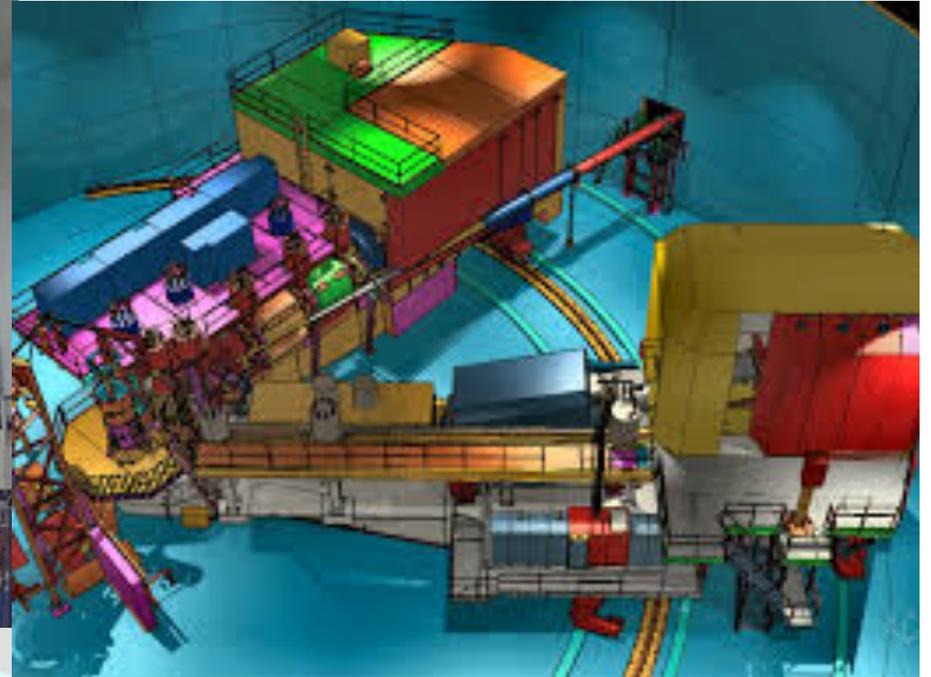
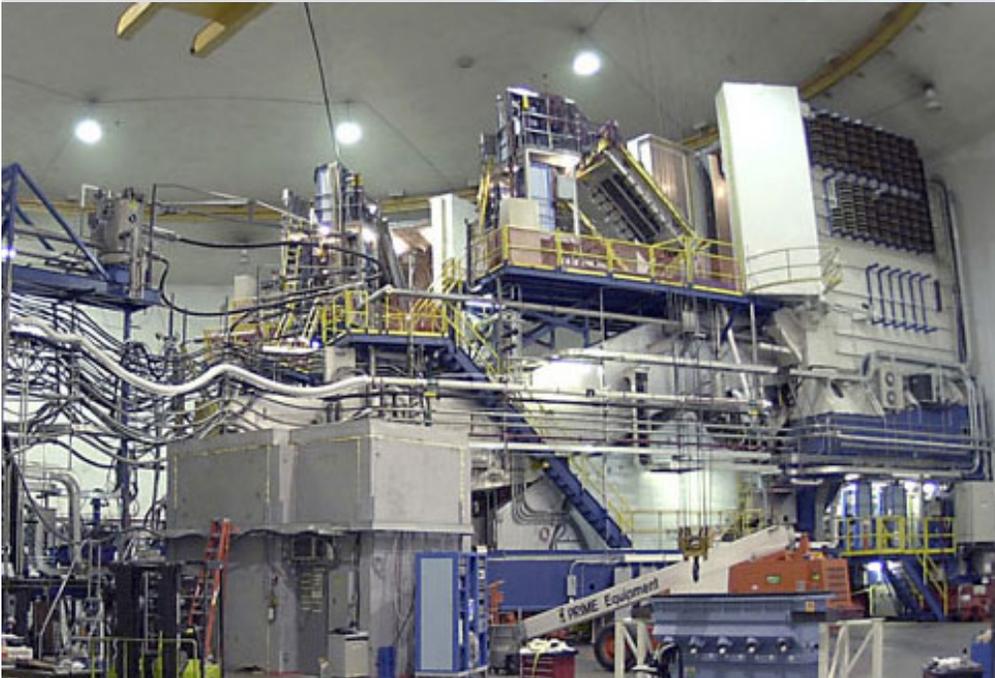


Quark-Hadron Duality and Nucleon Moments

Thia Keppel

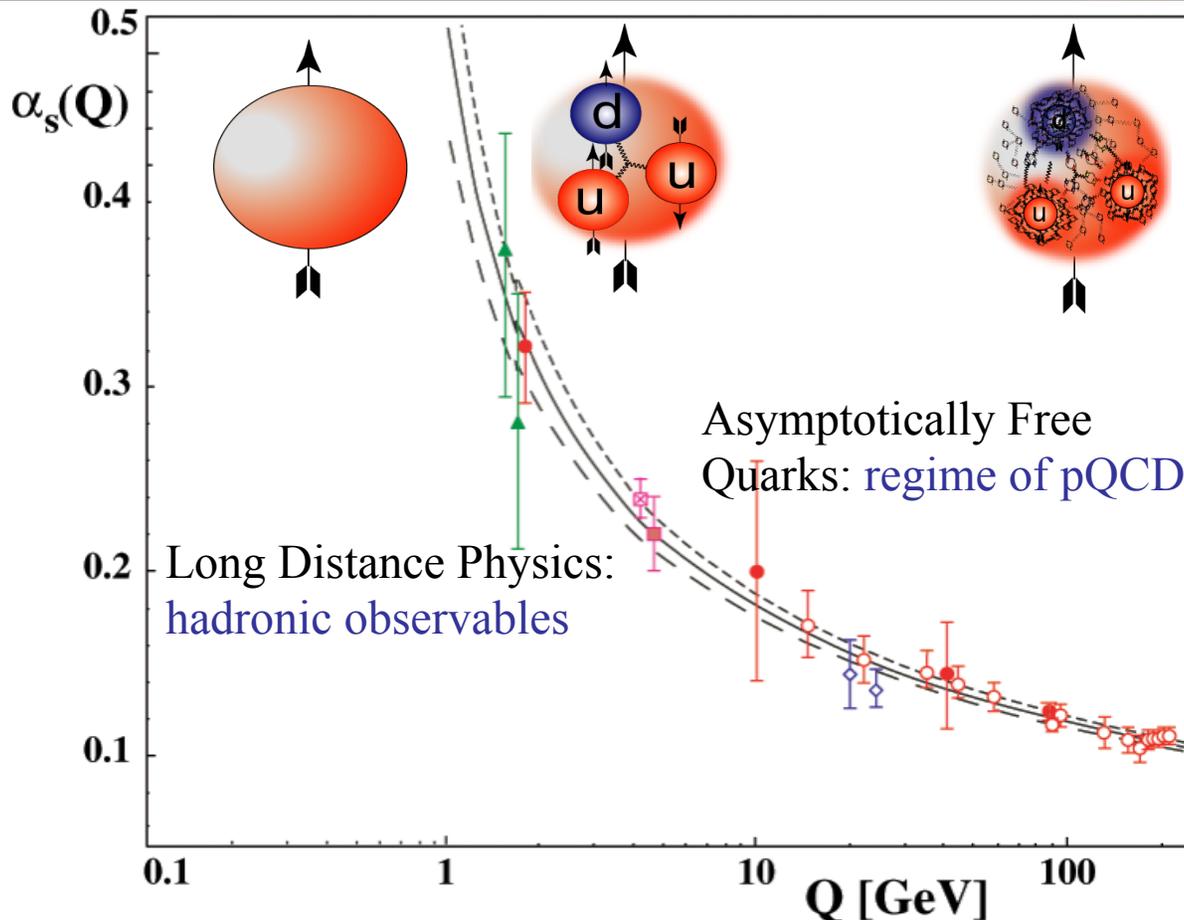
HiX 2014



Mostly an Experimental Overview/Update

- What is quark-hadron duality?
- Duality appears to be a fundamental property of nucleon structure
 - duality in electron scattering
 - lots of data, old and new
- Challenges to experimental quantification
- Understanding duality remains an intriguing challenge

What is duality?



pQCD is well defined and calculable in terms of *asymptotically free* quarks and gluons, yet...

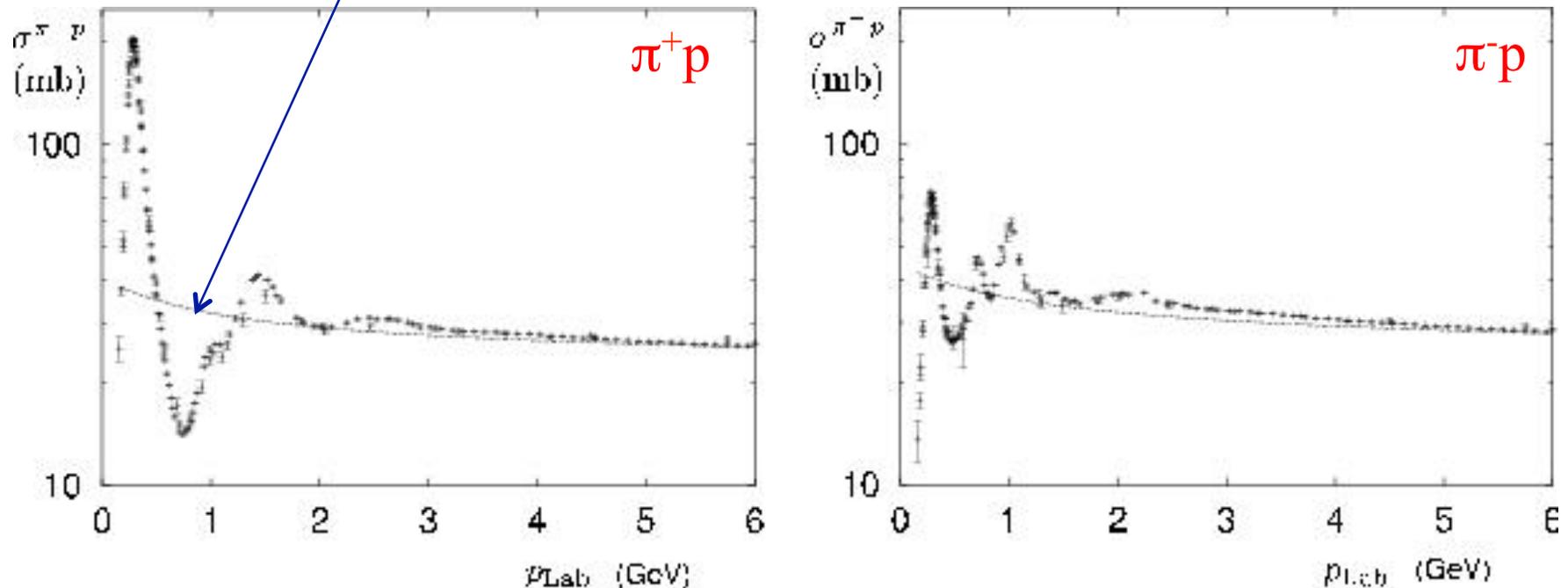
confinement ensures that hadrons are observed – pions, protons,...

Quark-hadron duality allows us, under certain circumstances, to bridge the gap between the theoretical predictions and experimentally observable quantities.

Some examples...

