

Wealth of data being produced to investigate why quark-hadron duality works in local regions and at surprisingly low energies: at the root of the quark-hadron transition

Proton	Measured F_2 and R up to Q^2 ~ 5 (also down to Q^2 = 0) Measure "g_1" with CLAS, and g_2 constraints in Hall C
Deuteron	Measured "F_2", and R approved up to Q^2 ~ 5 Measure "g_1" with CLAS, and g_2 constraints in Hall C
Neutron	"F_2" with BONUS approved up to Q^2 ~ 5
^{3}He	Measured "g_1" in Hall A + g_2 measurements
Nuclei	Measured "F_2" over large region of *x* (but not complete) Measured R at low (x,Q^2) only
Semi-Inclusive	Measured (10 out of 20 days) for $^{1,2}H(e,e'\pi^{+/-})$ at large z
Exclusive	Some measurements potentially related (RCS, $D(\gamma,\pi)$) DVCS test would be interesting

Hall C Research Program on N* and Meson Properties

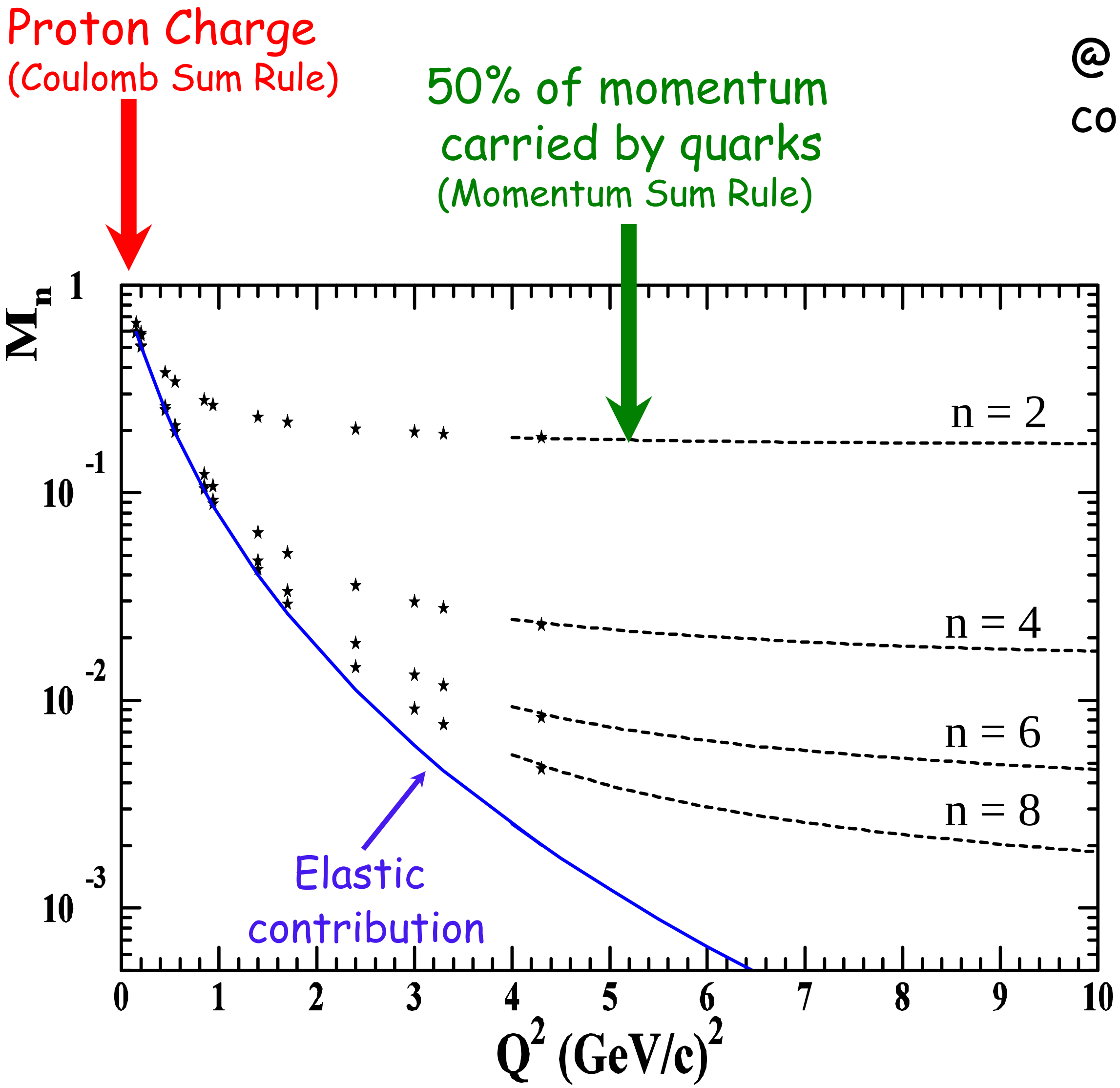
- 8 (+1) (Conditionally) Approved Experiments (25%)
- 7 of these have finalized data taking
- 1 (+1) Related Experiments, in "Sum Rules Topic"
- 92 (+ 40) PAC Days (17%)
- Mostly concentrating on F_2 and R (= σ_L/σ_T), g_1 and g_2, N-Δ and N-S_{11} Transition Form Factors at High Q^2
- "Outliers": Sub-threshold J/ψ Photoproduction

