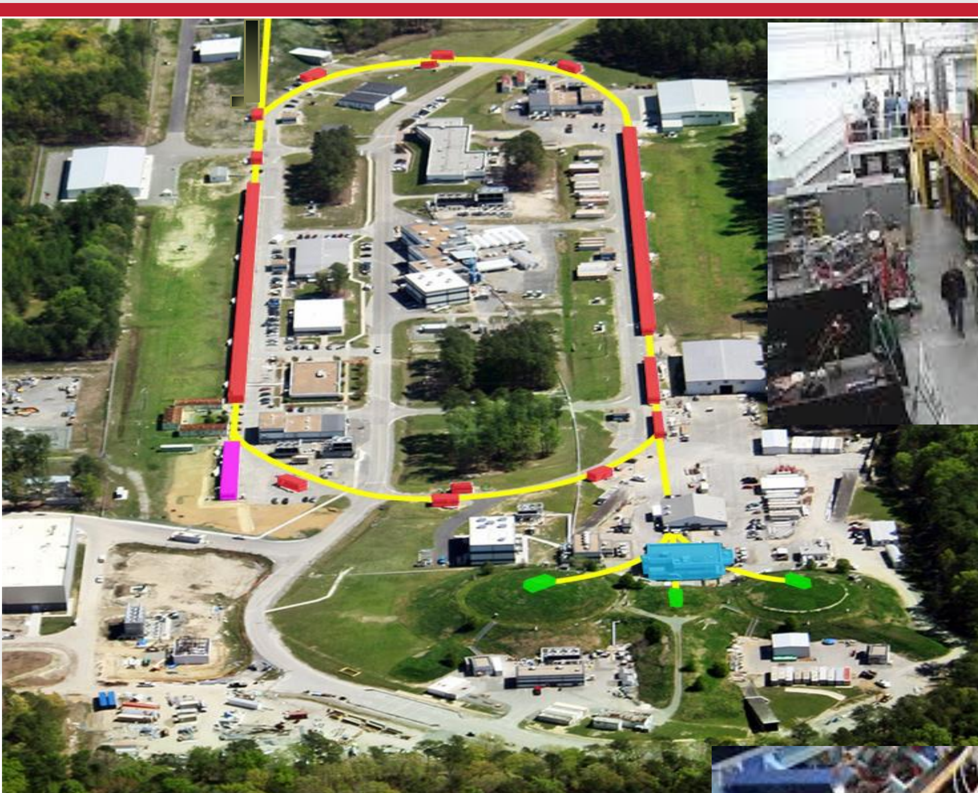
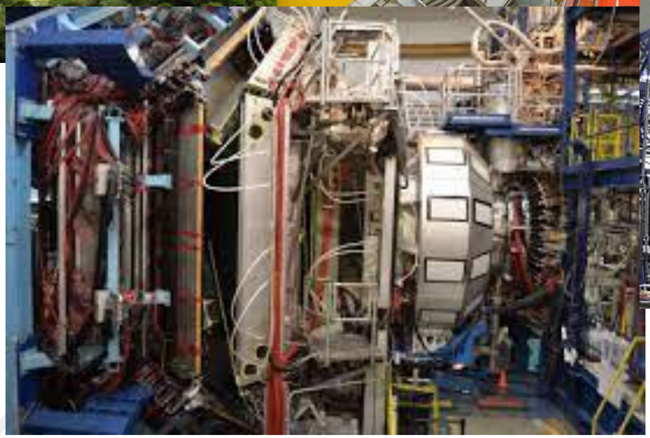
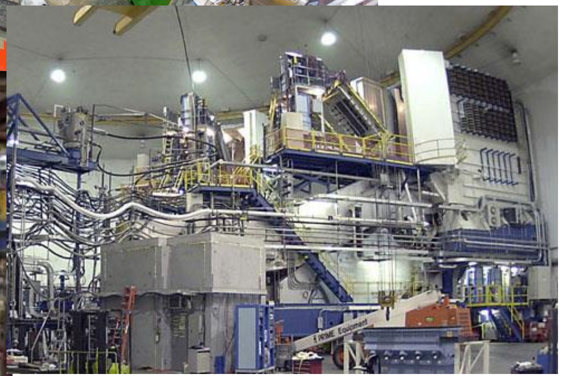
Quark-Hadron Duality and Beyond



Thia
Keppel





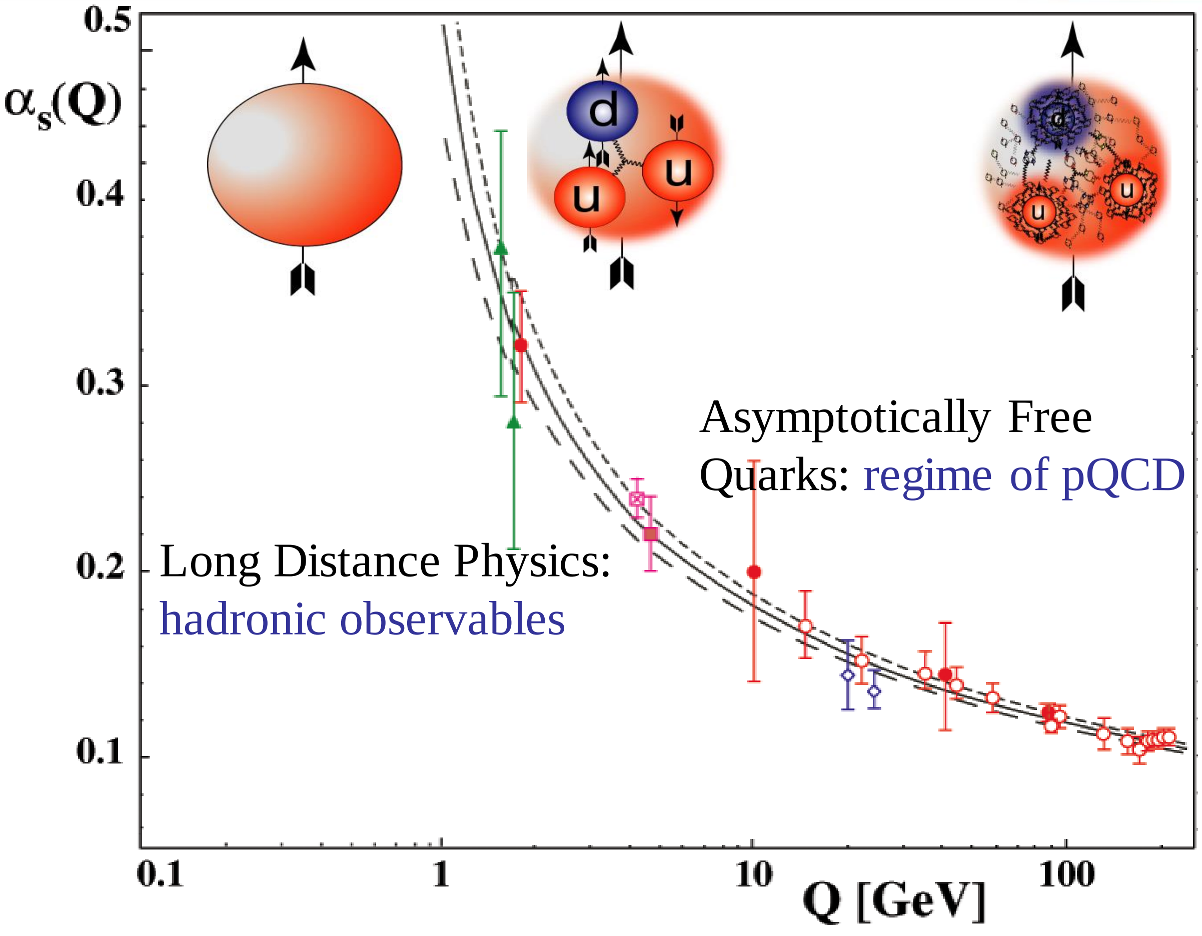
Nucleons and Nuclei from
Inclusive Measurements
June 2023, Jefferson Lab

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

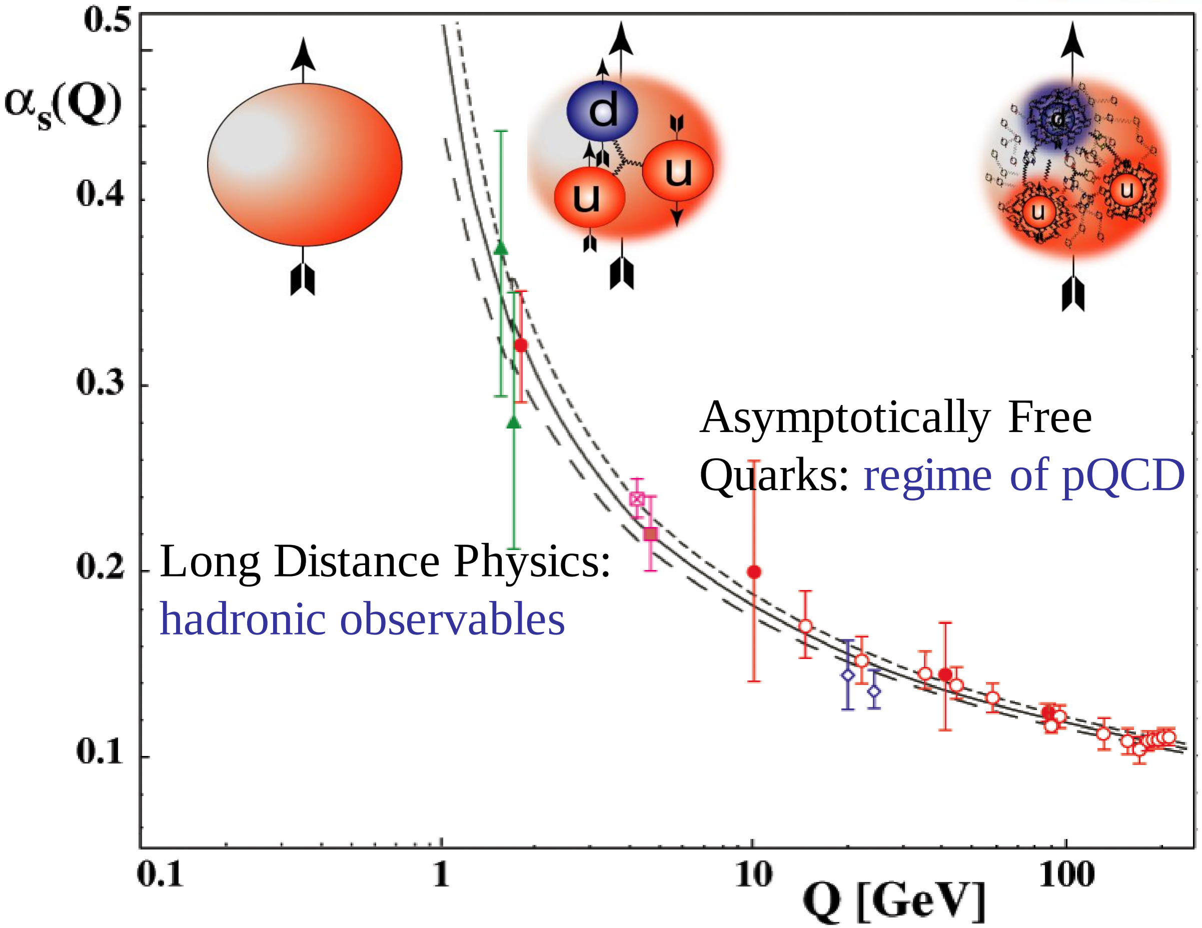
What is duality?



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

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

What is duality?



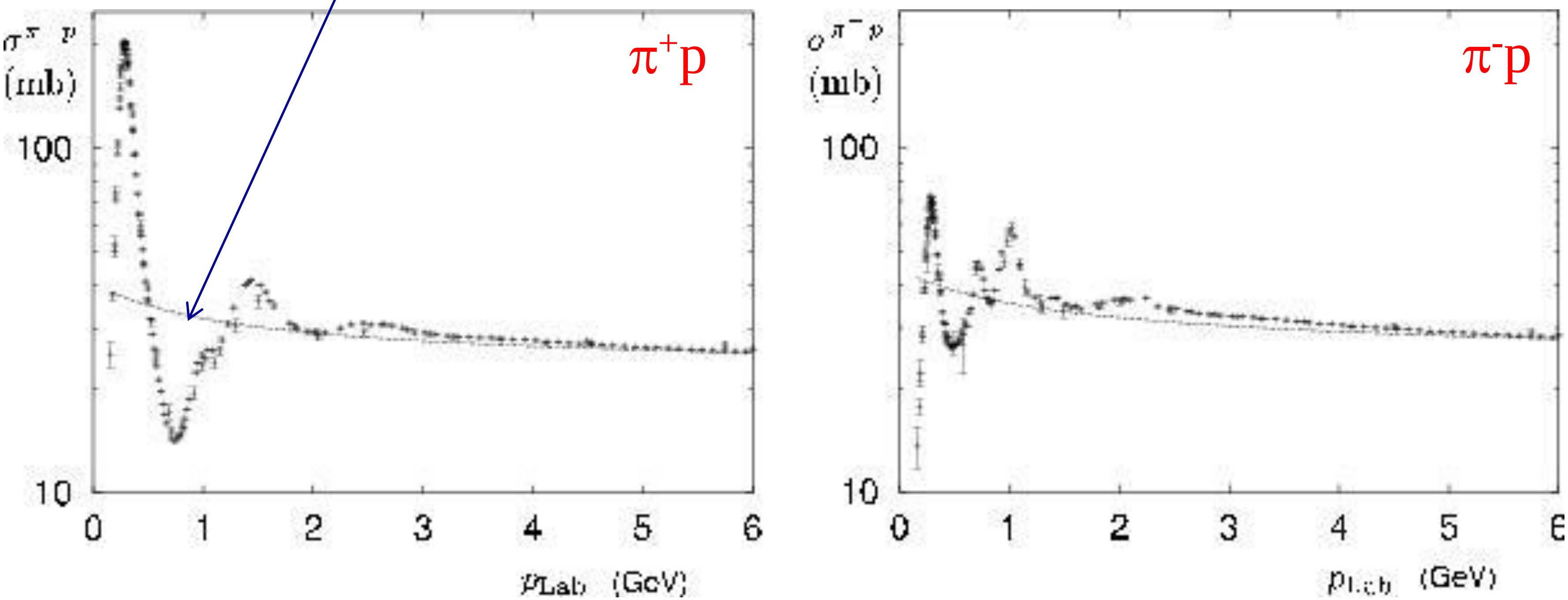
pQCD is well defined and calculable in terms of *asymptotically free* quarks and gluons, yet…