Quark-Hadron Duality – History

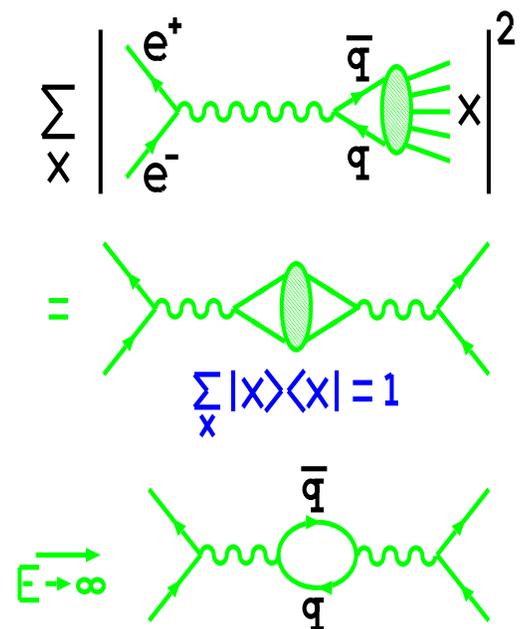
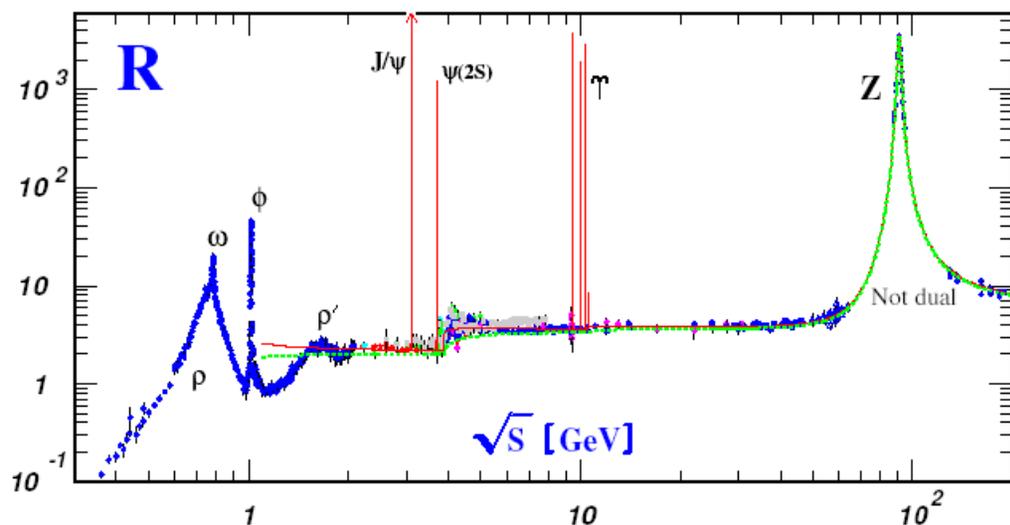
~1960's total pion-proton cross sections compared with Regge fit to higher energy data



- *low-energy hadronic cross sections on average described by the high-energy behavior.*
- *finite energy sum rules quantify a “duality” between s -channel resonances and t -channel Regge descriptions*

~1970's $e^+e^- \rightarrow$ hadrons

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



Poggio, Quinn and Weinberg suggest that inclusive hadronic cross sections at high energies, appropriately averaged over an energy range, have to (approximately) coincide with the cross sections one could calculate in quark-gluon perturbation theory.

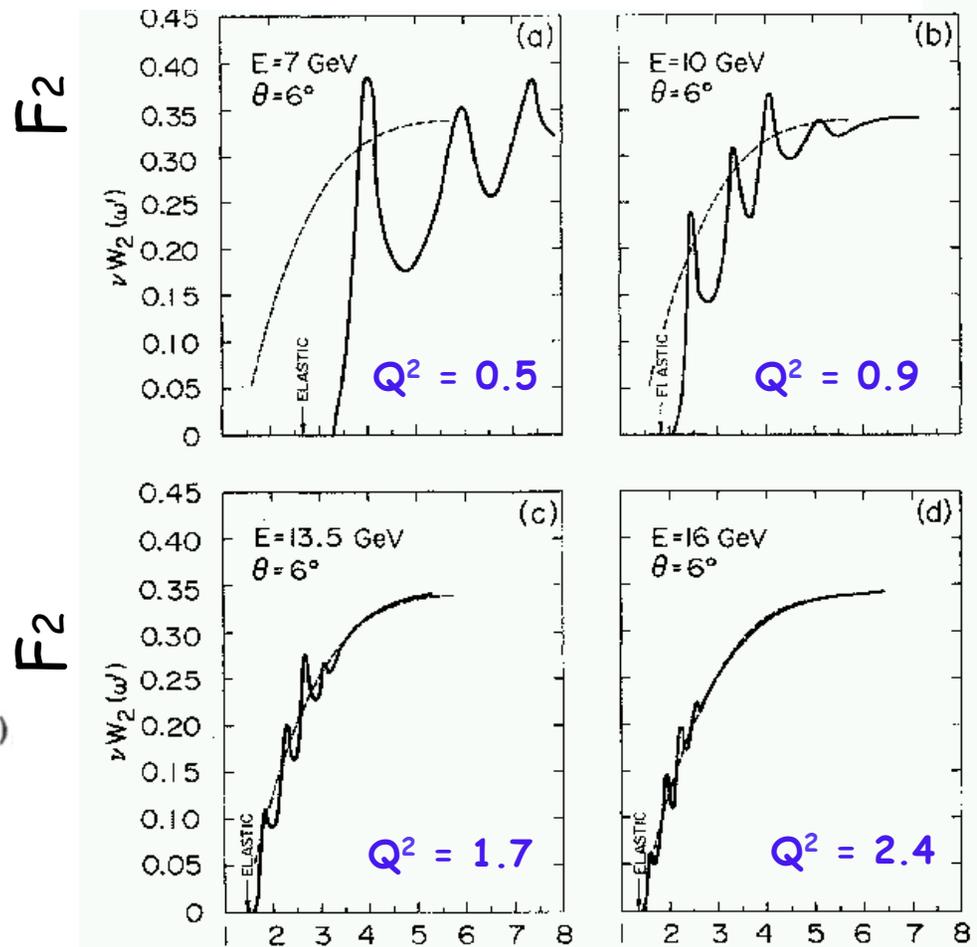
Also “Bloom-Gilman” Duality: Electron Scattering

photon mass in electroproduction and have scaling, we can directly measure a smooth curve which averages the resonances in the finite energy sum rule and

- 1970s: Bloom and Gilman at SLAC compared 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.
- Finite energy sum rule:

$$\frac{2M}{q^2} \int_0^m d\nu \nu W_2(\nu, q^2) = \int_1^{(2M\nu_m + m^2)/q^2} d\omega' \nu W_2(\omega')$$

- Resonances oscillate around curve *at all* Q^2



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

Quark-Hadron Duality

At high enough energy:

Hadronic Cross Sections
averaged over appropriate energy
range

Perturbative
Quark-Gluon Theory

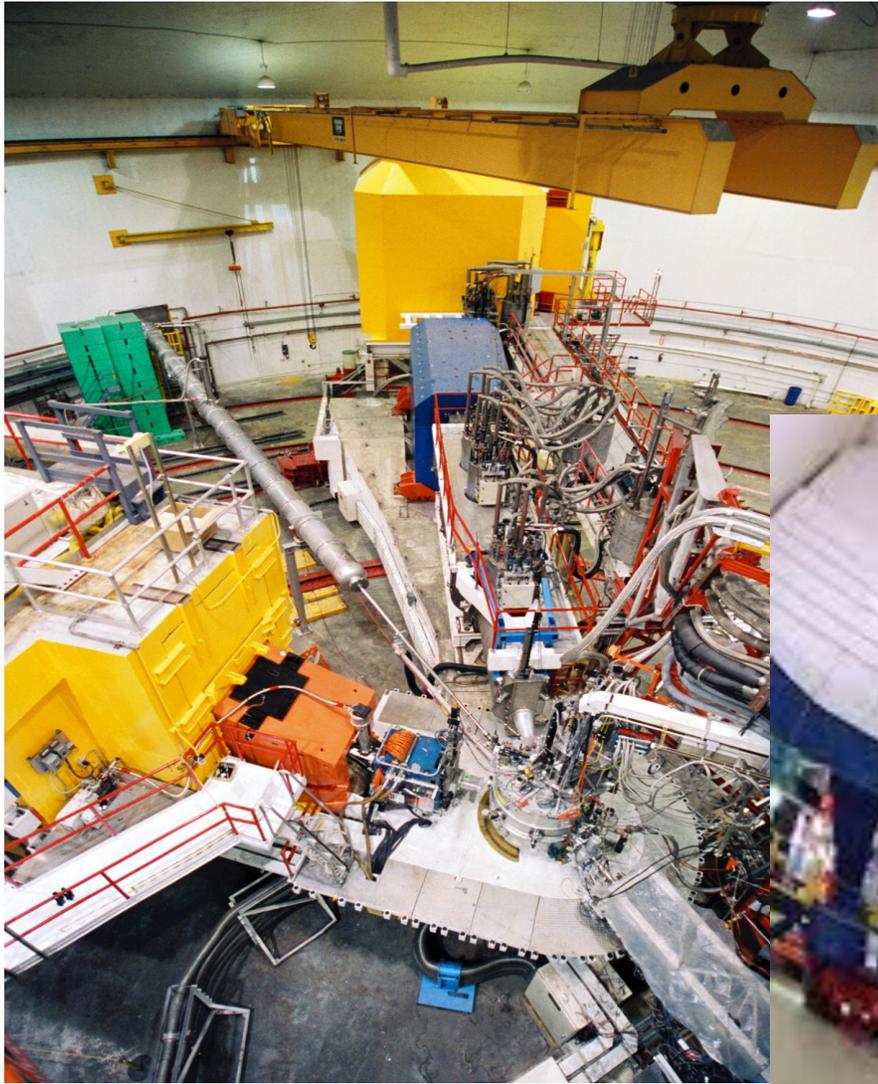
$$\Sigma_{\text{hadrons}} = \Sigma_{\text{quarks+gluons}}$$

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

But.... what about limited, local energy ranges?

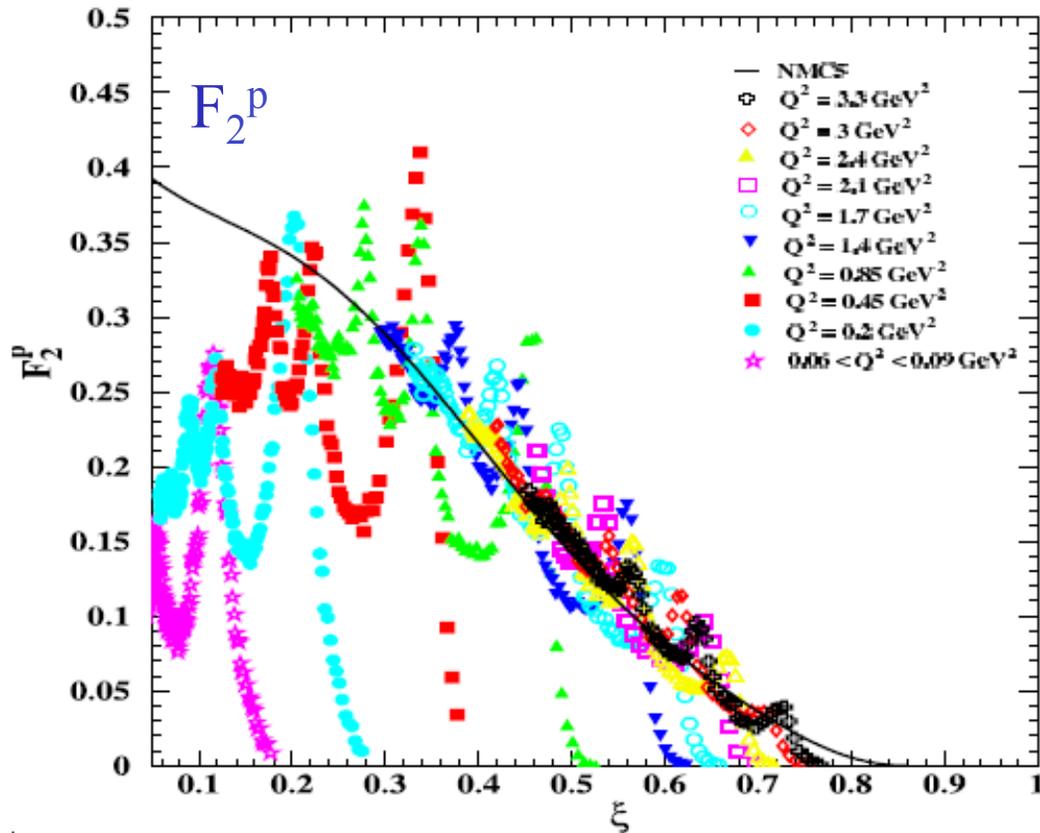
How accurate is duality? Can violations be predicted?