  Parity-Violating N-Δ

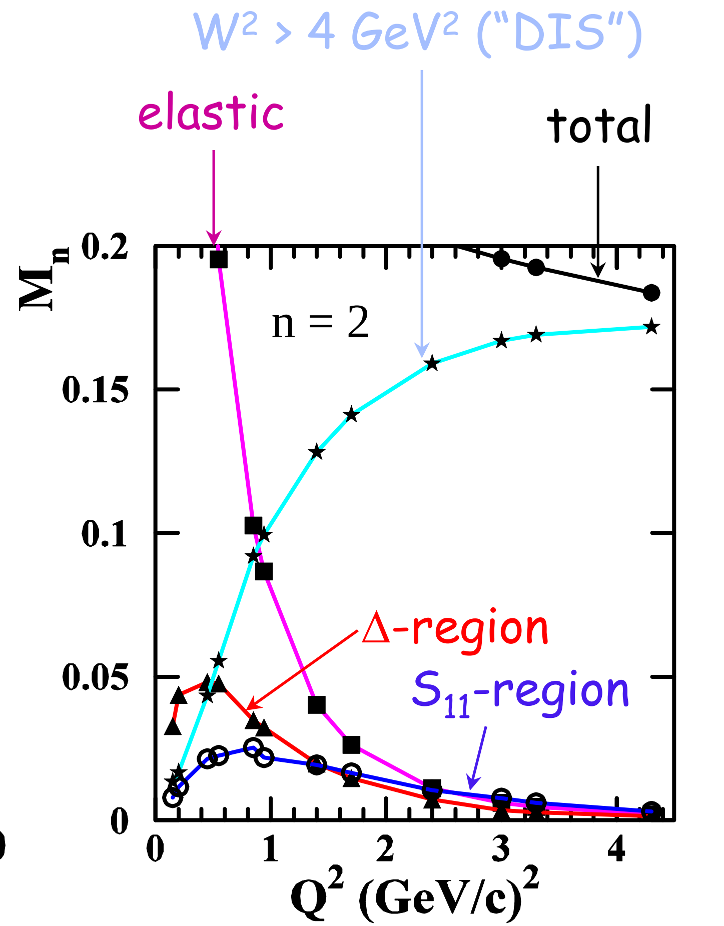
N-N* Experiments/Proposals

• The Δ(1232) Form Factor at High Momentum Transfer (1996 - PRL, PRD)	Stoler	10 days
• Measurement of $R = \sigma_L/\sigma_T$ in the Nucleon Resonance Region (1999 – draft PRL, PRC)	Keppel	9 days
3) Measurement of the Nuclear Dependence of $R = \sigma_L/\sigma_T$ at low Q^2 (2000 – analysis nearly final)	Bruell/Dunne/Keppel	16 days
4) F_2^N at Low Q^2 (2003)	Keppel/Niculescu	8 days
• Measurement of H and D Inclusive Resonance Cross Sections at Intermediate Q^2 for Parton-Hadron Duality Studies (2003)	Christy/Keppel	3 days
6) Baryon Resonance Electroproduction at High Momentum Transfer (2003)	Bosted/Frolov/Jones/ Koubarovski/Stoler	25 days
7) Precision Measurement of the Nucleon Spin Structure Functions in the Region of the Nucleon Resonances (2002)	Jones/Rondon	14 days
8) Sub-Threshold J/Ψ Photoproduction	Bosted/Dunne	7 days
• Measurement of the Parity-Violating Asymmetry in the N to Δ Region	Simicevic/Wells	(0 days)
10) Measurement of $R = \sigma_L/\sigma_T$ on Deuterium in the Nucleon Resonance Region	Christy/Keppel	13 days
11) Spin Asymmetries on the Nucleon Experiment	Choi/Meziani/Rondon	(27 days)

Moments of F_2^p @ Low Q^2



@ Q^2 = 2 $(GeV/c)^2$ 30% of M_2 comes from the resonance region



Combining the various pion electroproduction data, the ratios of favored to unfavored fragmentation functions, and down to up parton distribution functions, only show little z and *x* dependence, respectively (similarly for z < 0.7).