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

Duality is an apparent experimental bridge between free and confined partons

Quark-Hadron Duality – History

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

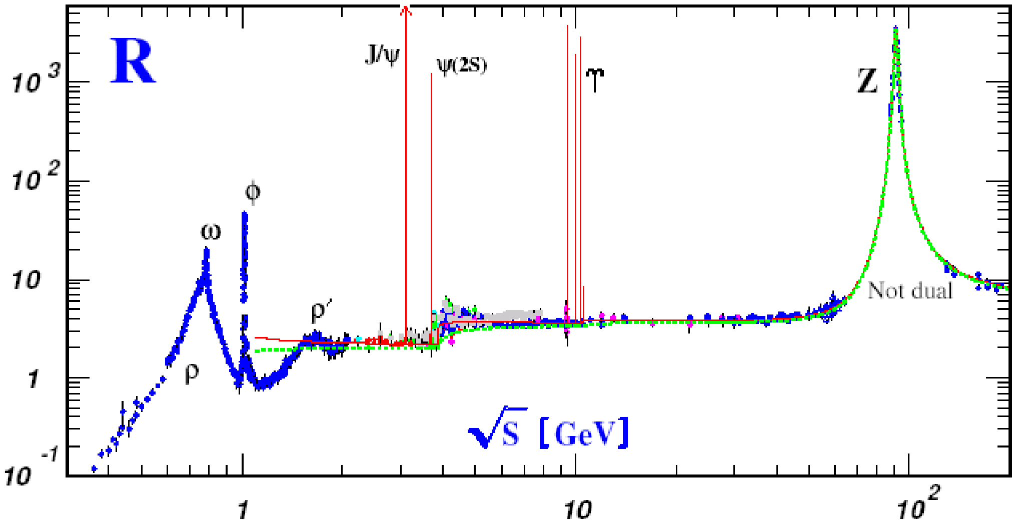


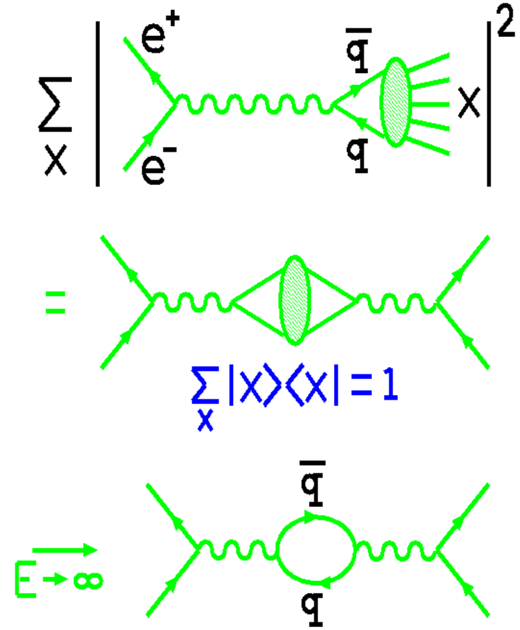
→ *low-energy hadronic cross sections on average described by the high-energy behavior.*

→ *finite energy sum rules quantify a "duality" between s-channel resonances and t-channel Regge descriptions*

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

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





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.

Physics of quarks predicts physics of hadrons

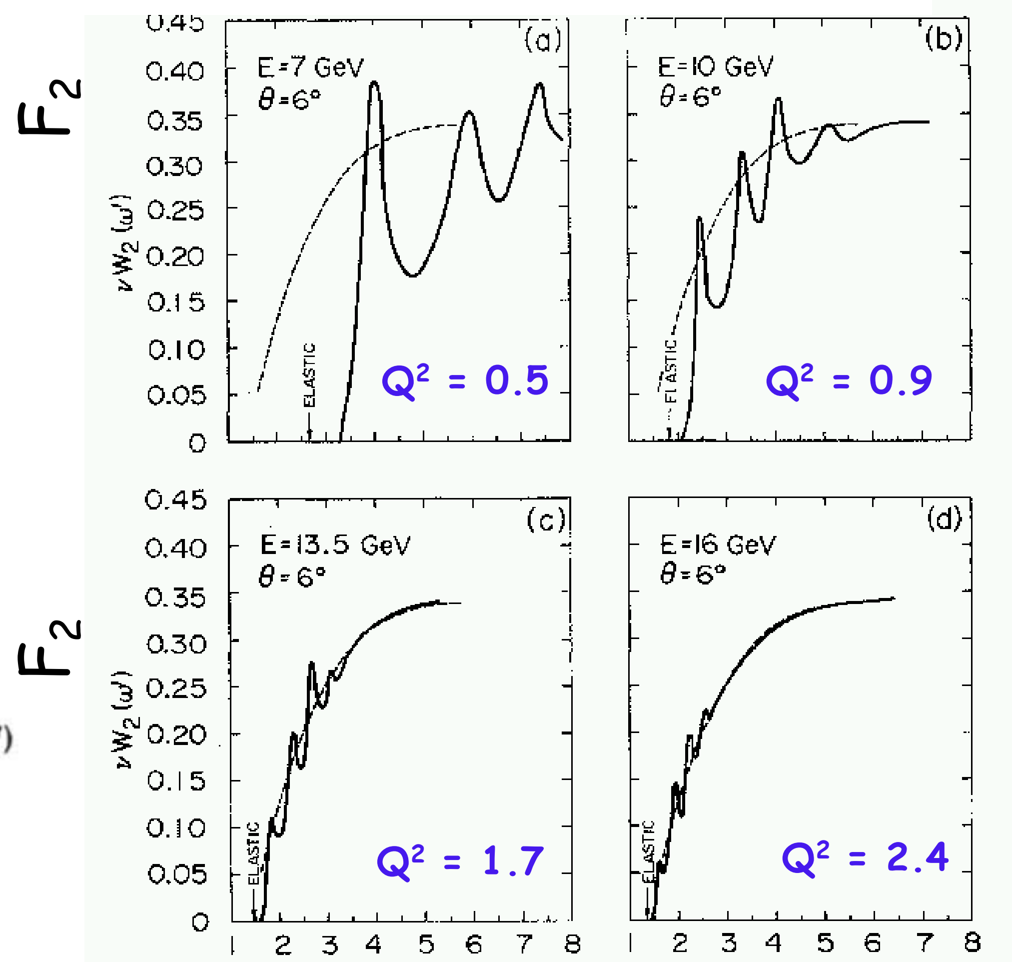
Also “Bloom-Gilman” Duality: Electron Scattering

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:

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

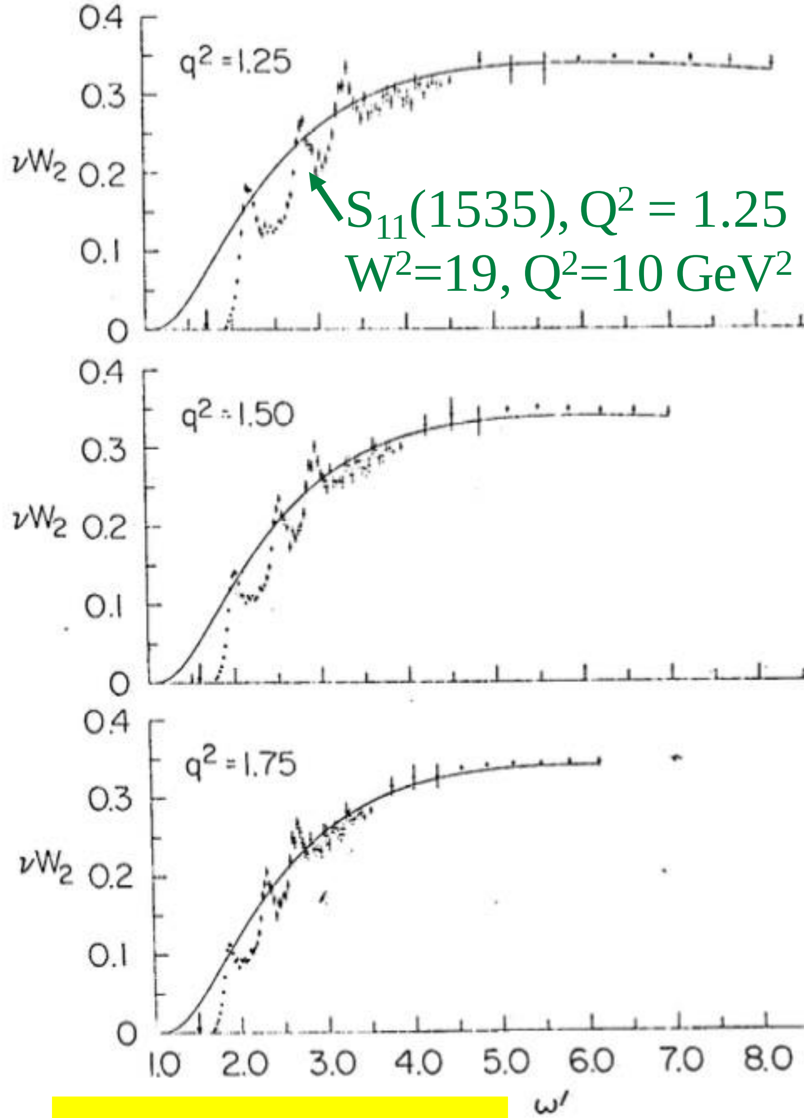
- Resonances oscillate around curve *at all Q^2*



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

A closer look at the phenomenon….

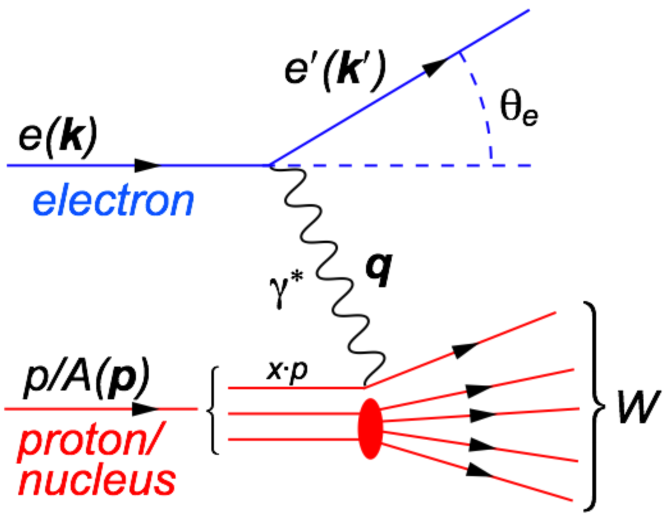
- Deploy variable to directly compare high W,Q to low (resonance region) W,Q
- Resonances *average* to scaling curve
- Resonances "slide along" scaling curve in Q^2
- Resonances do not disappear with increasing Q^2 relative to background under them
- "….the prominent nucleon resonances have a behavior which is strongly correlated with the scaling behavior…"

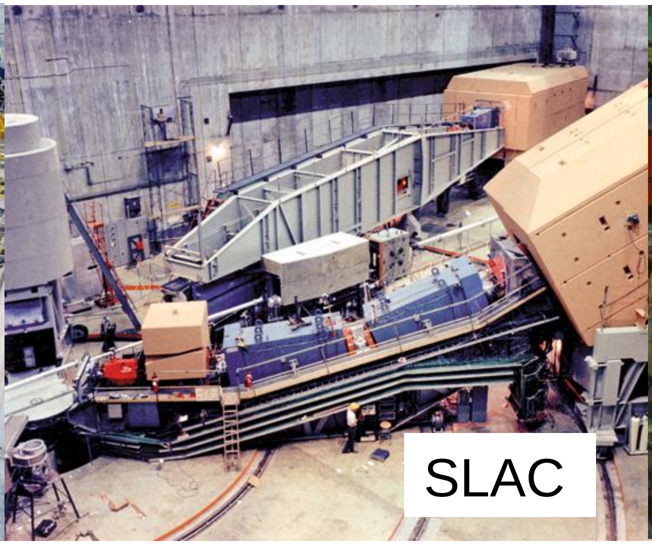


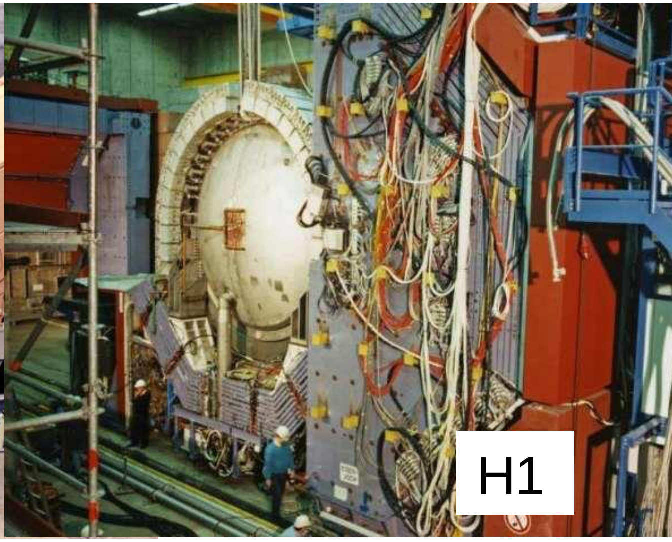
$\omega' = 1 + W^2/Q^2$

Three Decades Later….