Multiple Experiments from Jefferson Lab in 6 GeV Era



Duality Re-observed

I. Niculescu, et al., PRL 85 (2000), 1186



One of the first Jefferson Lab measurements –

Duality clearly observed, but...

What to use for curve(s)?

What to use for variable?

What's the right interval to use for the integration?

How to test precisely?

Duality observed for:

✓ F_2^p

*If it works for F_2^p , what about F_1 ,
 F_L separately?*

F_2^d ?

F_2^n ?

F_2^A ?

$2xF_1$ from Hall C

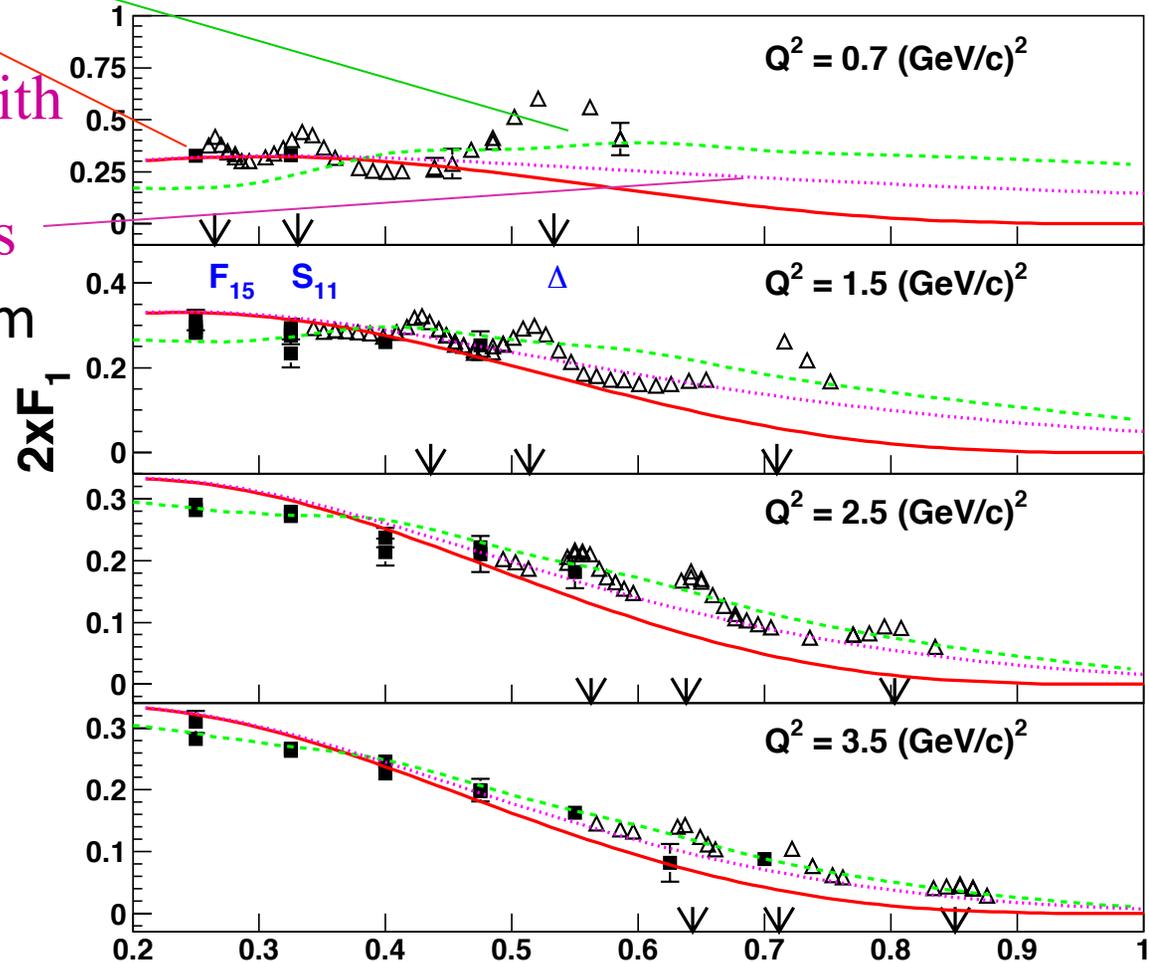
Alekhin NNLO

MRST NNLO

MRST NNLO with
Barbieri Target
Mass Corrections

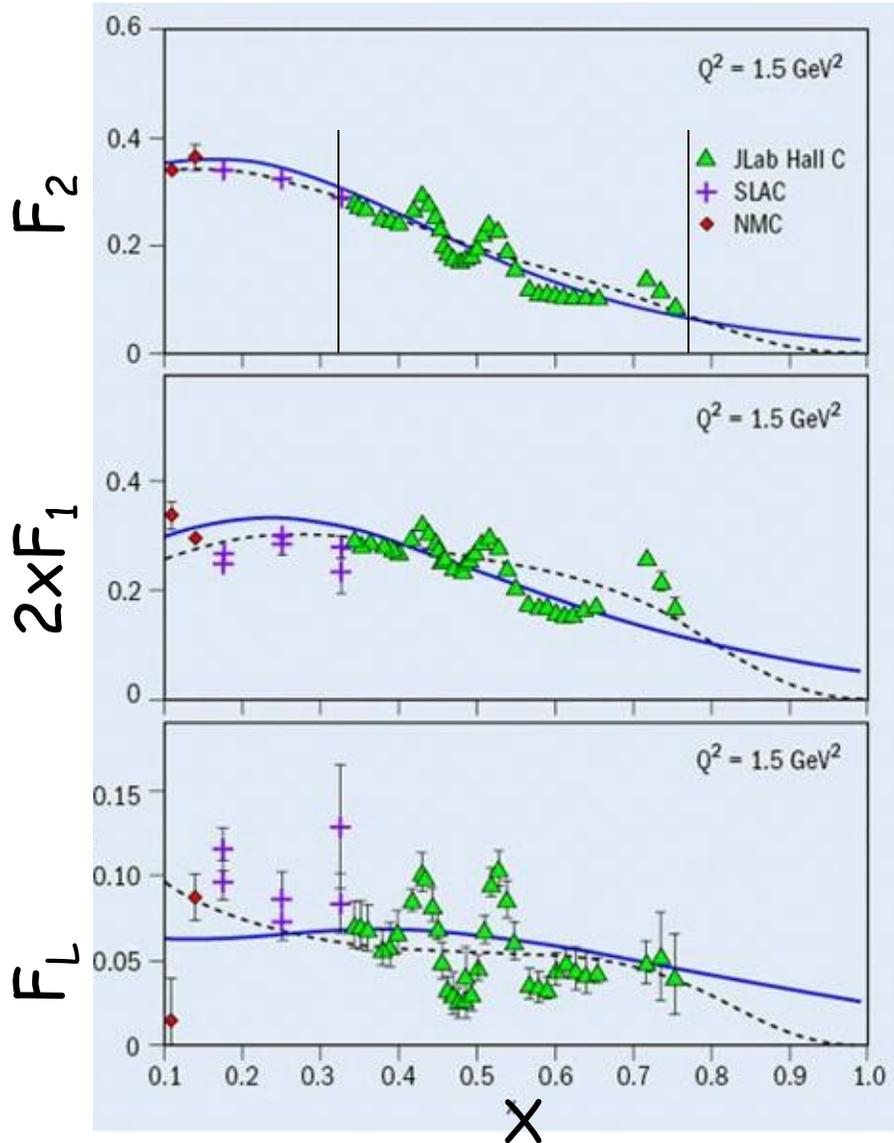
- Smooth transition from DIS (solid squares) to resonance region
- Resonances oscillate about perturbative curves
- True for a range of Q^2
- Target mass corrections large and important

Arrows indicate prominent resonance regions.



X Y. Liang et al., E94-110

Separated Proton Structure Functions



- Duality observed for all spin-averaged proton structure functions
- Compare now with DIS data (R1998, F2ALLM) or PDF fits
- Use Bjorken x instead of Bloom-Gilman ω'
 - Causes fit extrapolation
- JLab E94-110 results: “Quark-Hadron Duality” works quantitatively to better than 10% down to surprisingly low $Q^2 \sim 1 \text{ GeV}^2$
 - What is the right interval?

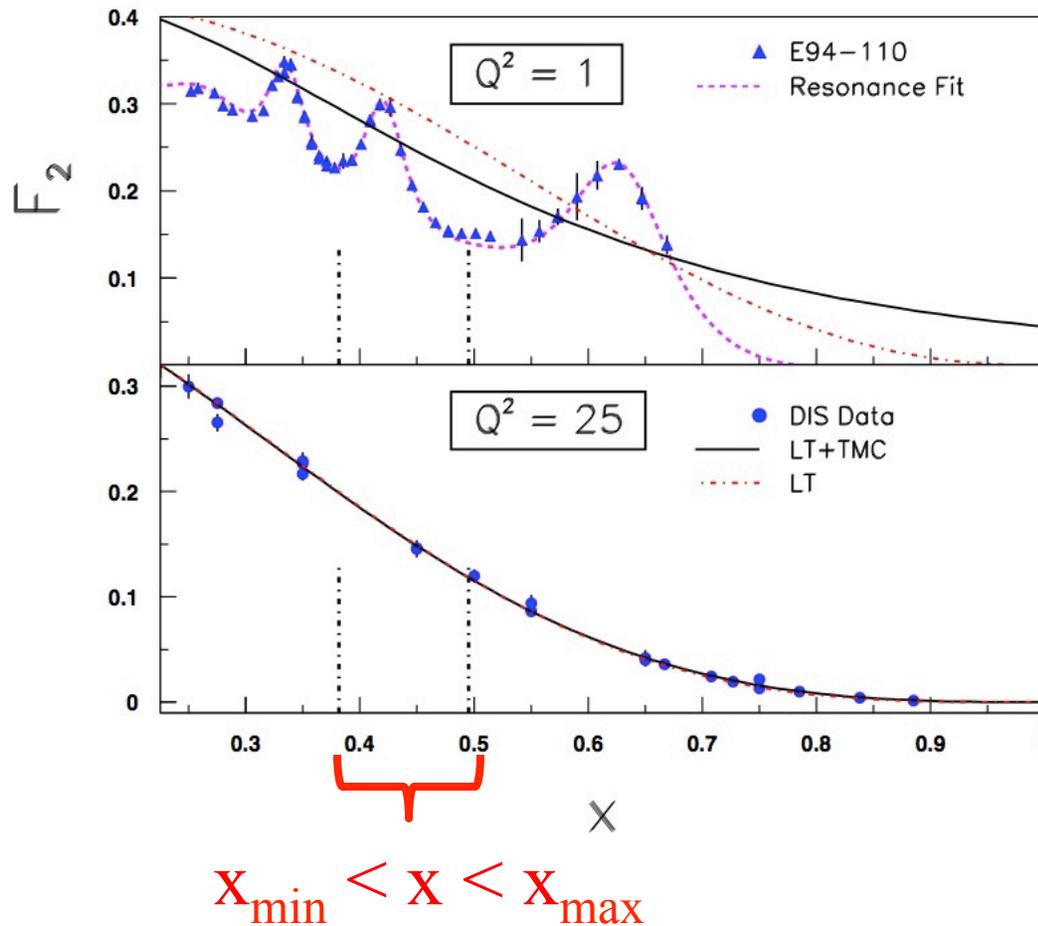
(CERN Courier, December 2004)

Duality observed for...

- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p

Towards Better Quantification: Truncated Moments

$$\mathcal{M}_n(x_{\min}, x_{\max}, Q^2) = \int_{x_{\min}}^{x_{\max}} dx x^{n-1} q(x, Q^2)$$



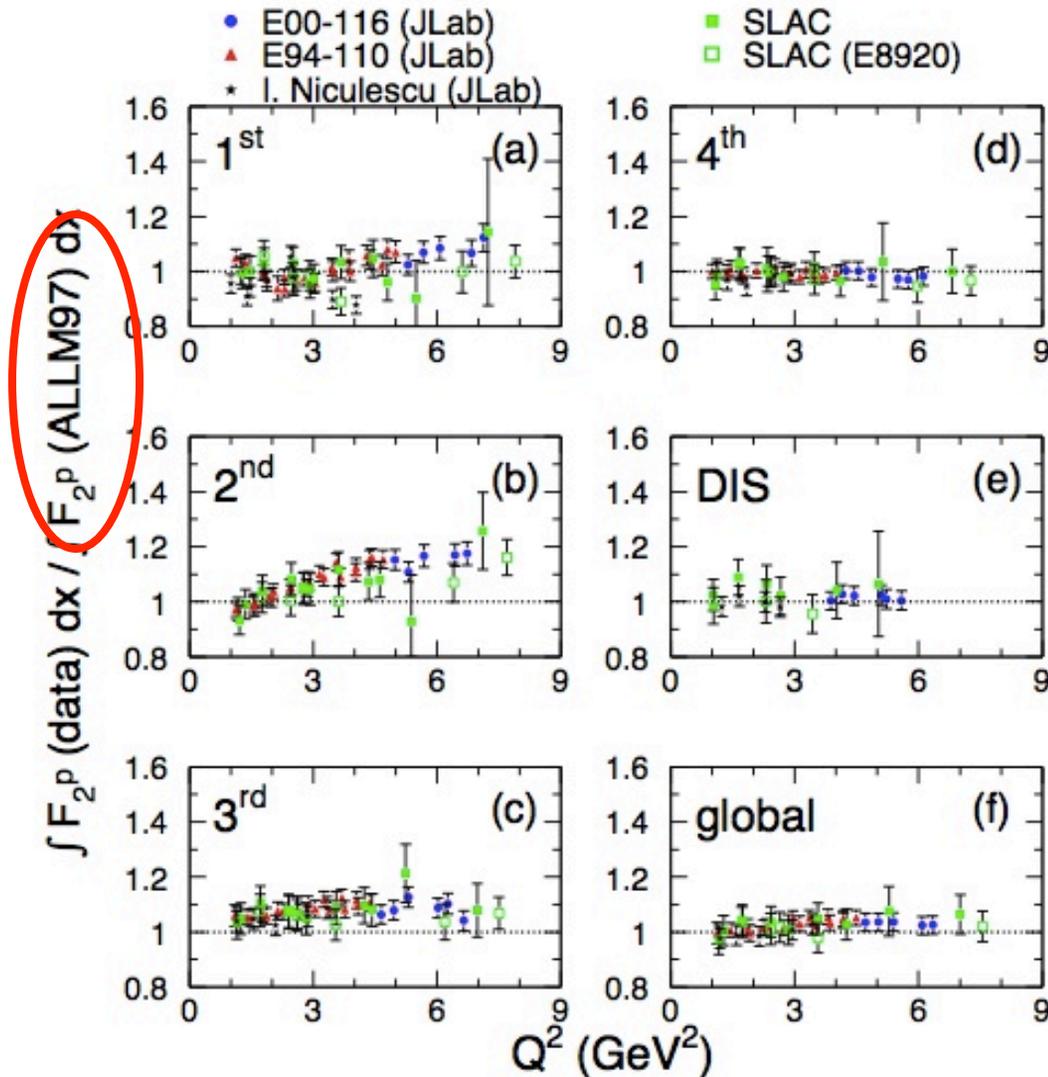
Can choose averaging region, defines range in x

Obey same Q^2 evolution as leading twist PDFs

Facilitates description of resonance region/duality in QCD

A. Psaker, W. Melnitchouk, M.E. Christy, CK, Phys. Rev. C78 (2008) 025206

Truncated Moments, More Data, and Precision Testing



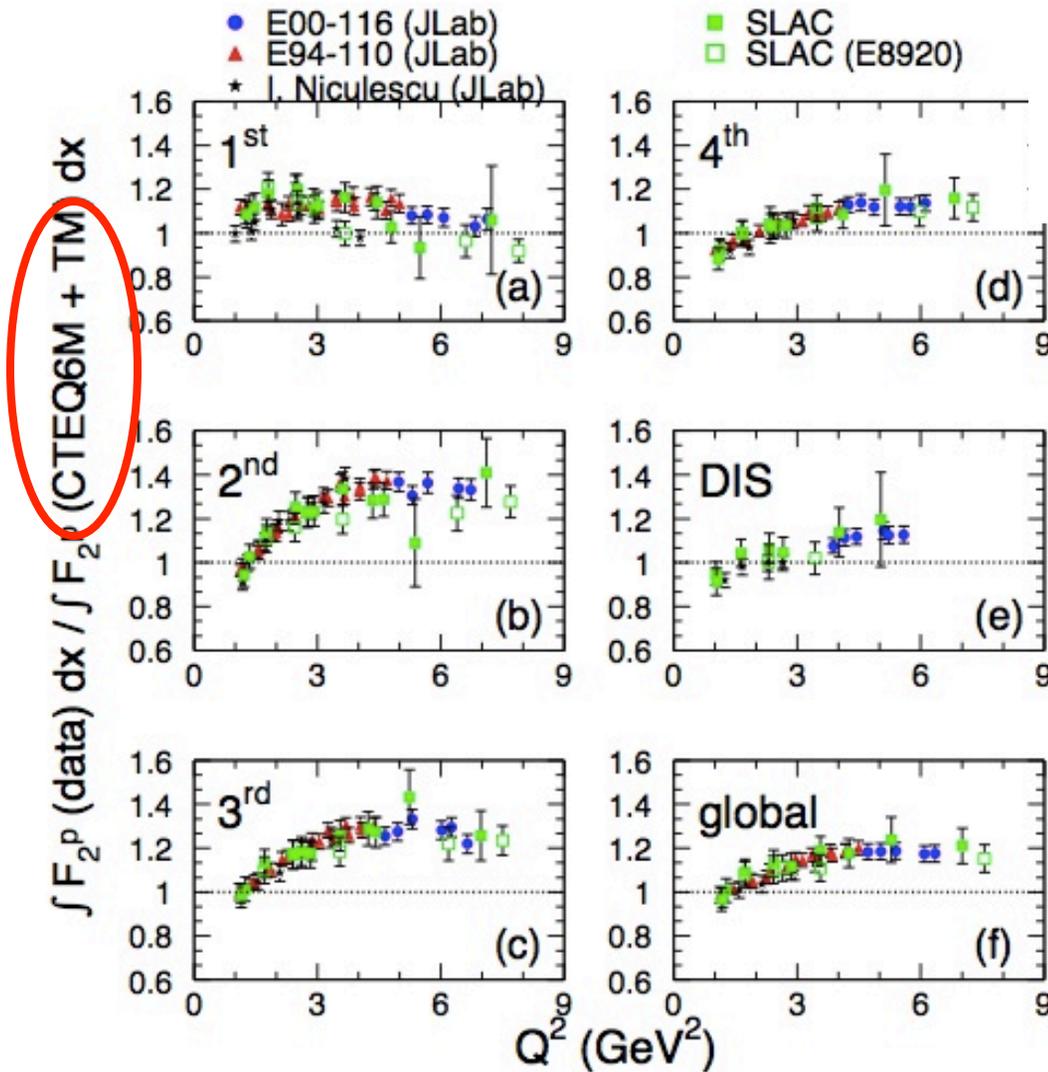
1. first region (1st) → $W^2 \in [1.3, 1.9] \text{ GeV}^2$
2. second region (2nd) → $W^2 \in [1.9, 2.5] \text{ GeV}^2$
3. third region (3rd) → $W^2 \in [2.5, 3.1] \text{ GeV}^2$
4. fourth region (4th) → $W^2 \in [3.1, 3.9] \text{ GeV}^2$
5. DIS region (DIS) → $W^2 \in [3.9, 4.5] \text{ GeV}^2$

$$x = \frac{Q^2}{W^2 + Q^2 - M^2}$$

$$I = \frac{\int_{x_{\min}}^{x_{\max}} F_2^{\text{data}}(x, Q^2) dx}{\int_{x_{\min}}^{x_{\max}} F_2^{\text{param.}}(x, Q^2) dx}$$

S. Malace, et al., *Phys.Rev. C80*
(2009) 035207

But..... Agreement not as good with F_2 from CTEQ global fit....



$$I = \frac{\int_{x_{min}}^{x_{max}} F_2^{data}(x, Q^2) dx}{\int_{x_{min}}^{x_{max}} F_2^{param.}(x, Q^2) dx}$$

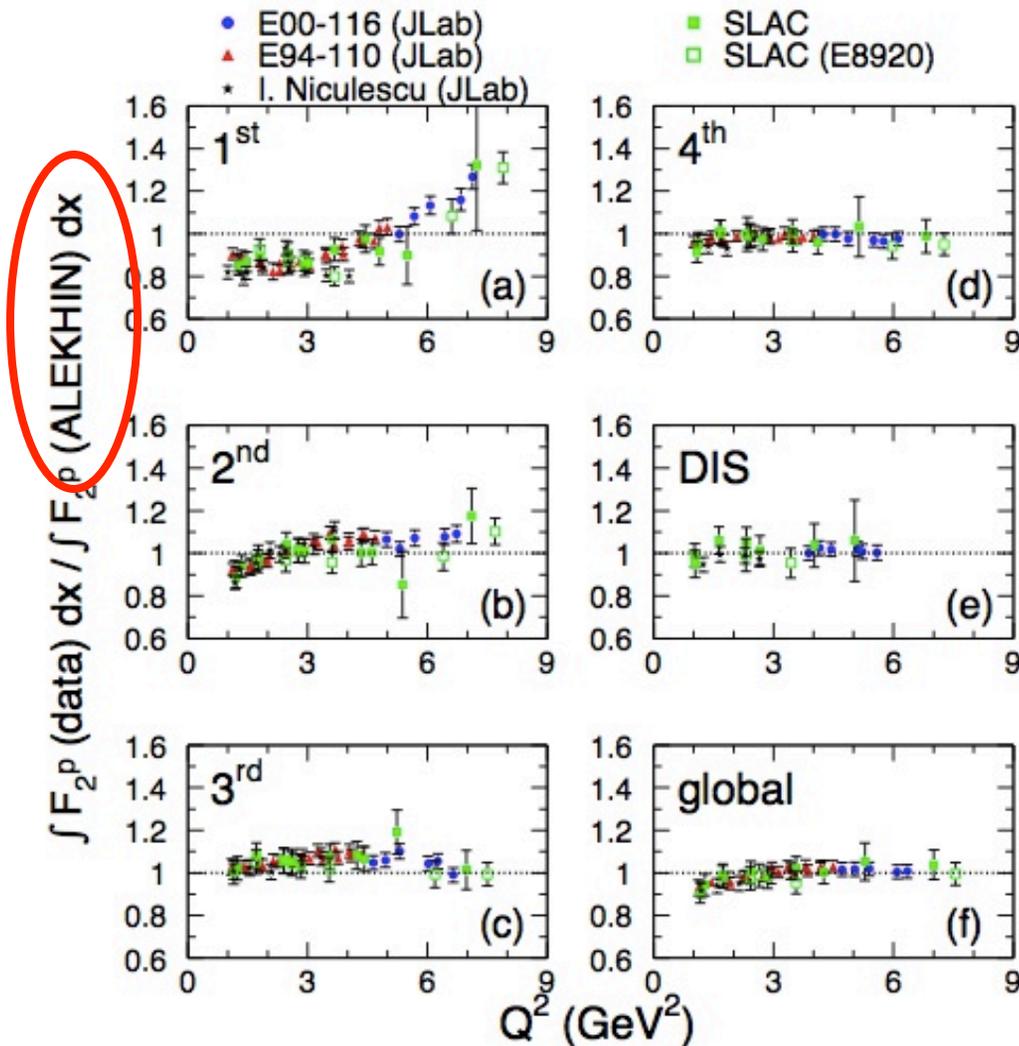
Only changed scaling curve choice

Integral ratio flattens in Q^2

- Q^2 behavior of scaling curve should be known
- Recall resonances “sliding” on DIS curve
- Seems to exhibit an onset at $Q^2 \sim 3 \text{ GeV}^2$

S. Malace, et al., *Phys.Rev. C80* (2009) 035207

....Or, better with Alekhin....