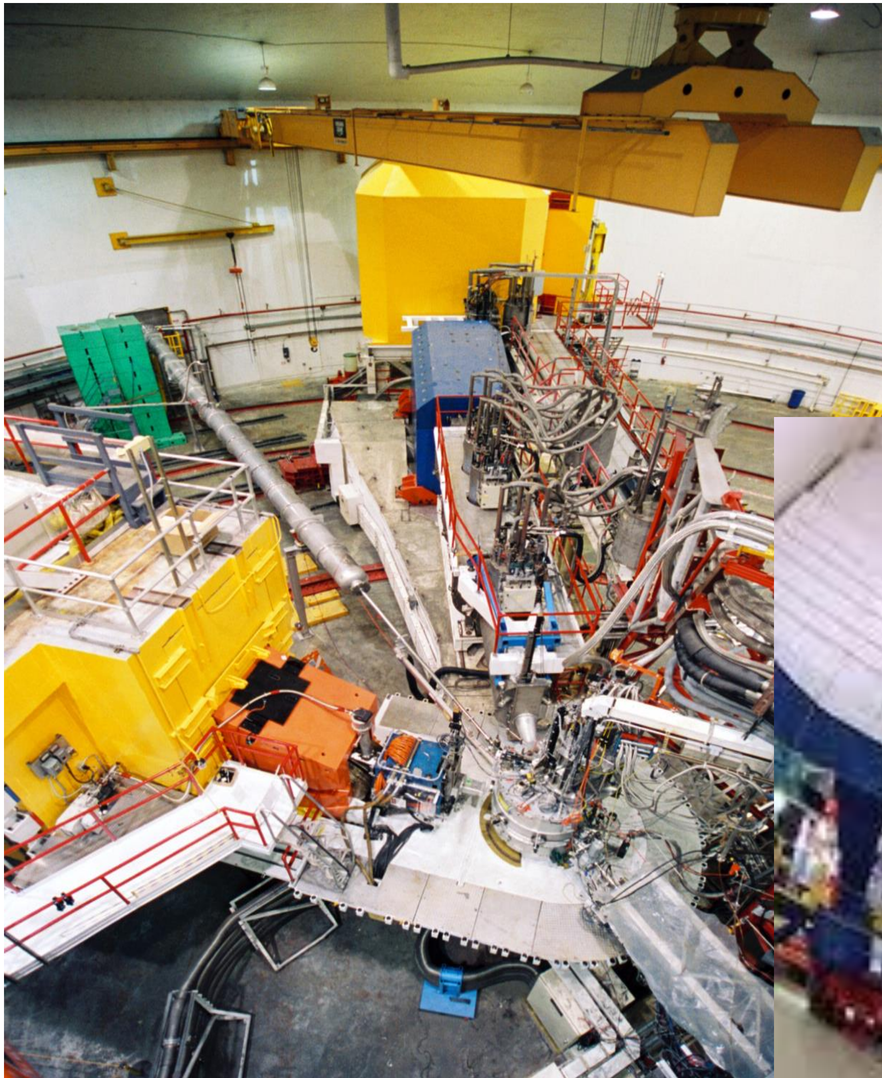
- 30+ years of charged lepton DIS at *multiple* laboratories
- Nucleon structure function well measured over broad range in x,Q^2
- DGLAP evolution equations for the parton densities, success of QCD
- It was time to revisit the resonances…..

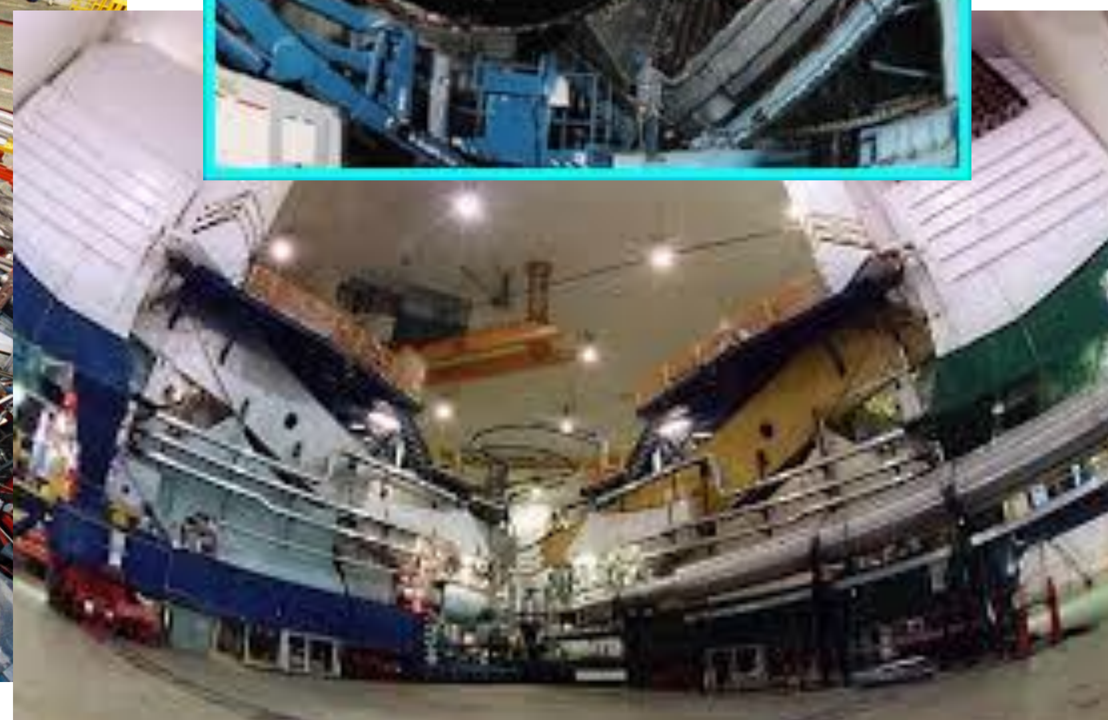




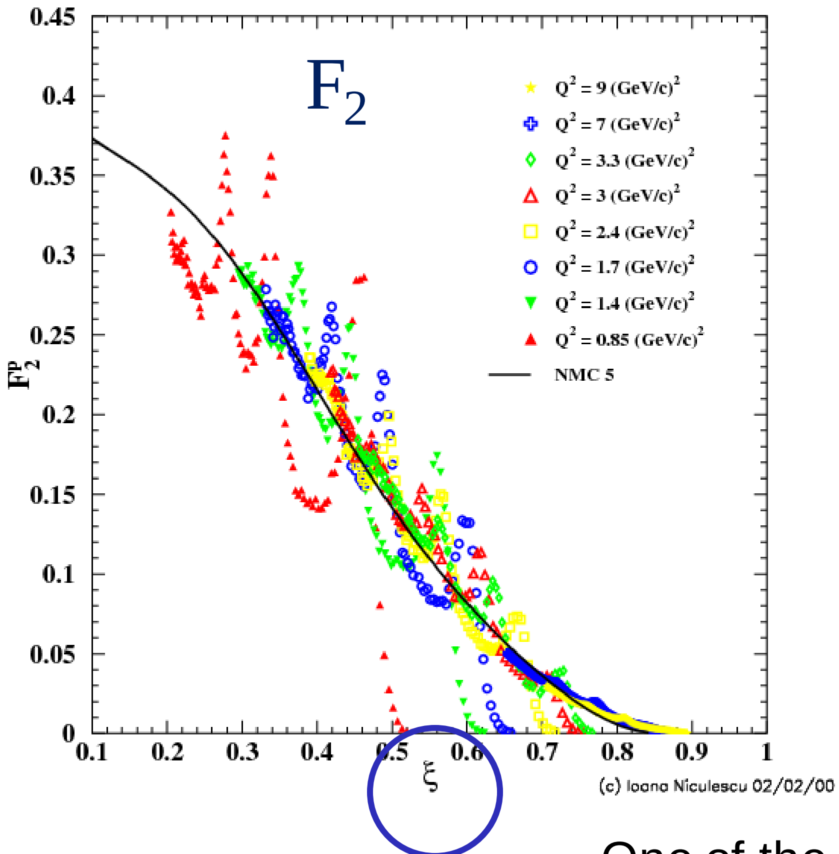


Multiple Experiments from Jefferson Lab in 6 GeV Era

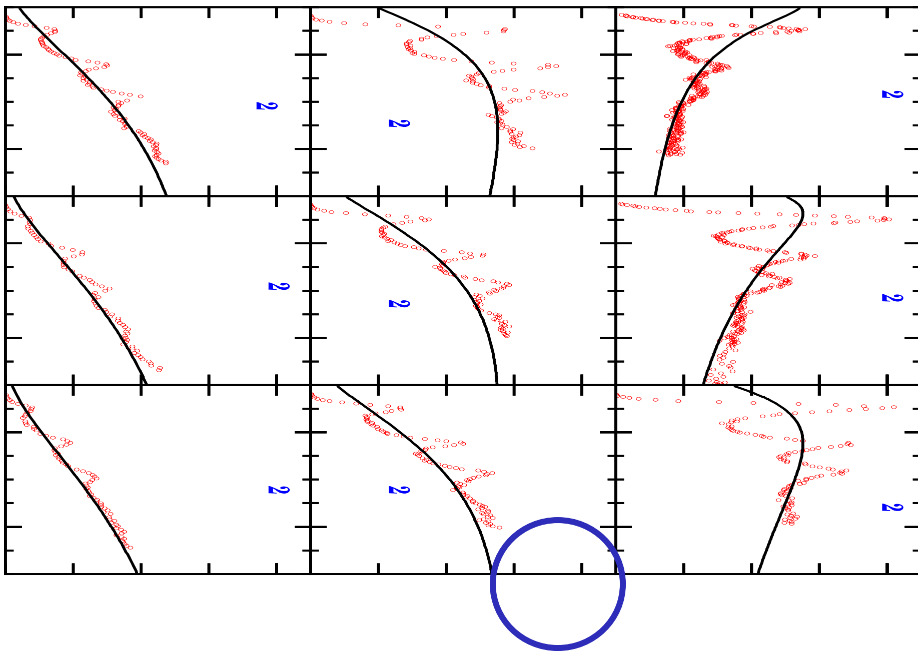




Duality Re-observed



I. Niculescu, et al., PRL 85 (2000), 1186 and 1182



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

One of the first Jefferson Lab 6 GeV era measurements

Duality clearly observed, but…

What to use for curve(s)? What to use for variable?

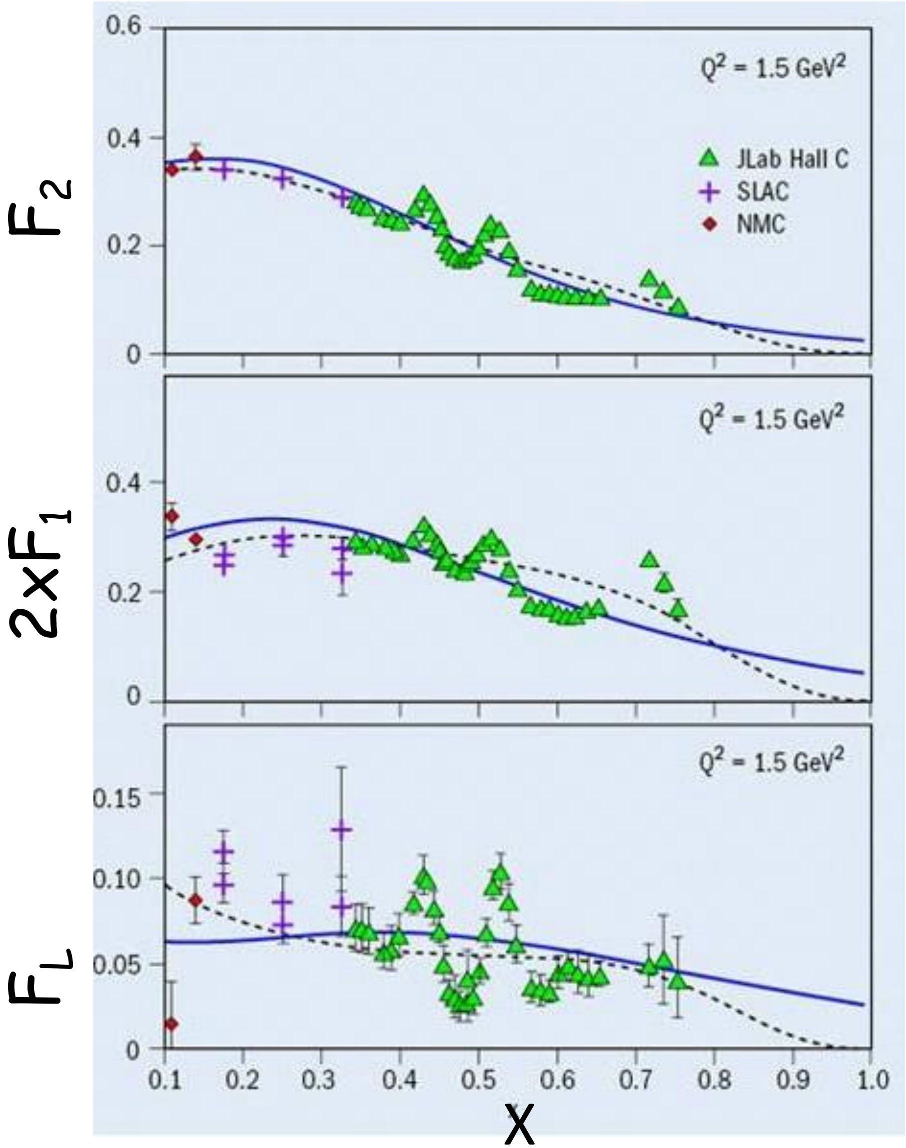
How to test precisely?

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?