Again, changed only scaling curve choice

PDF curves have large errors at large x , extrapolating to unconstrained region

Alekhin curve has higher twist

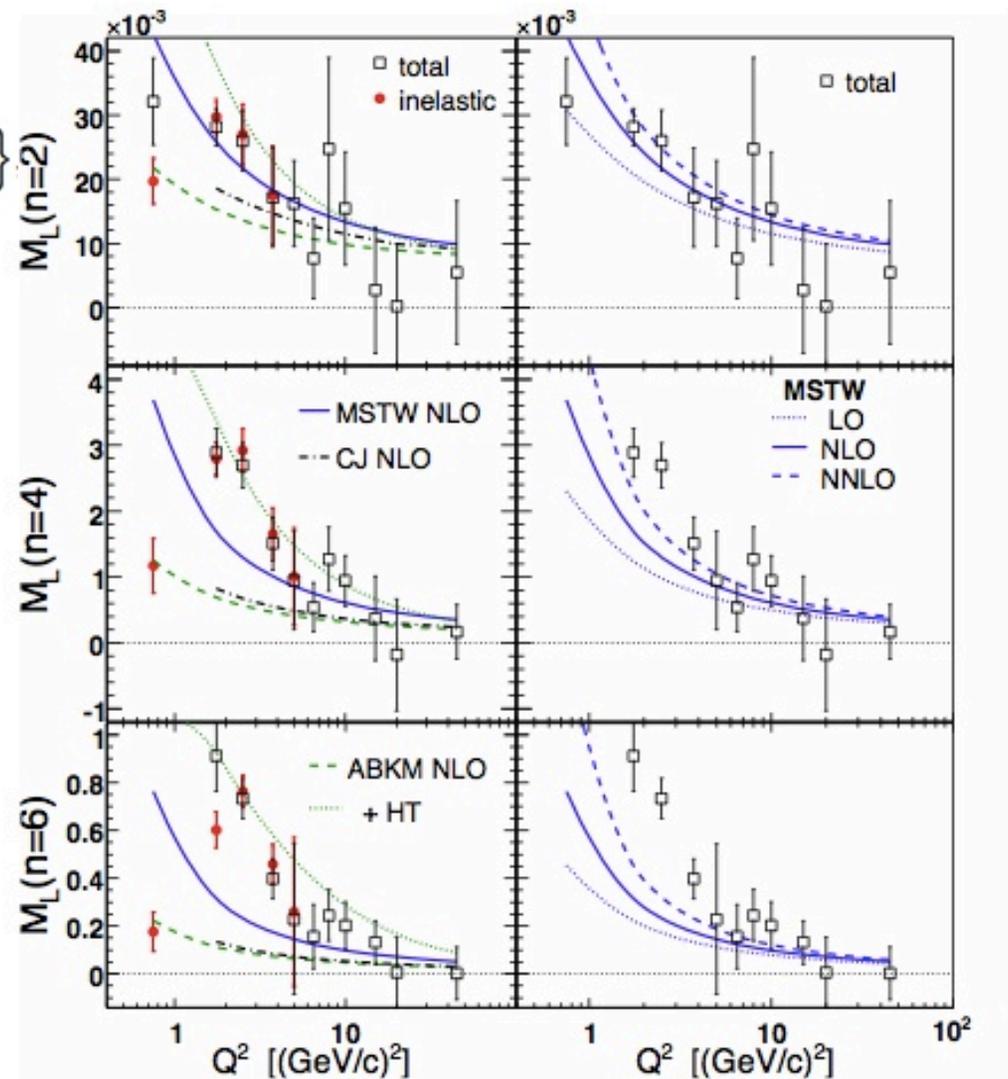
Works very well other than 1st region (dominated by single Delta resonance)

Scaling curve variations and uncertainties are now the limiting factor in precision duality testing

Moments of the F_L Structure Function

$$M_L^{(n)}(Q^2) = \int_0^1 dx \frac{\xi^{n+1}}{x^3} \left\{ F_L(x, Q^2) + 2(\rho^2 - 1) \frac{(n+1)/(1+\rho) - (n+2)}{(n+2)(n+3)} F_2(x, Q^2) \right\}$$

- Nachtmann moments to take target mass corrections into account
- Higher moments have higher x weighting (resonance region increasingly important)
- Elastic required at low Q^2
- NLO analyses differ
- NNLO increases agreement
- HT better at largest x



P. Monaghan, A. Accardi, M. E. Christy, CK, L. Zhu, Phys.Rev.Lett. 110 (2013) 15, 1520

Duality observed for...

- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p

But, quantification can be a challenge!

How local?

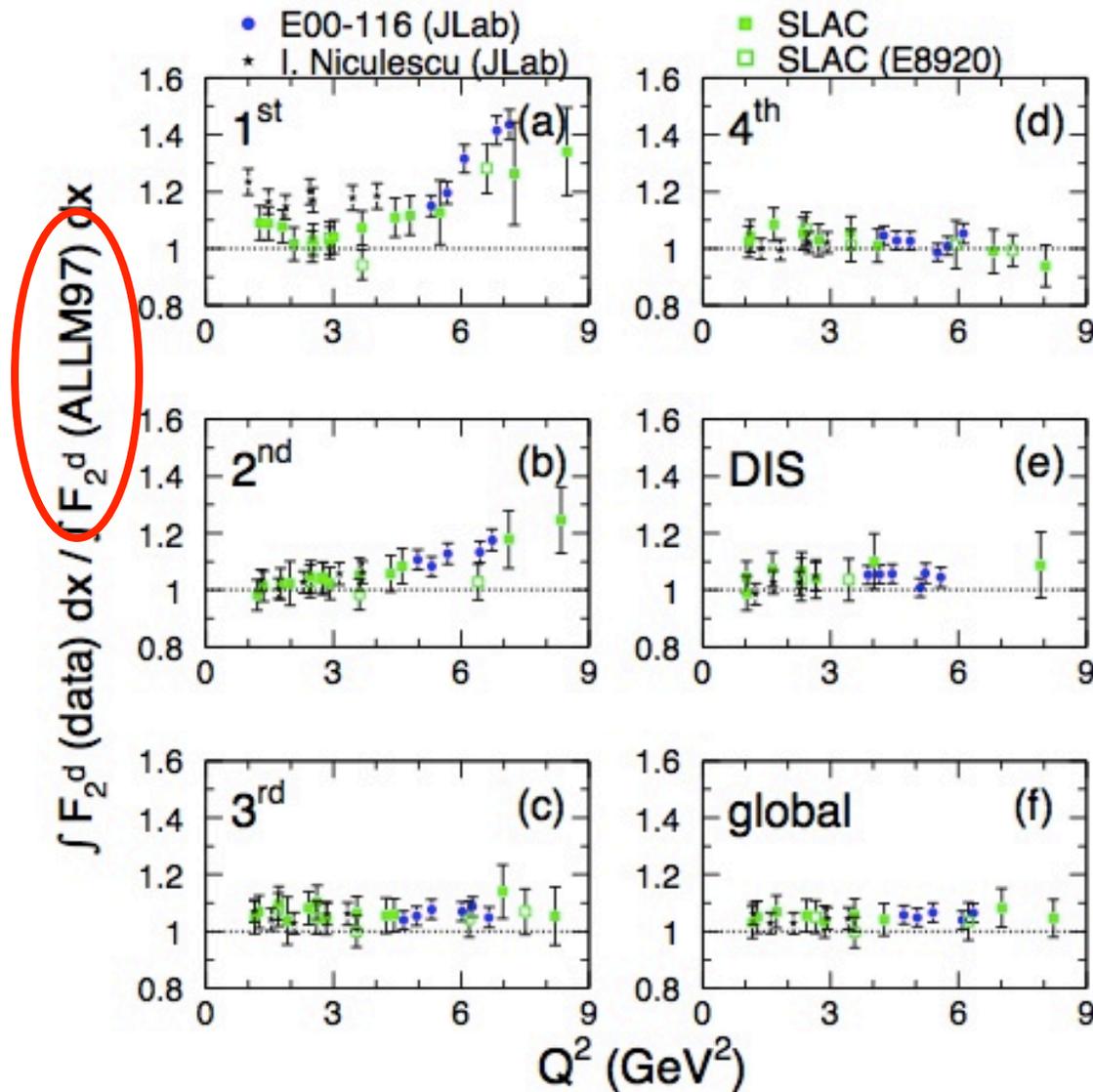
- Delta region often an issue
- Elastic needed in Low Q^2 moments

What is the scaling curve?

- Existing curves differ
- Uncertainty at large x

Let's boldly go
beyond the proton
anyway....

Moving on.... Deuterium data



$$I = \frac{\int_{x_{min}}^{x_{max}} F_2^{data}(x, Q^2) dx}{\int_{x_{min}}^{x_{max}} F_2^{param.}(x, Q^2) dx}$$