Separated Proton Structure Functions



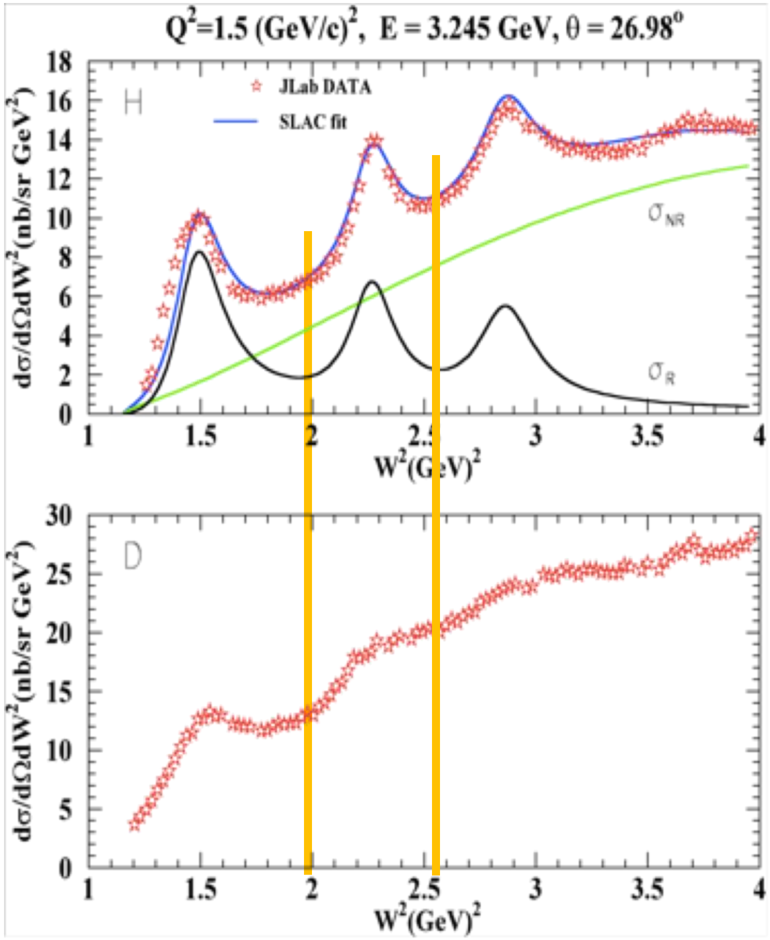
- Duality observed for *all* spin-averaged proton structure functions
- Compared now with curves from DIS data R1998, F2ALLM) or PDF fits
- Use Bjorken x instead of Bloom-Gilman ω'
  - *Causes fit extrapolation*
- JLab E94-110 results: "Quark-Hadron Duality" works quantitatively to better than 10% down to surprisingly low Q^2 ~1 GeV^2
  - What is the right interval?

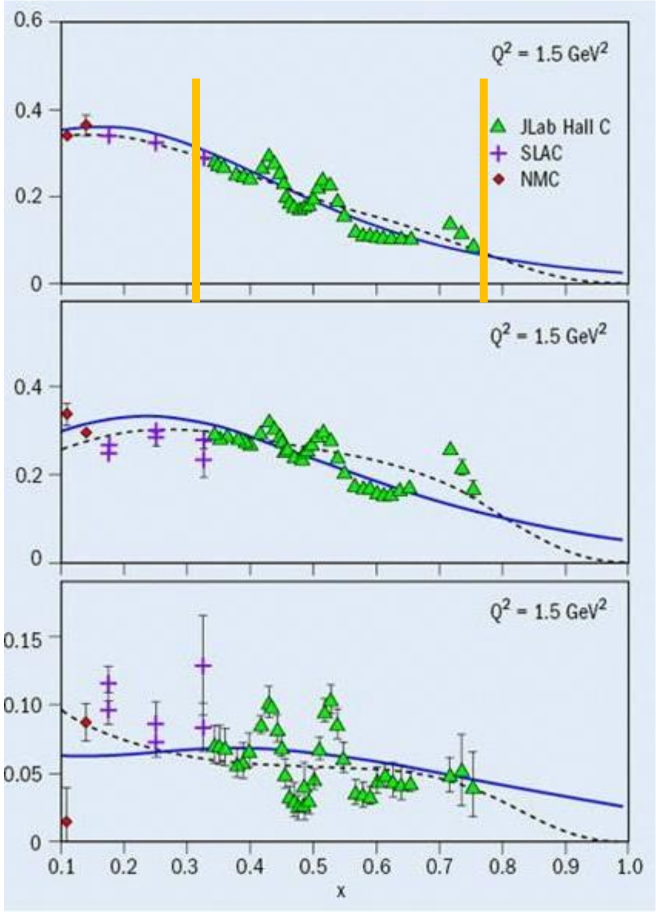
(CERN Courier, December 2004)

Duality observed for…

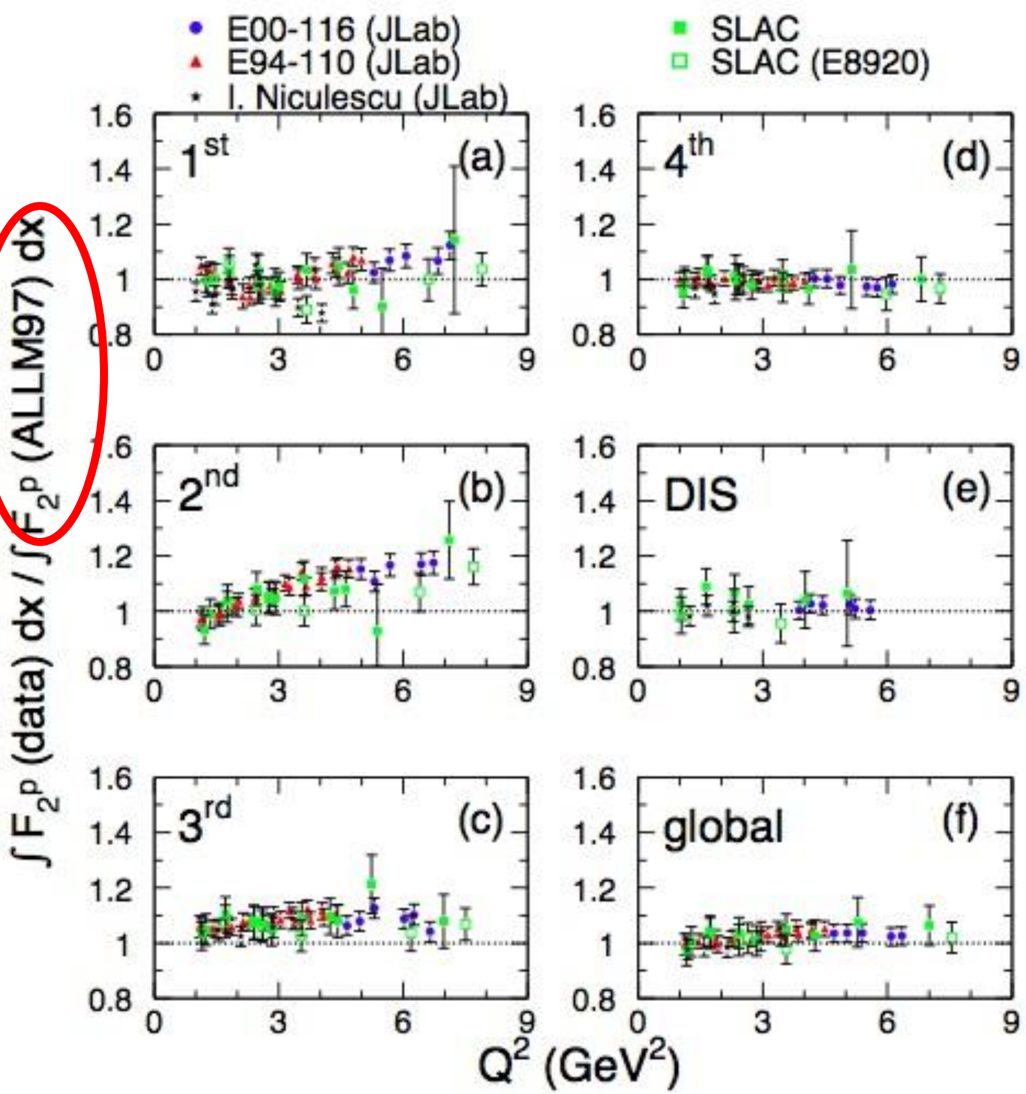
- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p

Further quantification… try integrating (moments)





Truncated Moments, More Data, and Precision Testing



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

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

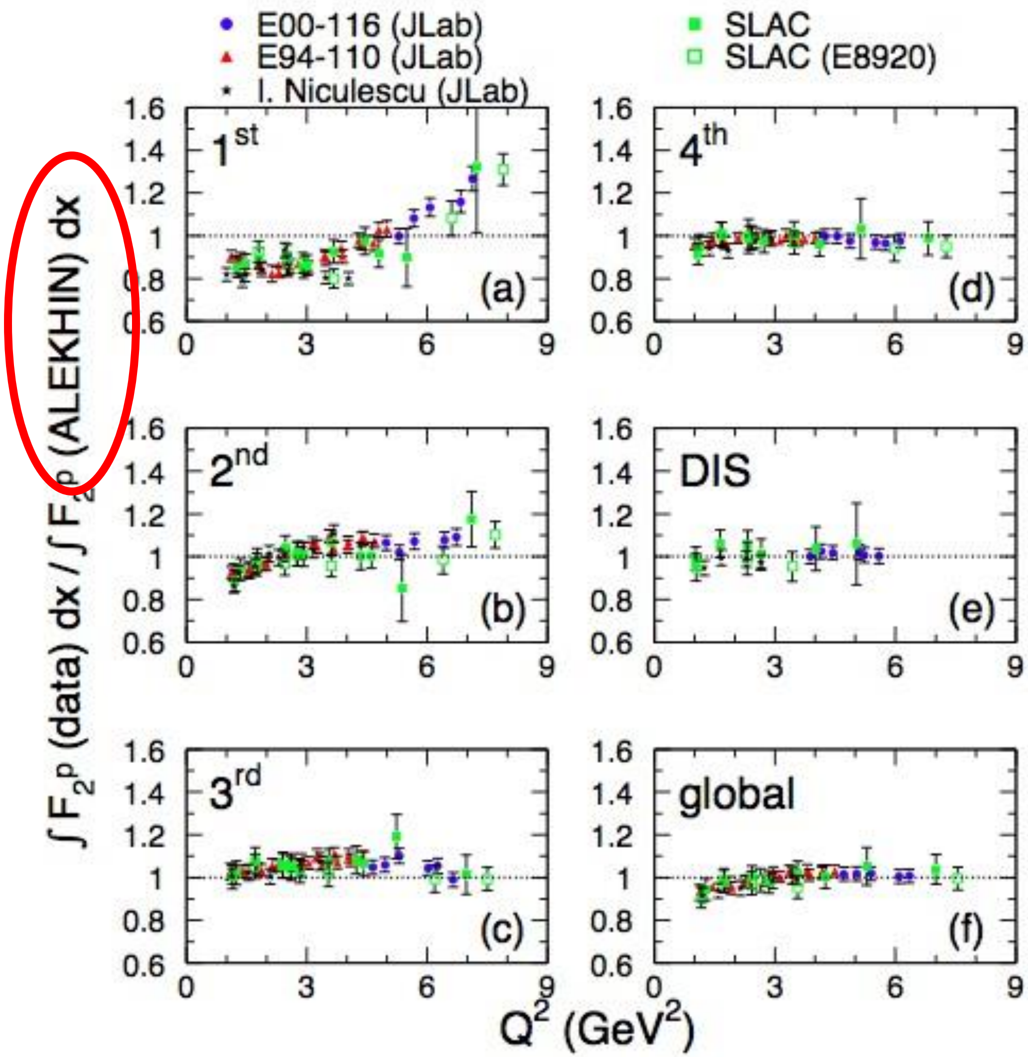
$$I = \frac{\int_{x_{min}}^{x_{max}} F_2^{data}(x, Q^2)dx}{\int_{x_{min}}^{x_{max}} F_2^{param.}(x, Q^2)dx}$$

In resonance region

From DIS only data

S. Malace, et al., Phys.Rev. C80 (2009) 035207
A. Psaker, W. Melnitchouk, M.E. Christy, CK Phys.Rev. C78 (2008) 025206

Different with Alekhin….