Reasonable agreement,
duality seems to hold

Lowest mass Delta
resonance worst

Single resonance in
interval

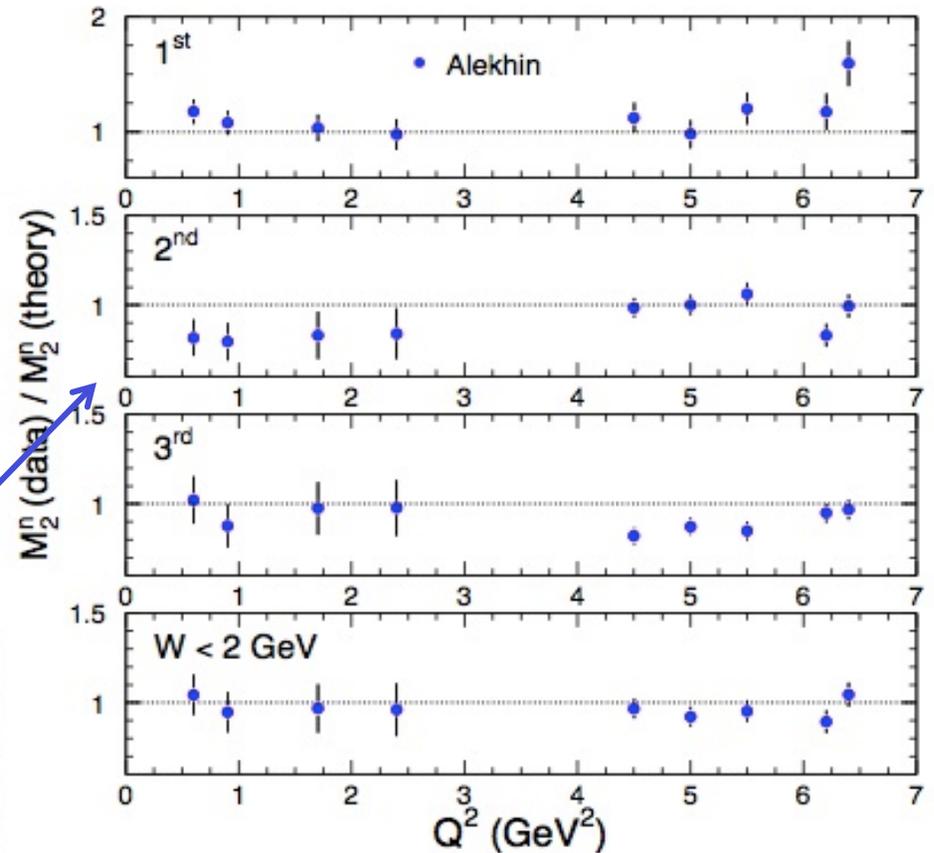
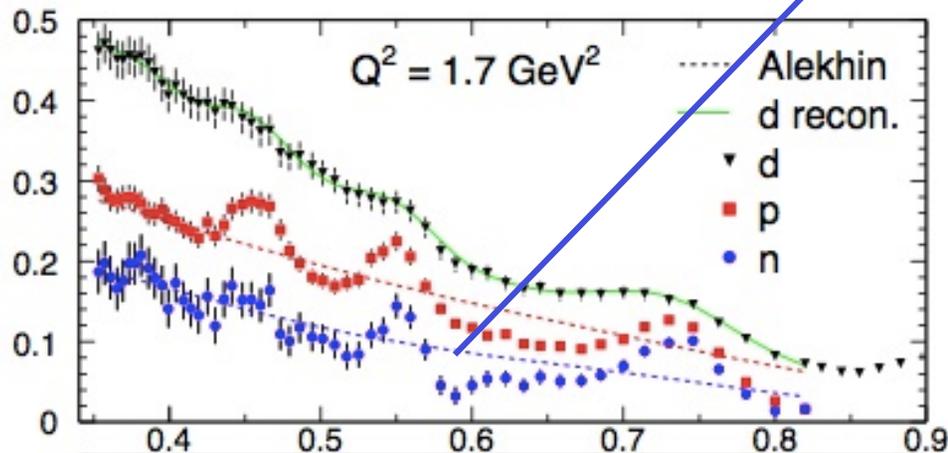
Neutron Duality using Deuterium Data

S.P. Malace, Y. Kahn, W. Melnitchouk, CK,
Phys.Rev.Lett. 104 (2010) 102001

State-of-the-art nuclear
corrections to extract n from d

F_2^n in resonance region,
compare to Alekhin + HT as
“theory”

First observation of neutron
duality

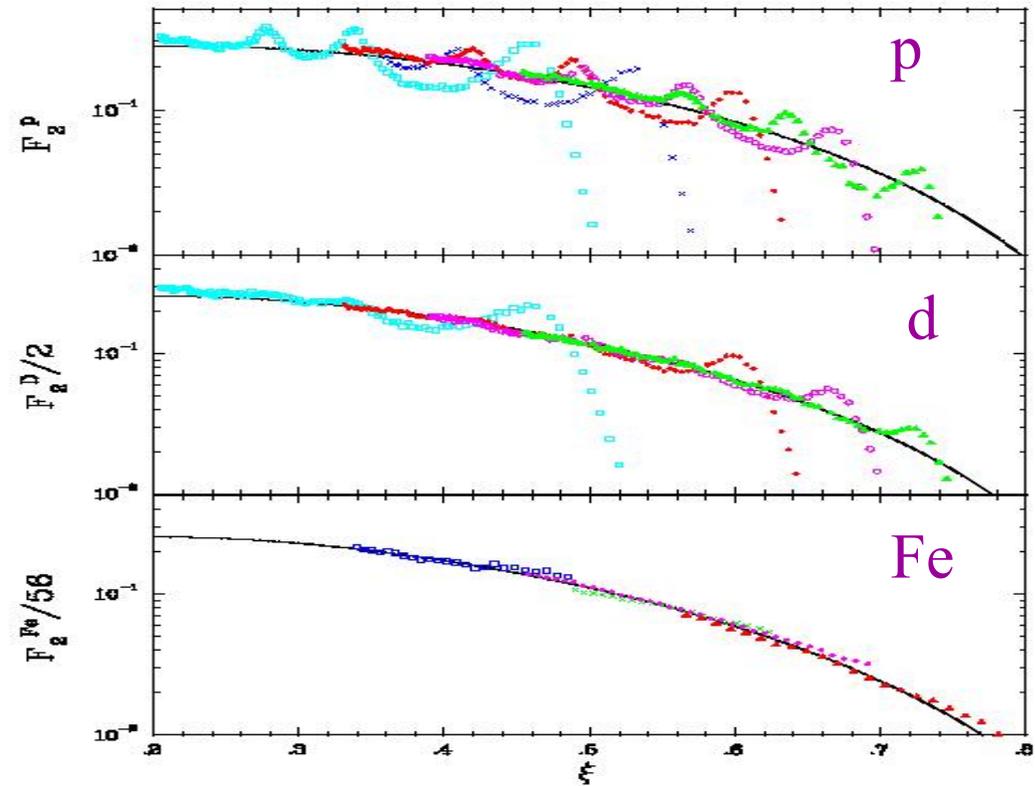


Neutron Duality using BONUS
data in I. Niculescu talk!

Duality also tested in higher mass nuclei

- Data in resonance region, spanning Q^2 range 0.7 - 5 GeV^2
- GRV scaling curve
- The nucleus (Fermi smearing) does the averaging!
- For larger A , resonance region indistinguishable from DIS
- See Gaskell, Arrington talks

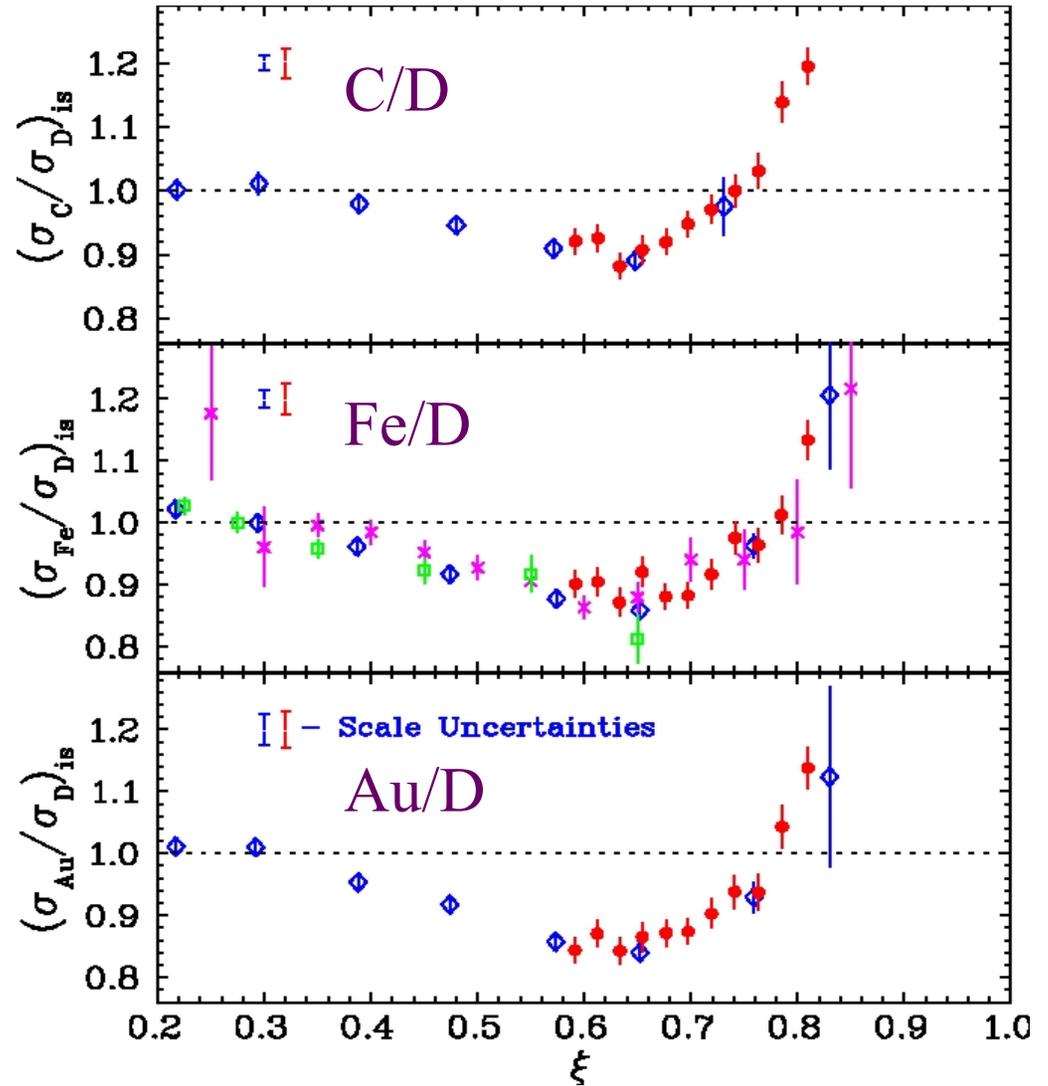
J. Arrington, et al., Phys.Rev.C73:035205 (2006)



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

Duality and the EMC Effect

- Red = resonance region data
- Blue, purple, green = deep inelastic data from SLAC, EMC
- Medium modifications to the structure functions *are the same* in the resonance region as in the DIS
- Duality observed in nuclei

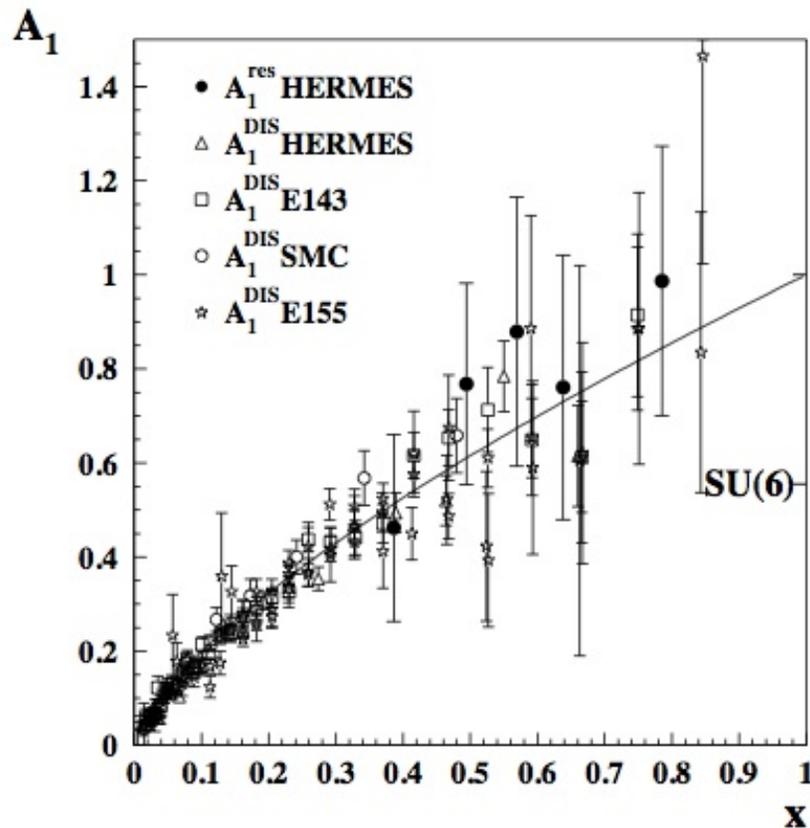


Duality observed for...

- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p
- ✓ F_2^n
- ✓ F_2^d
- ✓ F_2^C
- ✓ F_2^{Fe}
- ✓ F_2^{Au}

Try some spin
observables....

Inclusive $\vec{p}(\vec{e}^+, e')$ Scattering – HERMES first measurement



Just a few data points...

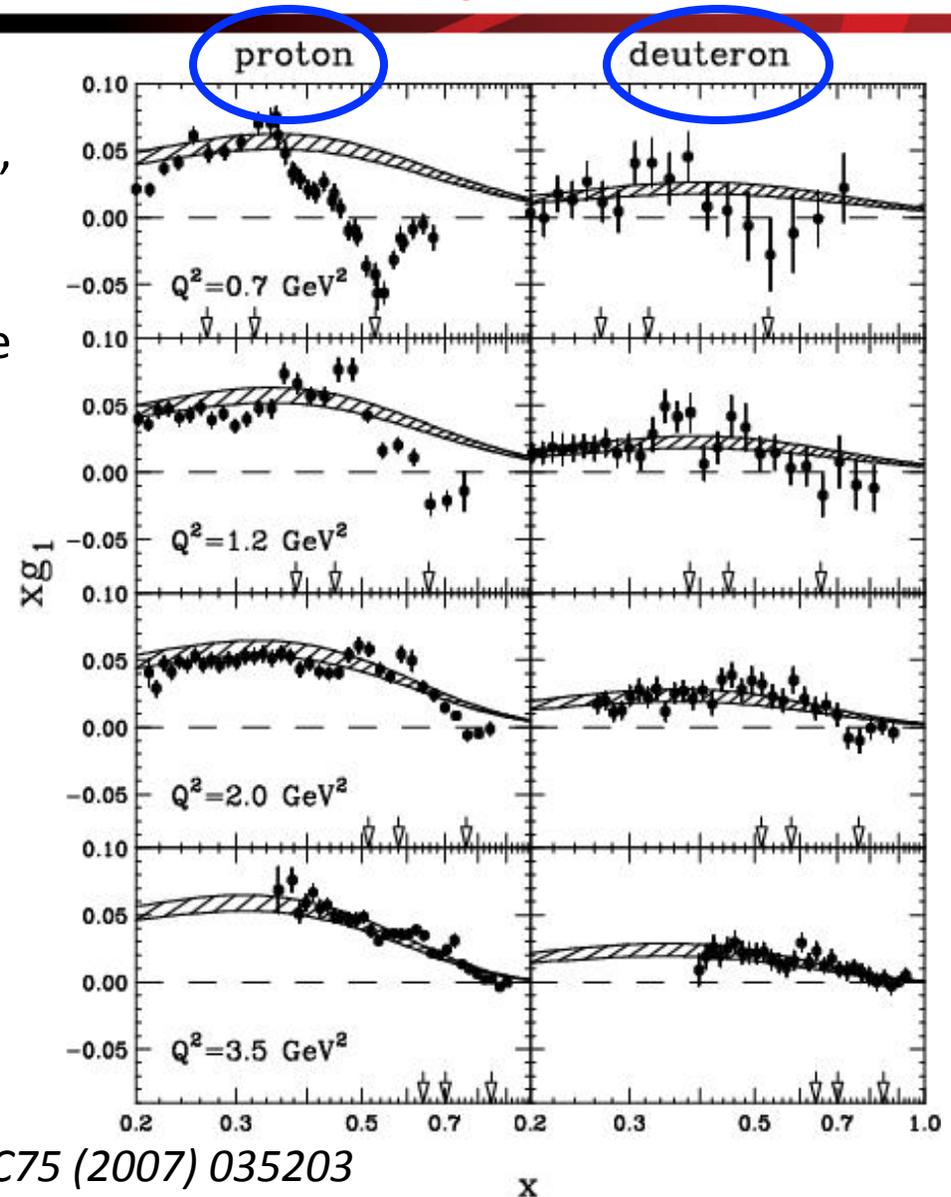
The average ratio of the measured A_{res} to the DIS fit is 1.11 ± 0.16 (stat.) ± 0.18 (syst.).

“..the first experimental evidence of quark hadron duality for the spin asymmetry $A_1(x)$ of the proton has been observed for Q^2 between 1.6 GeV^2 and 2.9 GeV^2 .”

A. Airapetian, et al., Phys.Rev.Lett.90:092002,2003

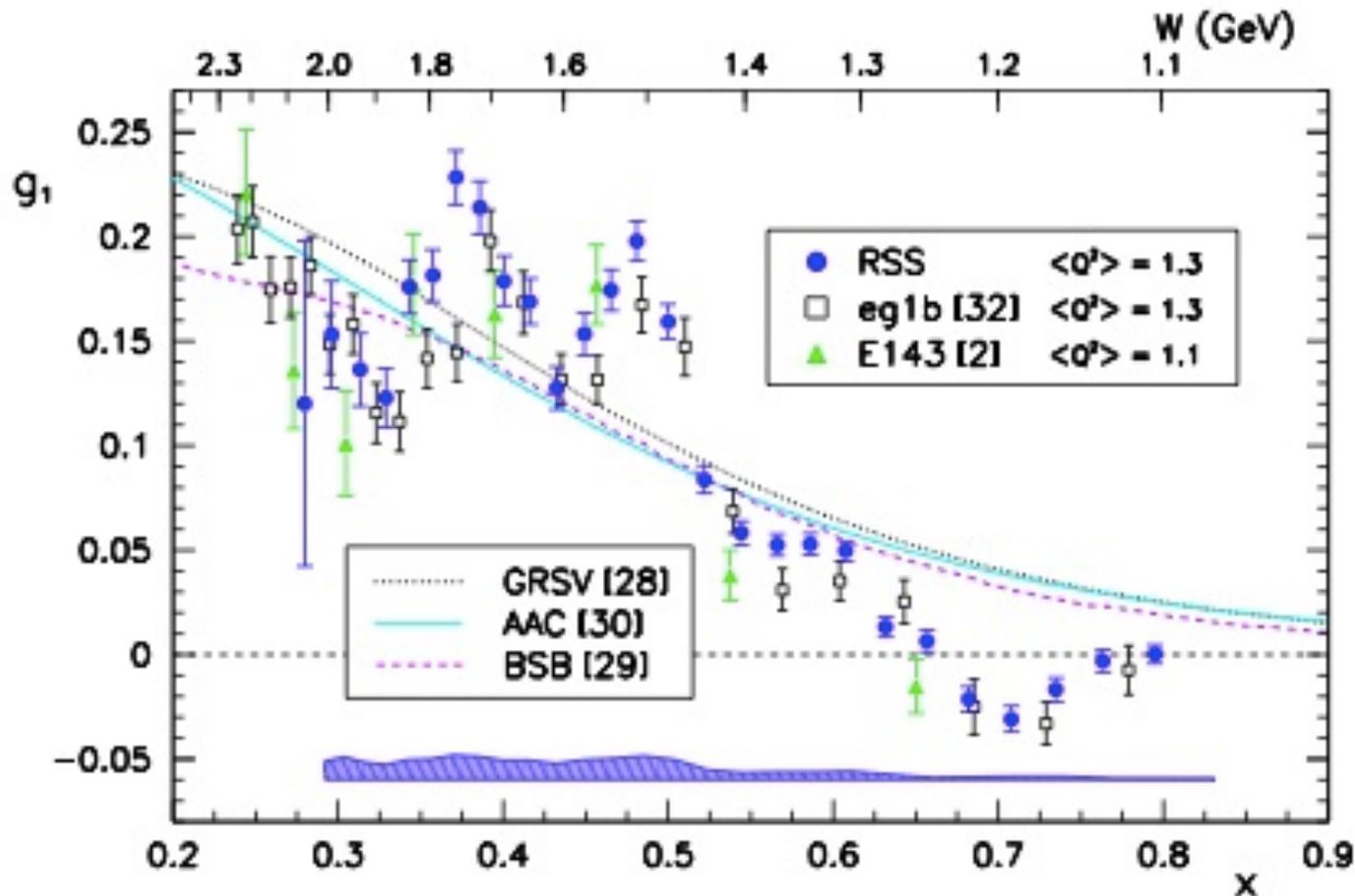
Duality in Polarized $^{1,2}\text{H}(\vec{e}, e')$ Scattering

- Arrows indicate the position of the three prominent resonance regions (“ Δ ”, “S”, “F”).
- The hatched band represents the range of g_1 predicted by NLO PDF fits (GRSV, AAC) + TM, evolved to the Q^2 of the data.
- “ Δ ” region remains below the NLO PDF fits for low Q^2 .
- “Averaged over the entire resonance region ($W < 2$ GeV), the data and QCD fits are in good agreement in both magnitude and Q^2 dependence for $Q^2 > 1.7$ GeV $^2/c^2$.”



P.E. Bosted et al., Phys.Rev. C75 (2007) 035203

Inclusive $\vec{p}(\vec{e}, \vec{e}')$ Scattering



F. Wessellmann, et al., Phys. Rev. Lett. 98 (2007) 132003

“We have established that Bloom-Gilman polarized duality is meaningful for the resonance region as a whole, although local polarized duality may yet be observed at higher Q^2 ranges.”

Delta (single state)
an issue

Scaling curve
uncertainties

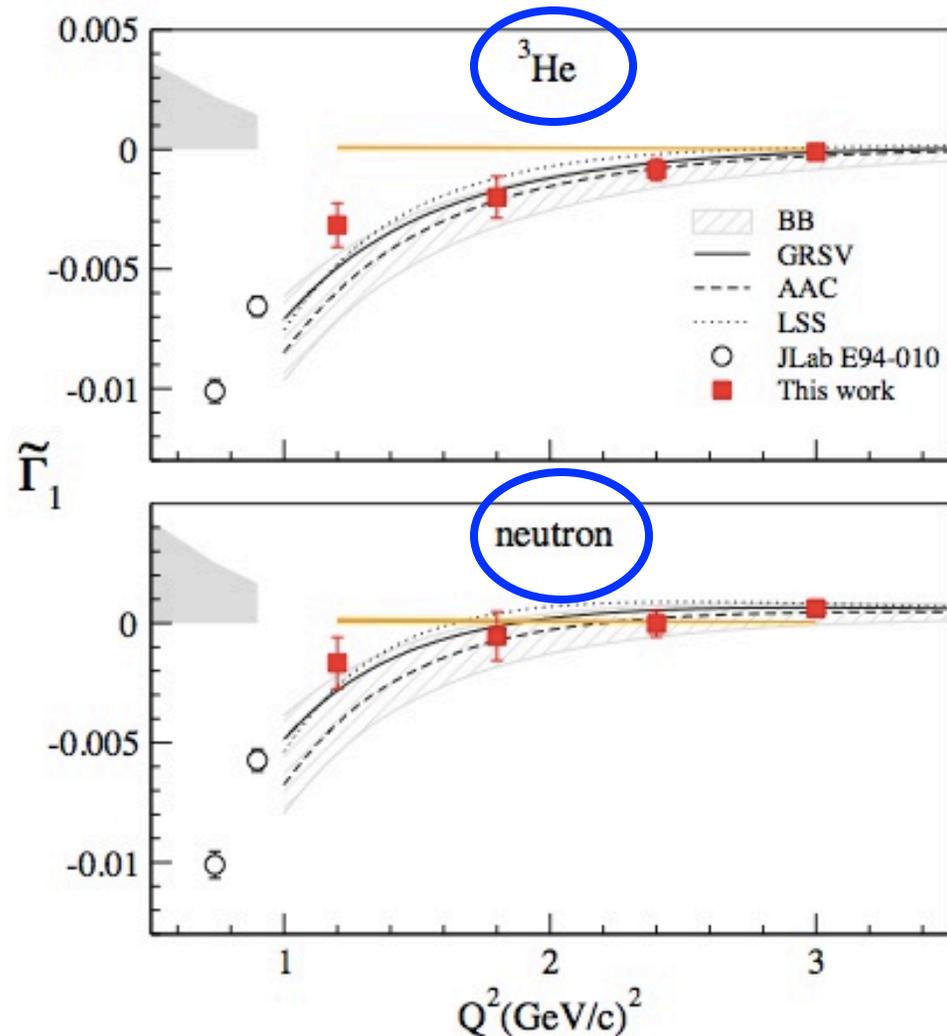
→ → Inclusive ${}^3\text{He}(e,e')$ Scattering