Changed only scaling curve choice

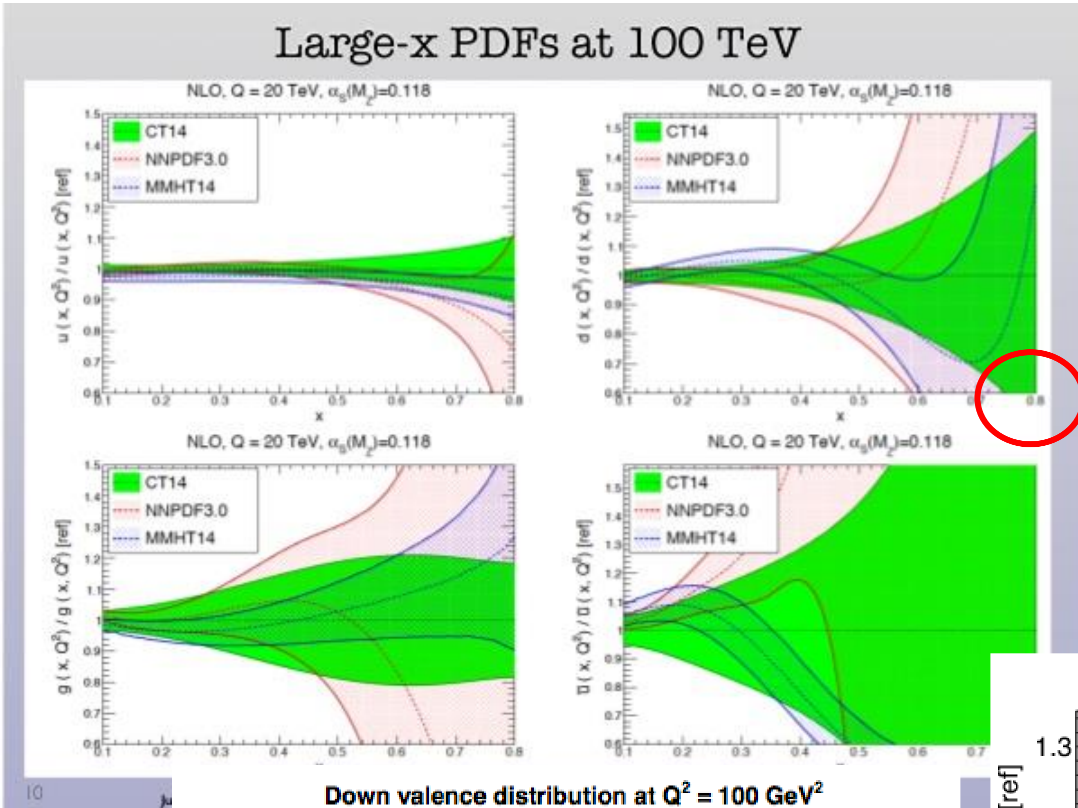
Works very well other than 1st region (dominated by single Delta resonance)

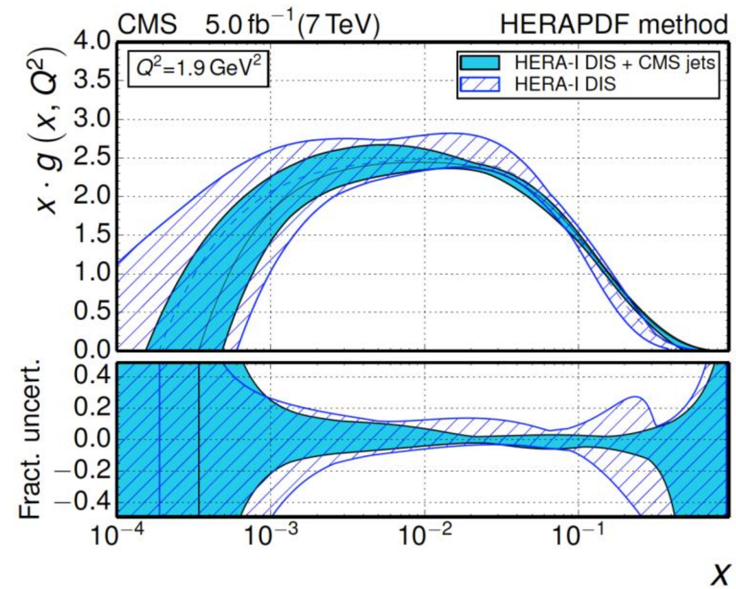
Alekhin curve has higher twist

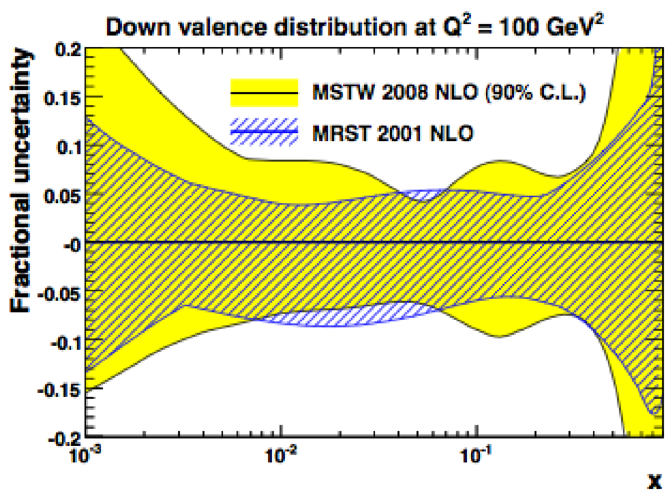
PDF curves have large errors at large x, extrapolating to unconstrained region

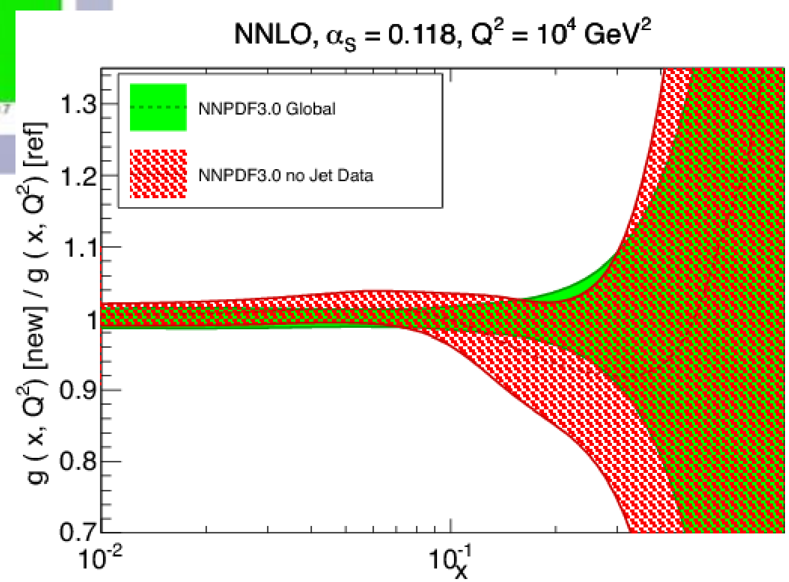
Scaling curve variations and uncertainties are now the limiting factor in precision duality testing

Present status: large uncertainties on PDFs at large x





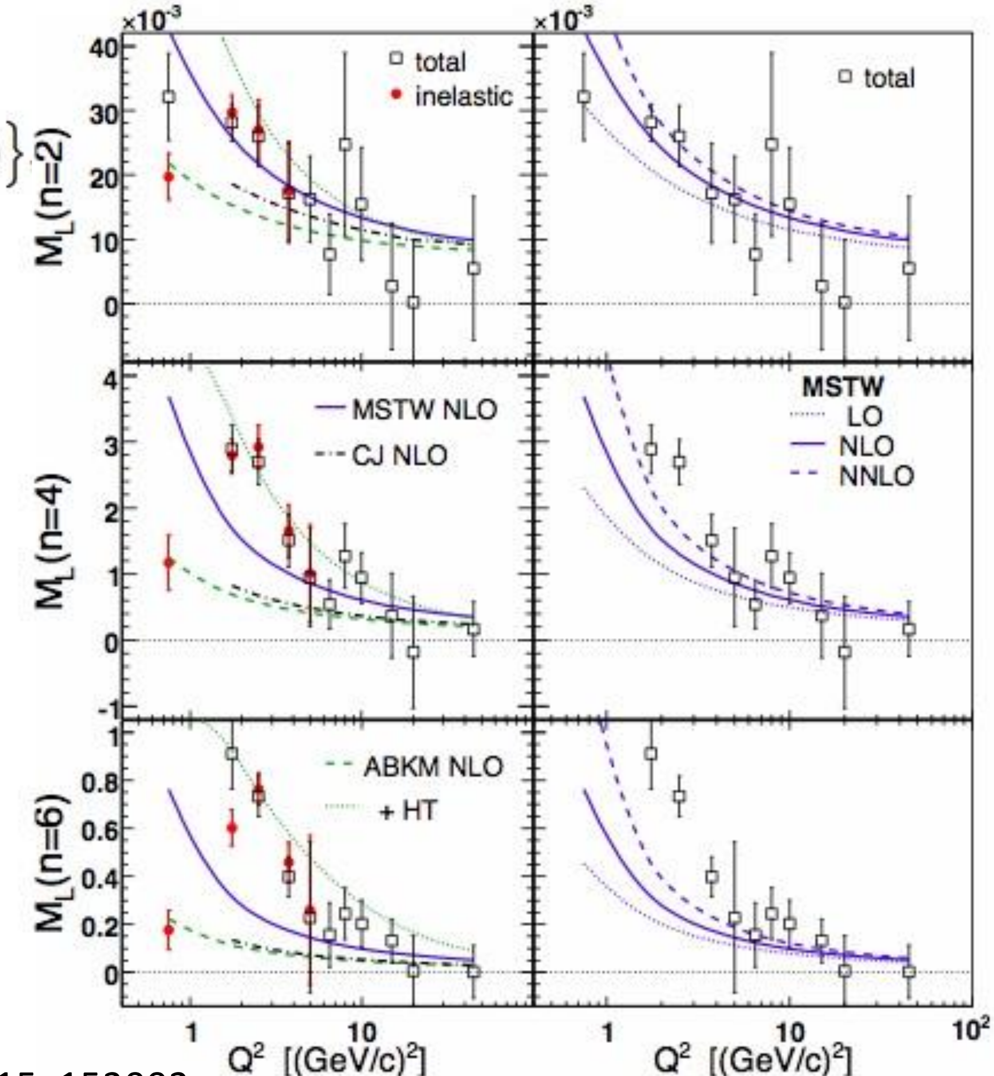




Moments of the F_L Structure Function

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

- 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, W. Melnitchouk, L. Zhu, Phys.Rev.Lett. 110 (2013) 15, 152002

Duality generally observed for…

- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p

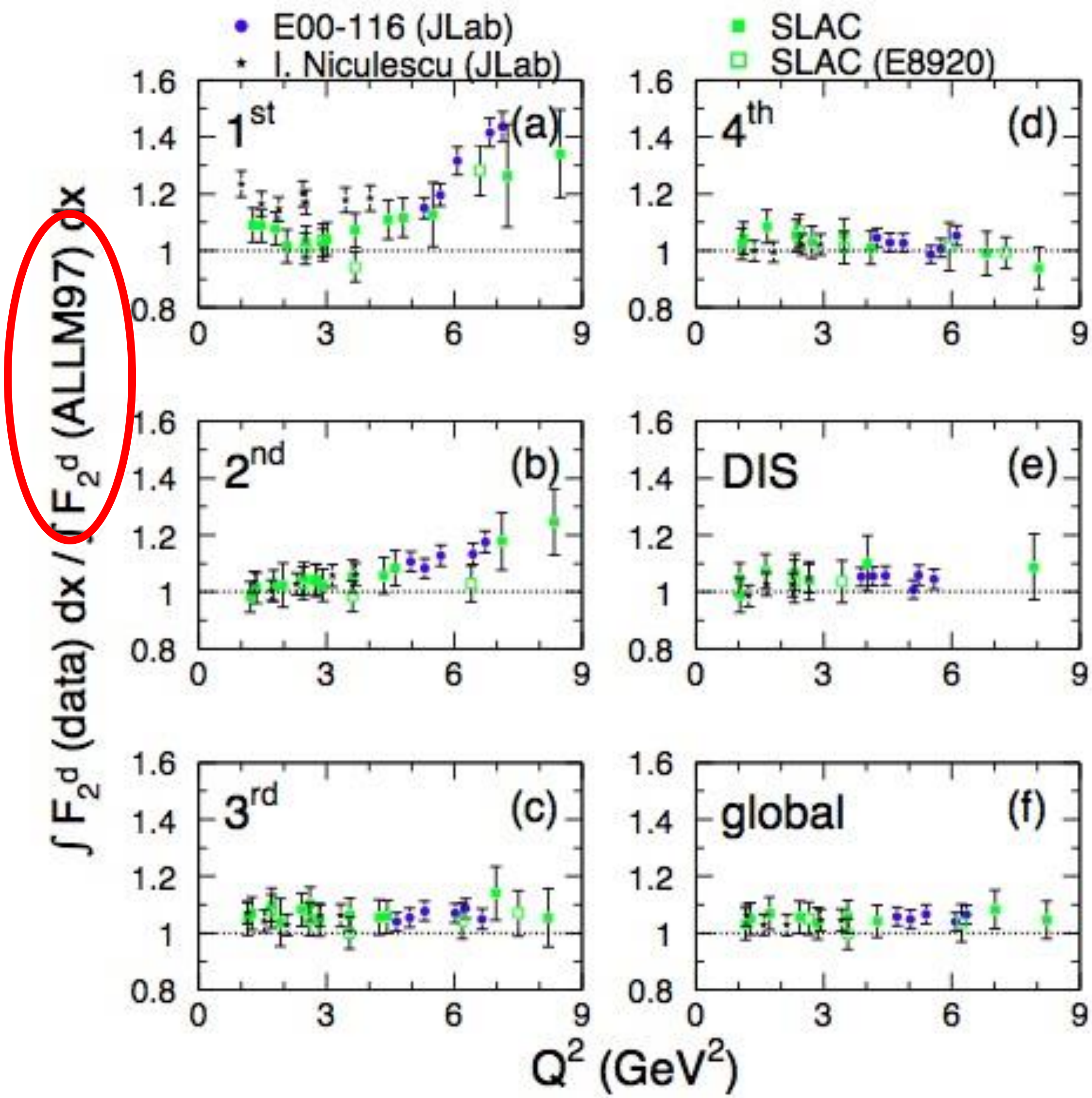
But, quantification can be a challenge!