To quantify: integrate g_1 in the resonance region and compare the integral with DIS expectations:

$$\tilde{\Gamma}_1(Q^2) = \int_{x_{1.905}}^{x_\pi} g_1(x, Q^2) dx$$

Construct experimental g_1 -integral for the neutron per Ciofi degli Atti prescription:

$$\tilde{\Gamma}_1^n = \frac{1}{P_n} \tilde{\Gamma}_1^{3\text{He}} - 2 \frac{P_p}{P_n} \tilde{\Gamma}_1^p$$



P. Solvignon, et al., Phys.Rev.Lett. 101 (2008) 182502

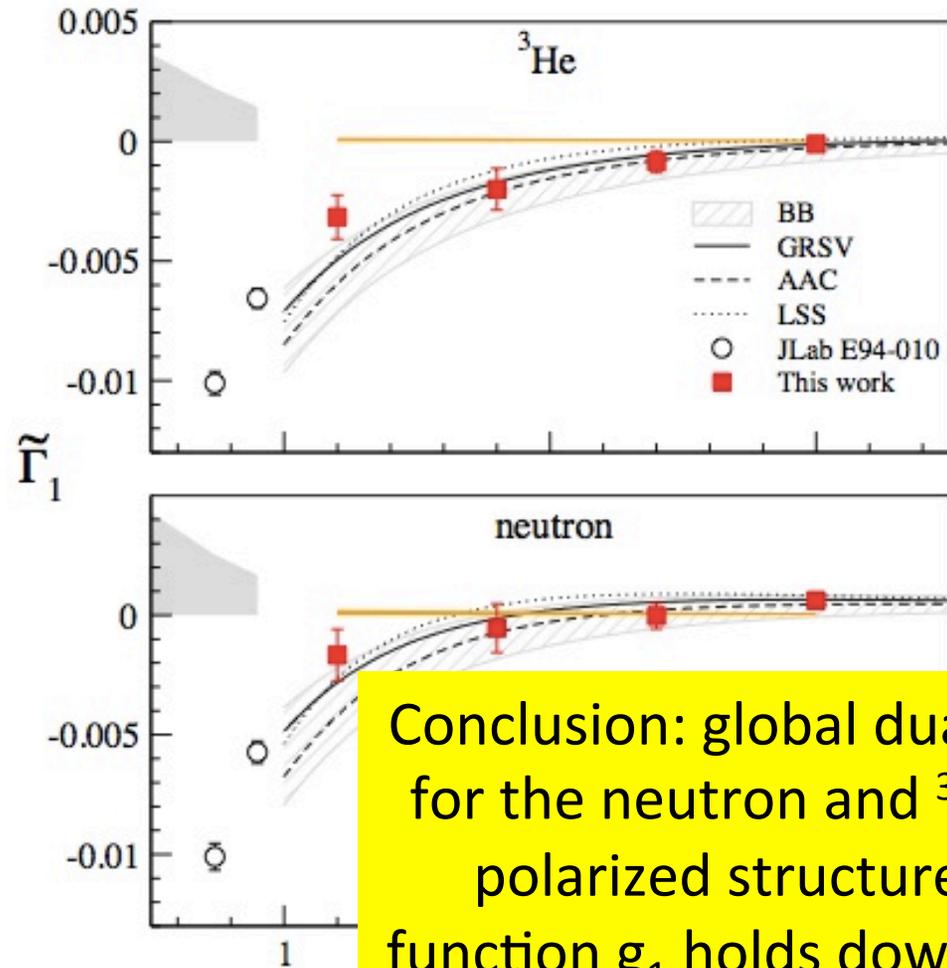
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Construct experimental g_1 -integral for the neutron per Ciofi degli Atti prescription:

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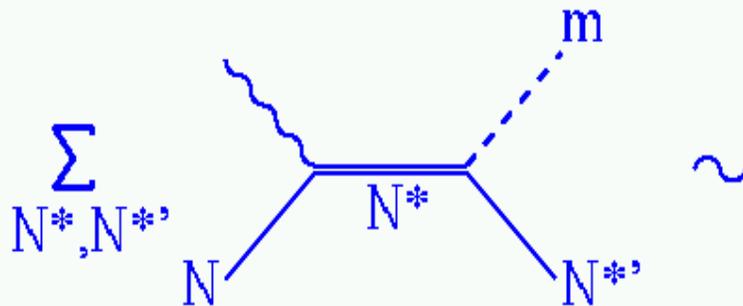
P. Solvignon, et al., Phys.Rev.Lett. 101 (2008) 162502

Duality observed for...

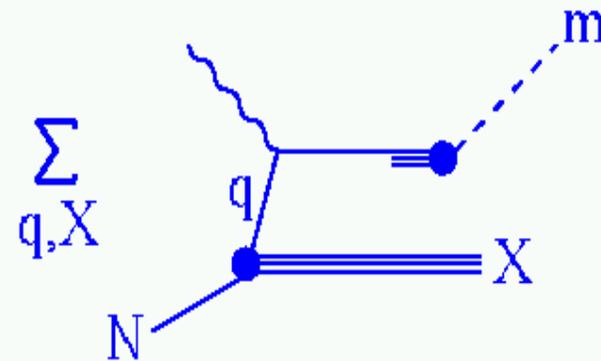
- ✓ F_2^p
 - ✓ F_1^p
 - ✓ F_L^p
 - ✓ F_2^n
 - ✓ F_2^d
 - ✓ F_2^C
 - ✓ F_2^{Fe}
 - ✓ F_2^{Au}
 - ✓ A_1^p
 - ✓ g_1^p
 - ✓ g_1^d
 - ✓ g_1^n
 - ✓ g_1^{3He}
- Typically duality holds better than 5-10%...except...
- Less well at lowest Q^2 values
- Less well at highest x , Δ , region
- Single state
 - Scaling curves

Duality in Meson Electroproduction

hadronic description



quark-gluon description



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

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

Transition
Form Factor

Decay
Amplitude

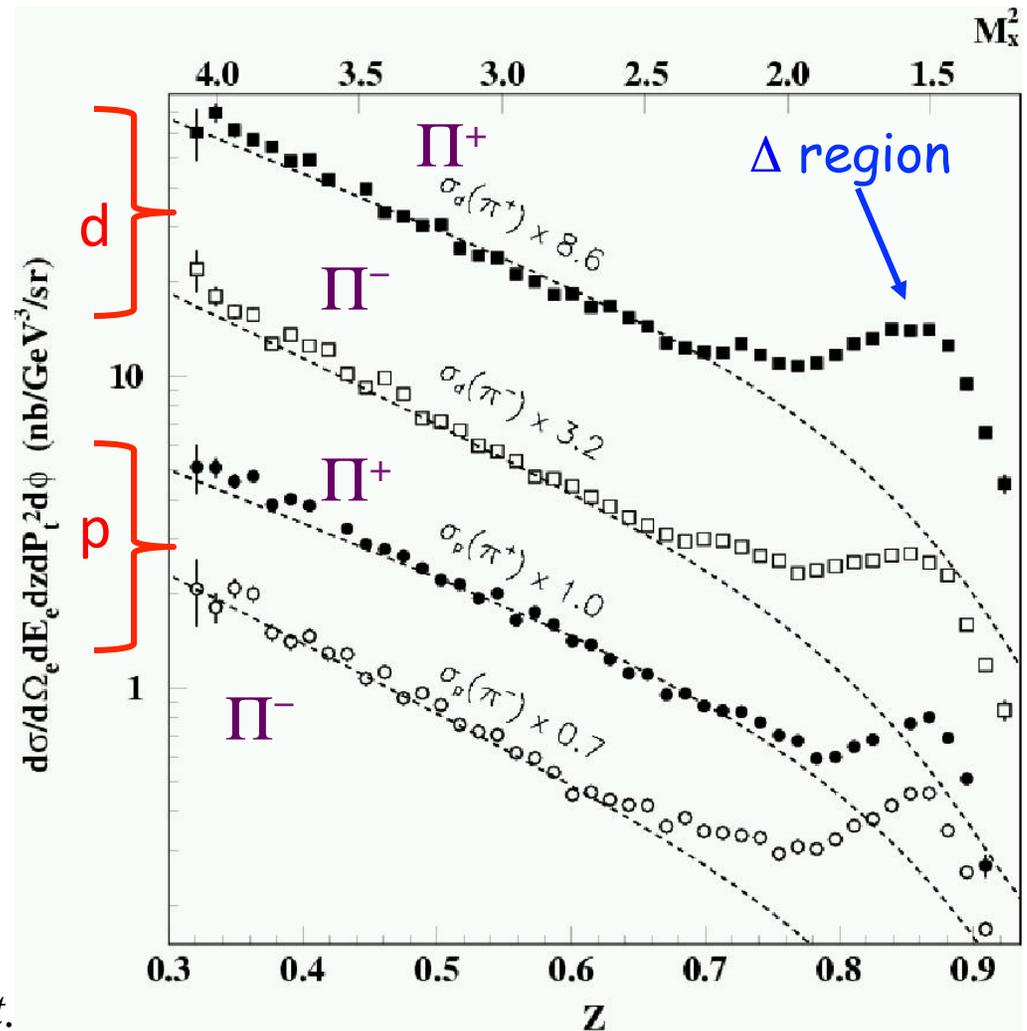
Fragmentation
Function

Duality and factorization possible for $Q^2, W^2 \leq 3 \text{ GeV}^2$
(Close and Isgur, Phys. Lett. B509, 81 (2001))

“If duality is not observed, factorization is questionable.”

Duality in (Semi-Inclusive) Pion Electroproduction

- $^{1,2}\text{H}(e,e'\pi^\pm)\text{X}$ cross sections at $x = 0.32$
- Dotted lines: simple Quark Parton Model prescription assuming factorization
- “These data conclusively show the onset of the quark-hadron duality phenomenon”



*T. Navasardyan, et al. Phys.Rev.Lett.
98 (2007) 022001*

Duality observed for...

- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p
- ✓ F_2^n
- ✓ F_2^d
- ✓ F_2^C
- ✓ F_2^{Fe}
- ✓ F_2^{Au}
- ✓ A_1^p
- ✓ g_1^p
- ✓ g_1^d
- ✓ g_1^n
- ✓ g_1^{3He}
- ✓ SIDIS $p \pi^+$
- ✓ SIDIS $p \pi^-$
- ✓ SIDIS $d \pi^+$
- ✓ SIDIS $d \pi^-$

Also...parity-violating electron scattering (see X. Zheng talk)

Near horizon:

- MINERvA (neutrinos, see K. McFarland talk)
- JLab at 12 GeV:
 - Improved neutron data
 - Possible pion target
 - Higher Q^2 polarized and unpolarized structure functions

And a bit farther:

- (m)EIC

IV. In conclusion: tasks for an EIC

1. Open low- x at high luminosity: evolution, shadowing and saturation; F_L .
2. Polarization and nucleon structure. Explore universality and, in concert with other facilities, its limitations.
3. Generalized parton distributions, nuclear ‘tomography’ and elastic scattering.
4. Diffraction studies. Study the “ $A - Q^2$ plane” to disentangle effects we know are there: $A^{4/3}$, $A(A - 1) \dots$
5. Propagation of scattered partons in nuclear medium. Complement AA; complete fixed-target.
6. Quark-hadron duality studies. Follow the histories of scattered quanta; confinement in action.

Summary

- Quark-hadron duality is somehow a fundamental property of nucleon structure
 - Works generally in every process studied
 - Studies now quite numerous!
 - Only talked about electron scattering
- Seems to need >1 state for averaging
 - Elastic add to moments
 - Delta alone a problem
 - But how many from a fundamental point of view?
- Challenges to quantifying experimentally
 - pQCD predictions for large x , low Q have large uncertainties
 - Use duality to access large x ? (CJ may try this)
- **If understood better, a powerful tool to understand confinement**
 - **Hadronic observables determined by pQCD calculations**

“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)