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

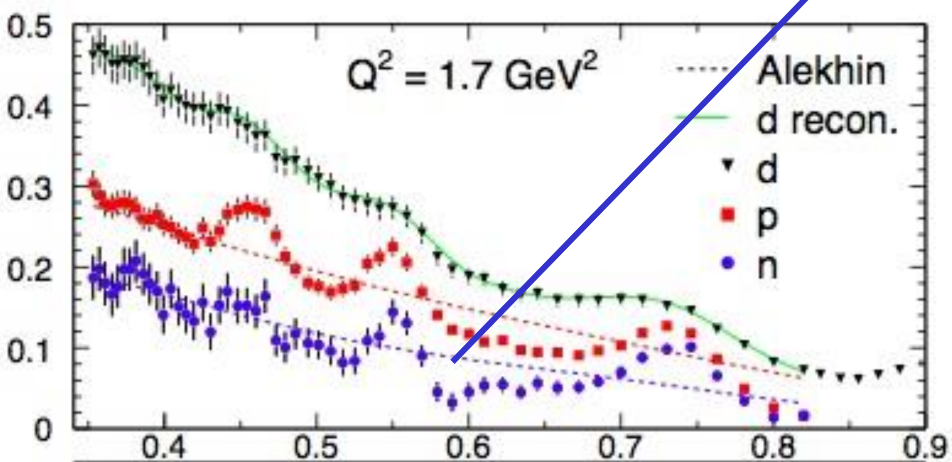
Neutron Duality using Deuterium Data

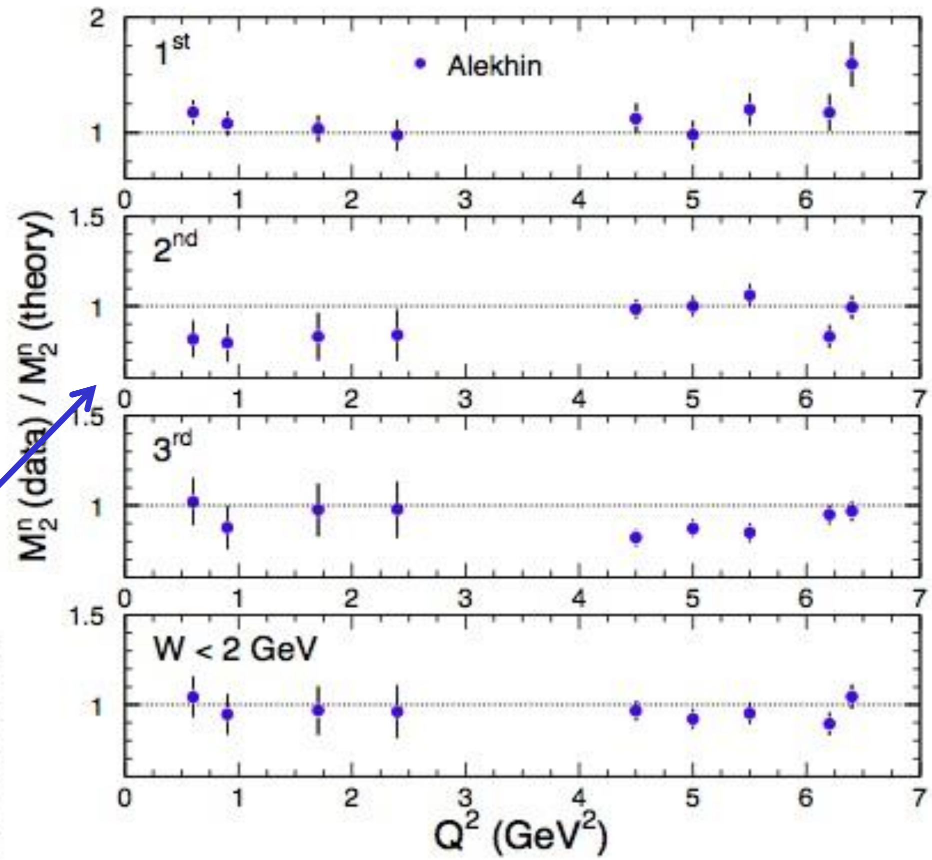
S.P. Malace, Y. Kahn, W. Melnitchouk, CK, Phys.Rev.Lett. 104 (2010) 102001

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



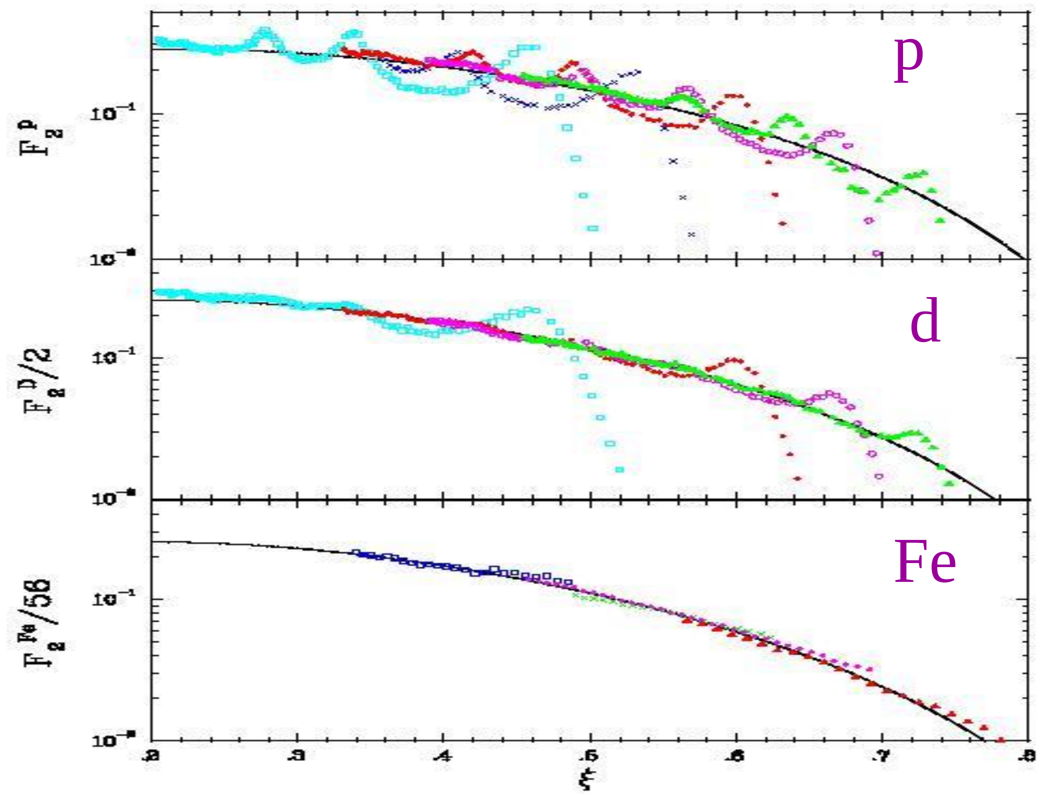


Also Neutron Duality studied using BONUS data! *I. Niculescu et al., Phys. Rev. C 91 (2015)*

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

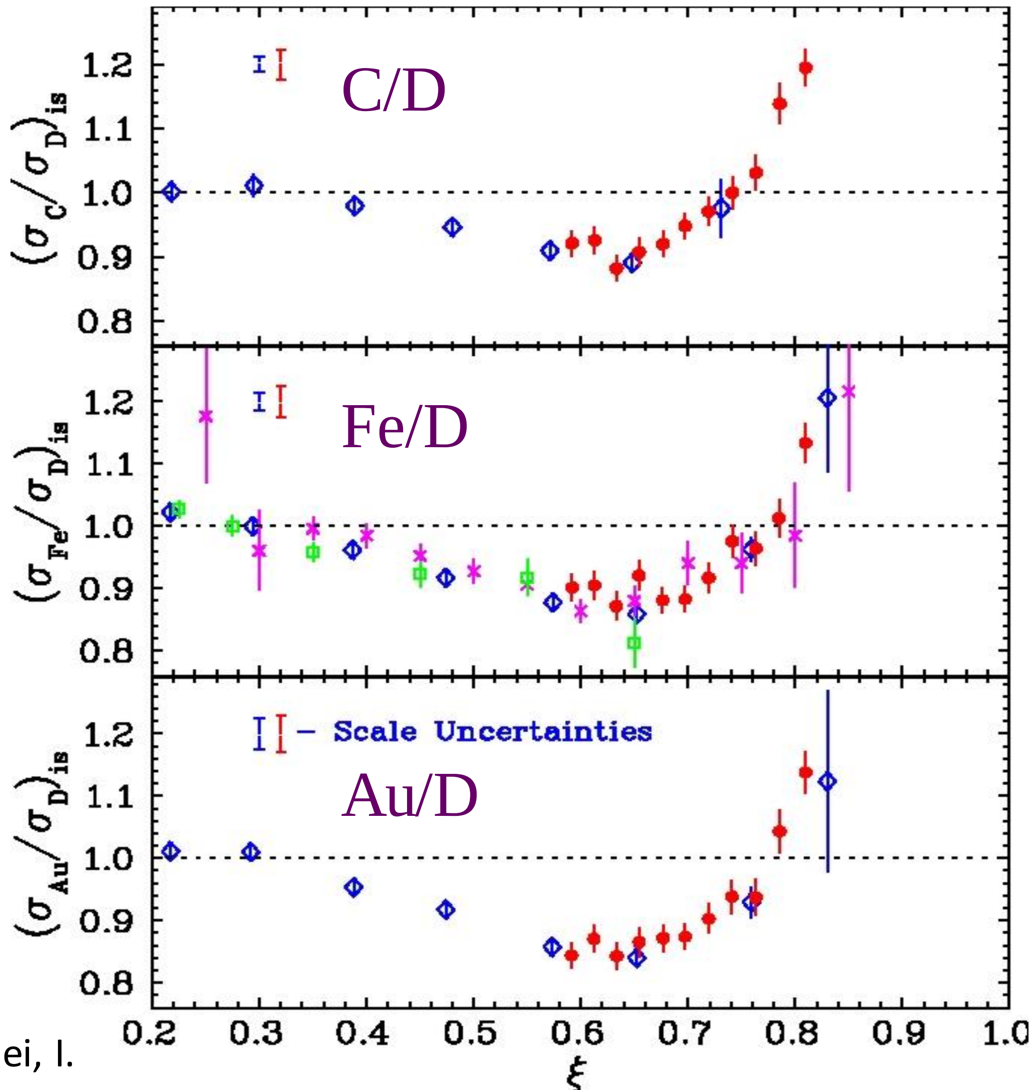
J. Arrington, et al., Phys.Rev.C73:035205 (2006)



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

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



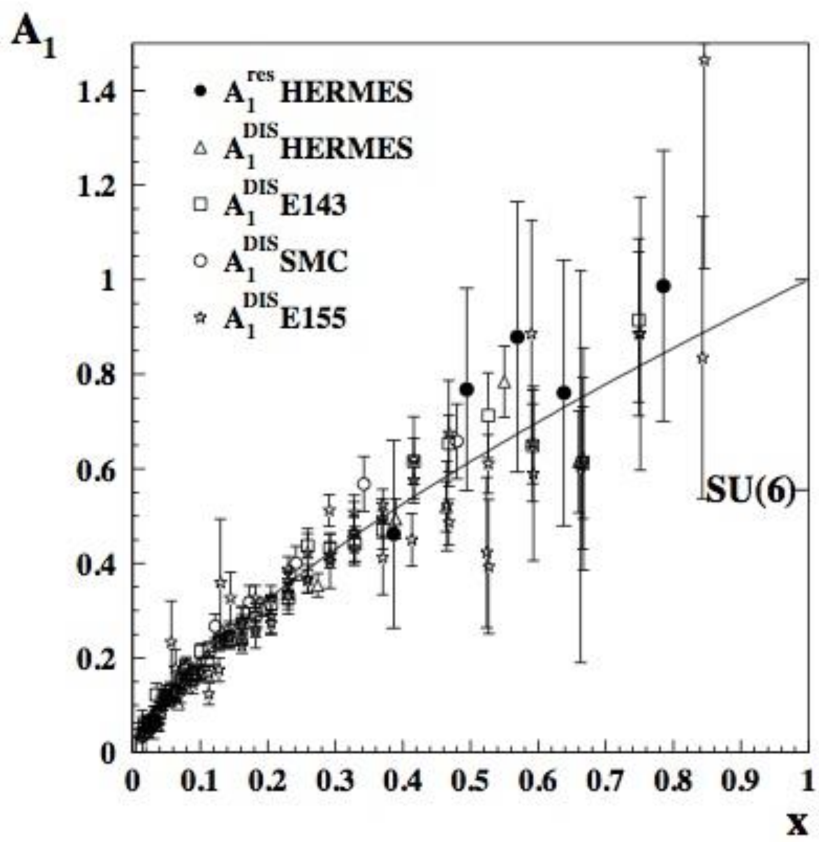
J. Arrington, R. Ent, CK, J. Mammei, I. Niculescu, **Phys.Rev. C73 (2006) 035205**

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



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."

Just a few data points…

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

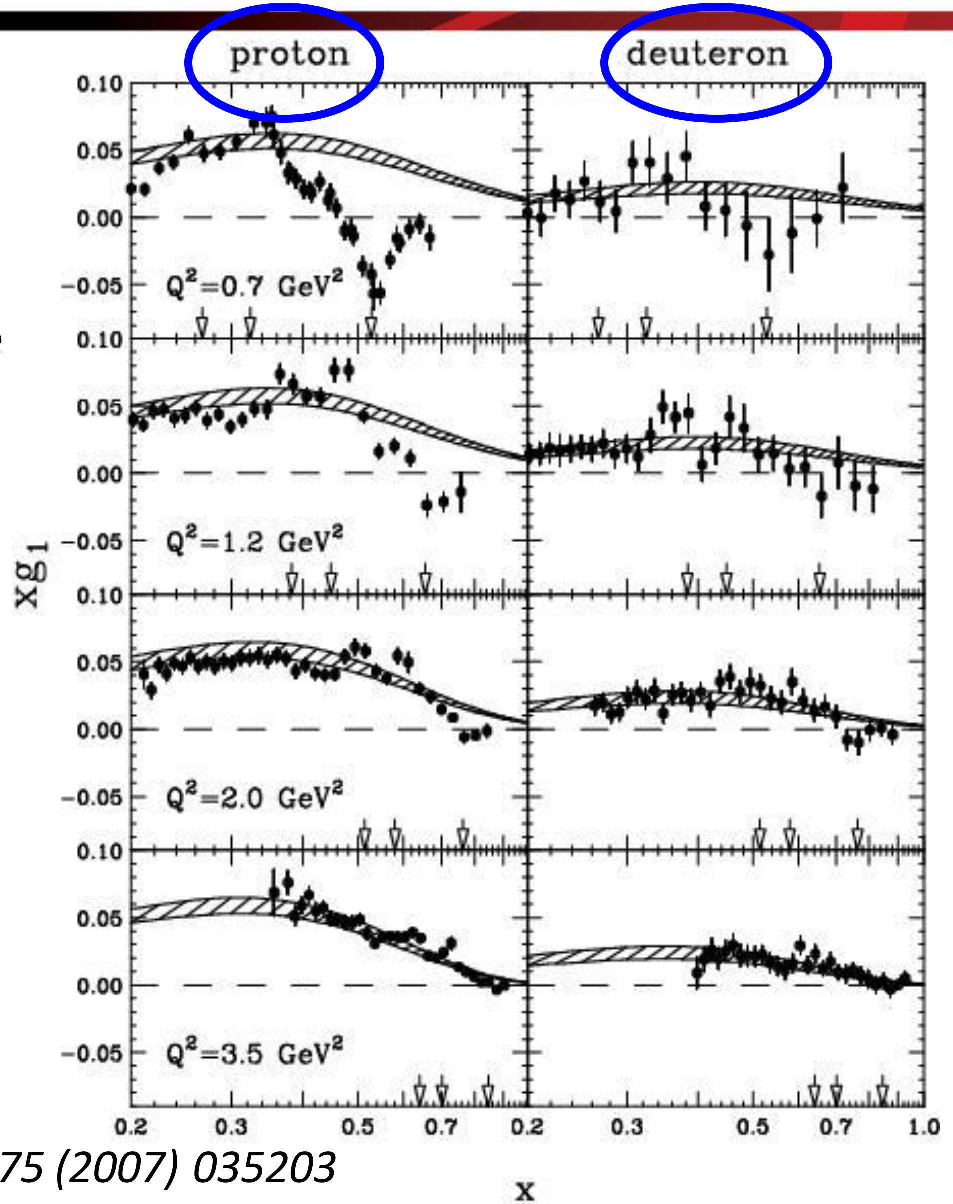
Duality in Polarized $^{1,2}\vec{H}(\vec{e}, e')$ Scattering

- 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.

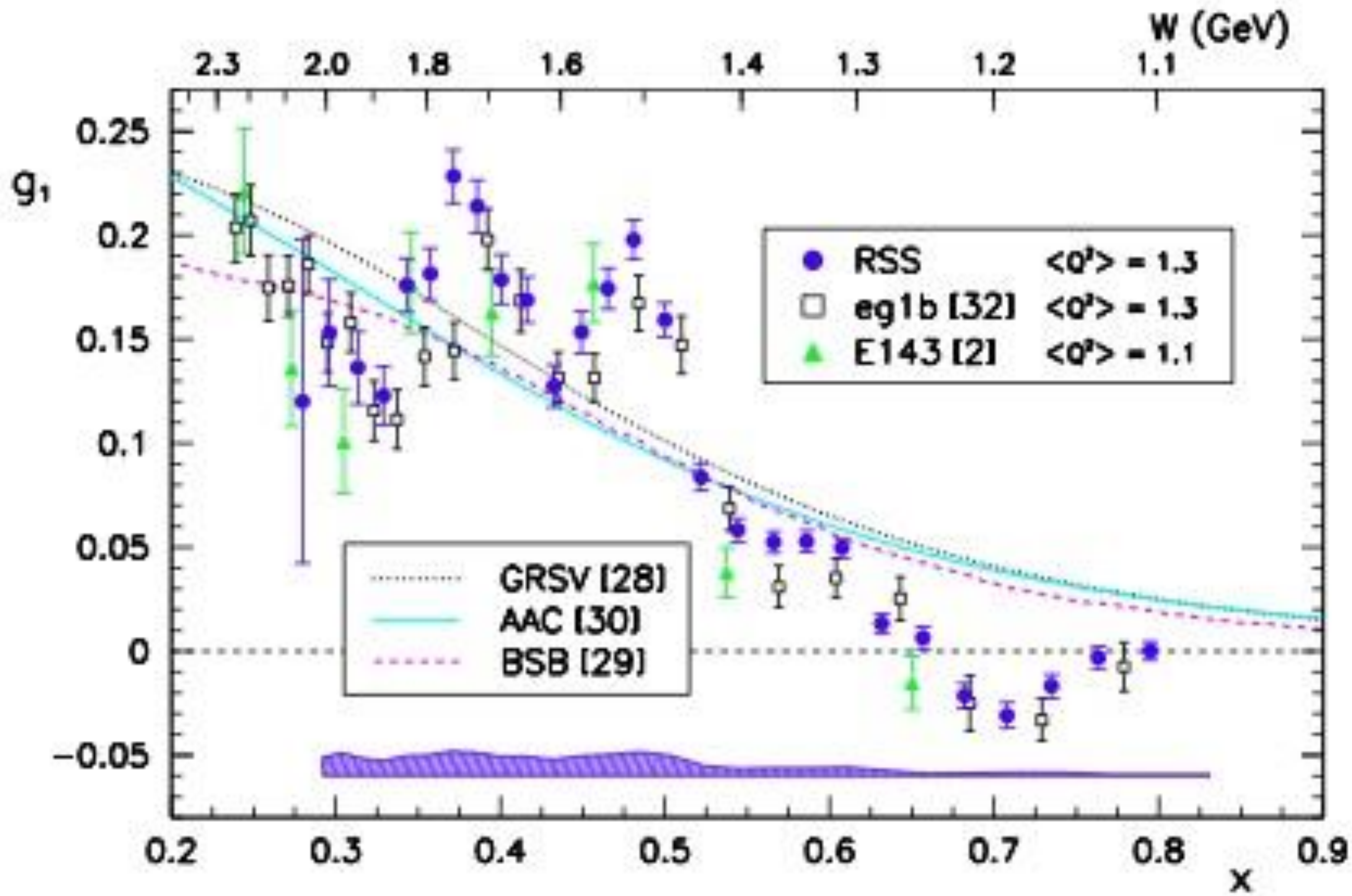
- "Δ" region remains below the NLO PDF fits for low Q^2.

- "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 $\vec{p}(\vec{e},e')$ 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

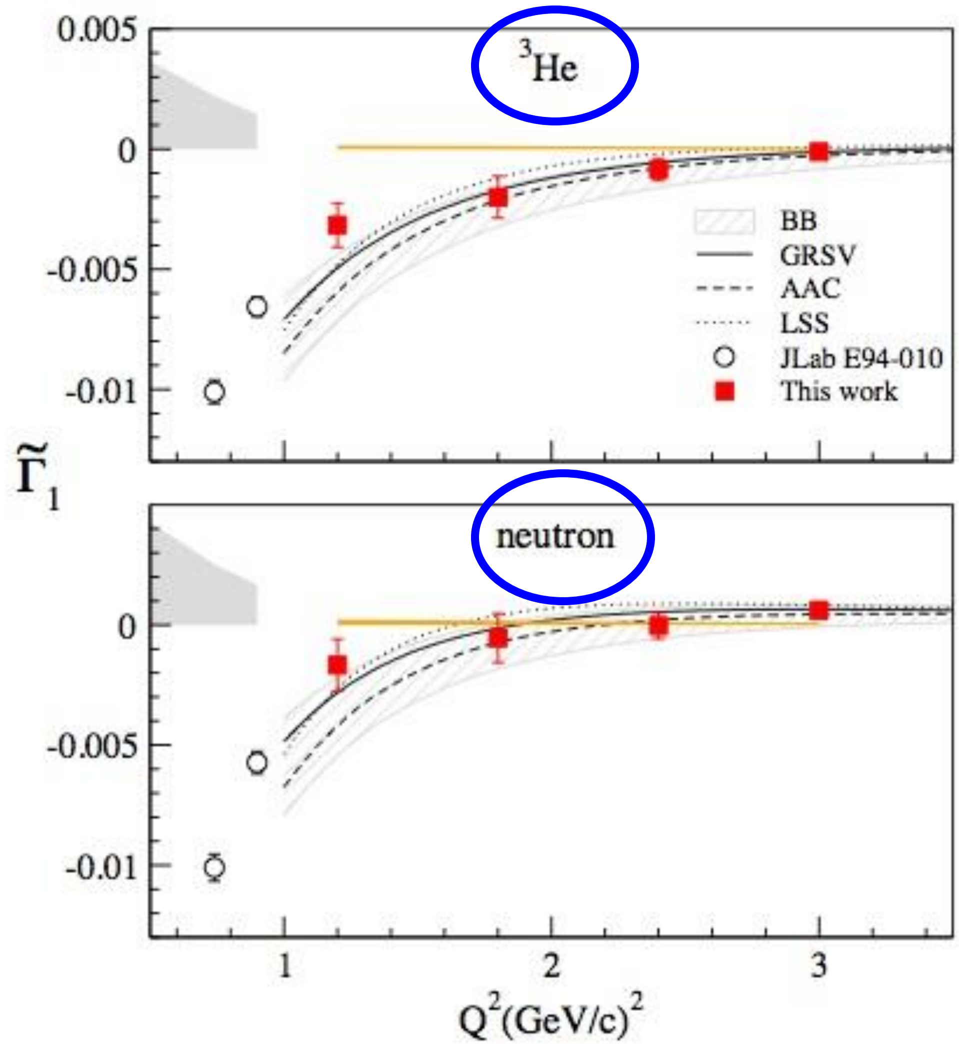
Inclusive $^3\vec{He}(\vec{e},e')$ Scattering

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

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

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

$$\tilde{\Gamma}_1^{n} = \frac{1}{p_n}\tilde{\Gamma}_1^{^3He} - 2\frac{p_p}{p_n}\tilde{\Gamma}_1^{p}$$



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

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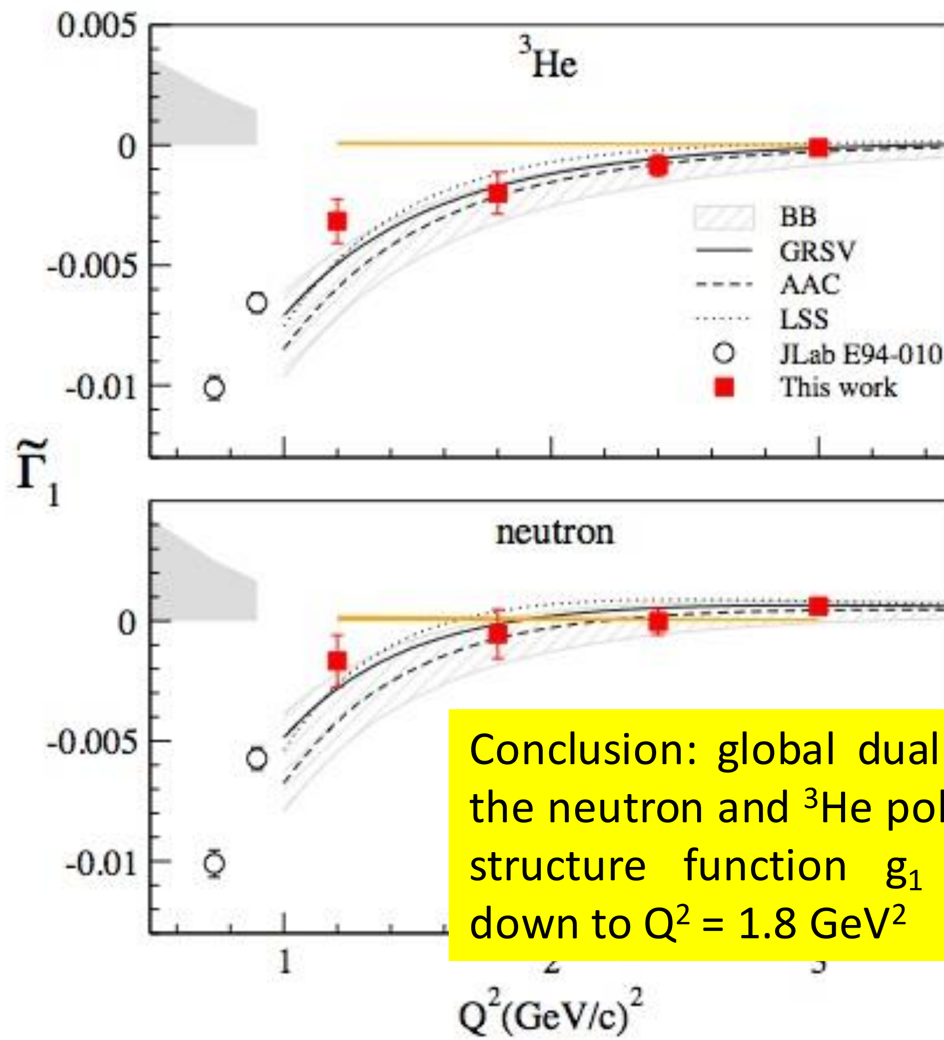


Conclusion: global duality for the neutron and ^{3}He polarized structure function g_1 holds down to Q^2 = 1.8 GeV^2

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

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…

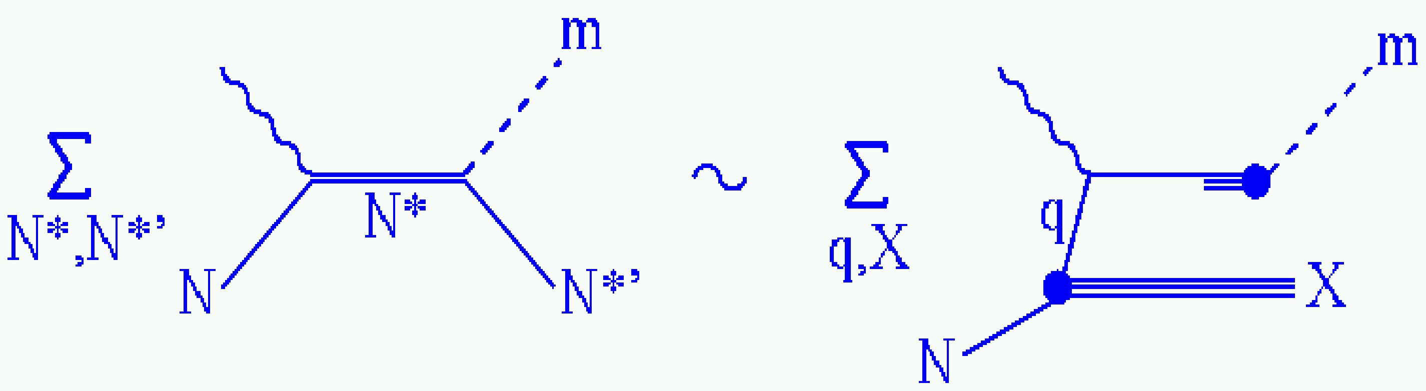
Less well at lowest Q^2 values

Less well at highest x, Delta, region
-Single state

Scaling curves vary – makes quantification difficult

Duality in Meson Electroproduction

hadronic description quark-gluon description



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

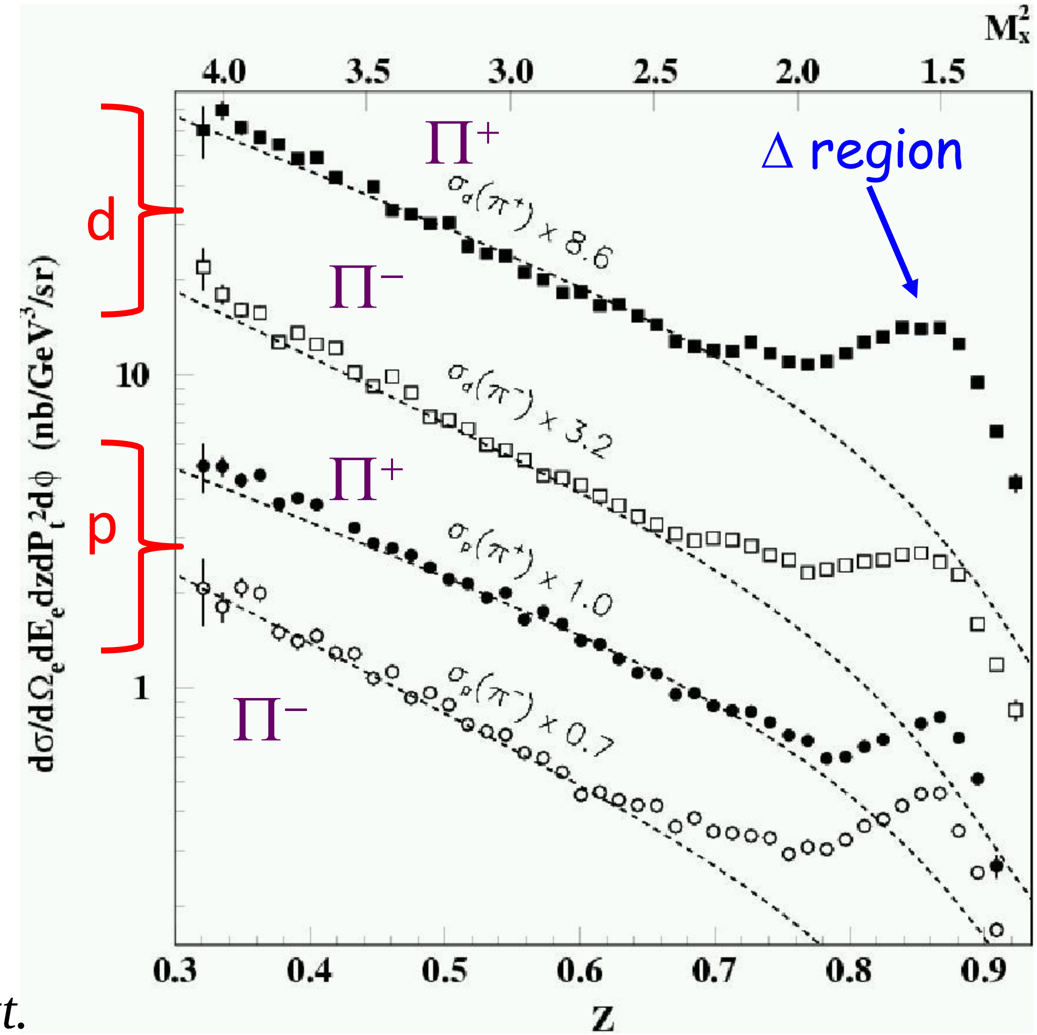
Transition Form Factor — Decay Amplitude — Fragmentation Function

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

Requires non-trivial cancellations of decay angular distributions
"If duality is not observed, factorization is questionable."

Duality in (Semi-Inclusive) Pion Electroproduction

- $^{1,2}H(e,e'\pi\pm)X$ 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…

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- ✓ 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 π^+
- ✓ SIDIS p π^-
- ✓ SIDIS d π^+
- ✓ SIDIS d π^-

- ✓ Also…parity-violating electron scattering

Duality appears to be a fundamental, non-trivial property of nucleon structure

– *clue to the nature of confinement?*

- *how to better understand this?*

- *some outstanding questions…*

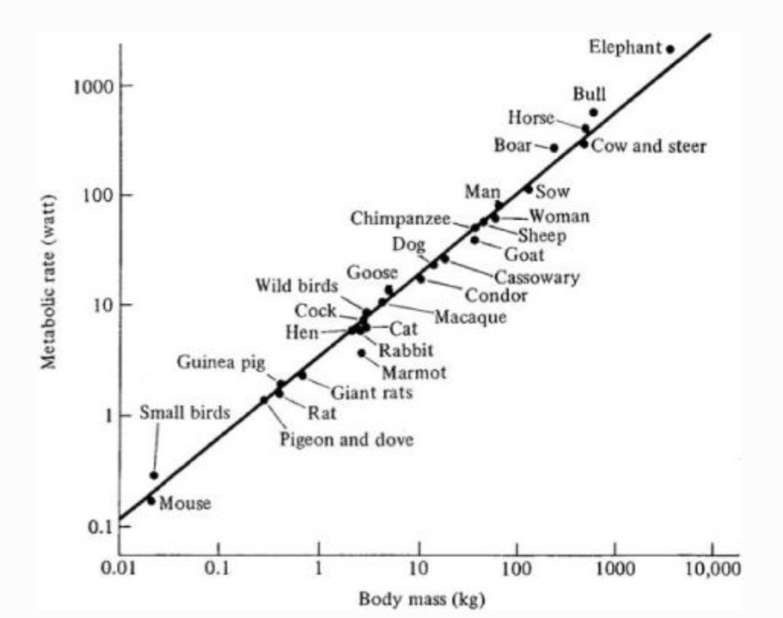
A larger picture….?...

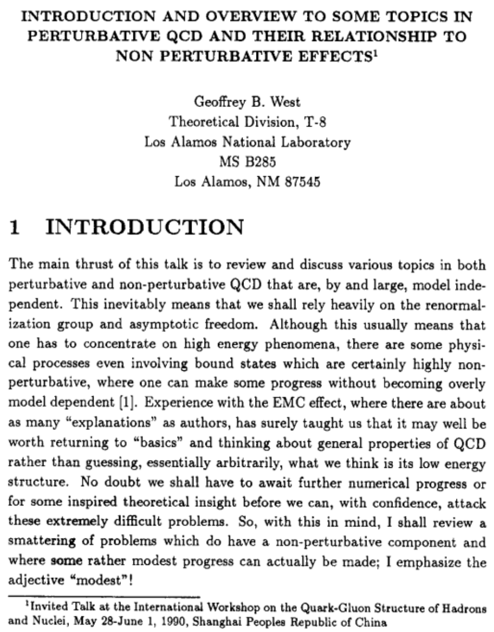
R. Casadio, A.Yu. Kamenshchik, O.V. Teryaev

Hawking radiation and the Bloom-Gilman duality

Class.Quant.Grav. 35 (2018)

"The decay widths of the quantum black hole precursors, determined from the poles of the resummed graviton propagator, are matched to the expected lifetime given by the Hawking decay. In this way, we impose a sort of duality between a perturbative description and an essentially non-perturbative description, bearing some similarity with the Bloom-Gilman duality for the strong interactions."





INTRODUCTION AND OVERVIEW TO SOME TOPICS IN PERTURBATIVE QCD AND THEIR RELATIONSHIP TO NON PERTURBATIVE EFFECTS[1]

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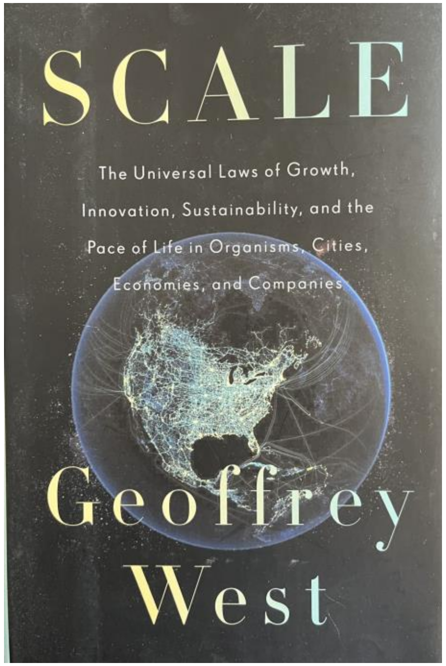
1 INTRODUCTION

The main thrust of this talk is to review and discuss various topics in both perturbative and non-perturbative QCD that are, by and large, model independent. This inevitably means that we shall rely heavily on the renormalization group and asymptotic freedom. Although this usually means that one has to concentrate on high energy phenomena, there are some physical processes even involving bound states which are certainly highly non-perturbative, where one can make some progress without becoming overly model dependent [1]. Experience with the EMC effect, where there are about as many "explanations" as authors, has surely taught us that it may well be worth returning to "basics" and thinking about general properties of QCD rather than guessing, essentially arbitrarily, what we think is its low energy structure. No doubt we shall have to await further numerical progress or for some inspired theoretical insight before we can, with confidence, attack these extremely difficult problems. So, with this in mind, I shall review a smattering of problems which do have a non-perturbative component and where some rather modest progress can actually be made; I emphasize the adjective "modest"!

[1]Invited Talk at the International Workshop on the Quark-Gluon Structure of Hadrons and Nuclei, May 28-June 1, 1990, Shanghai Peoples Republic of China

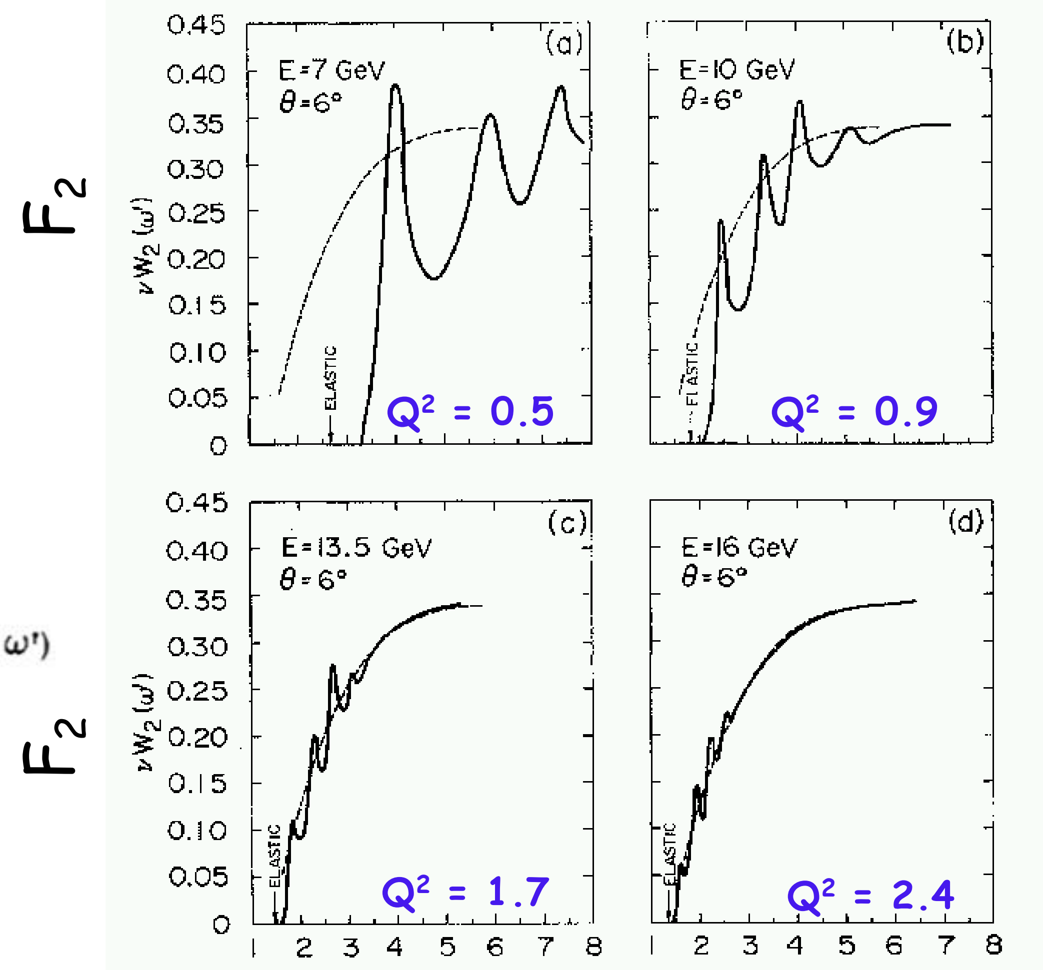


Back to the Basics

- Comparing low W,Q data to high W,Q data (or now pdf curve)
- Integrated F_2 strength in nucleon resonance region equals strength under scaling curve.
- Finite energy sum rule:

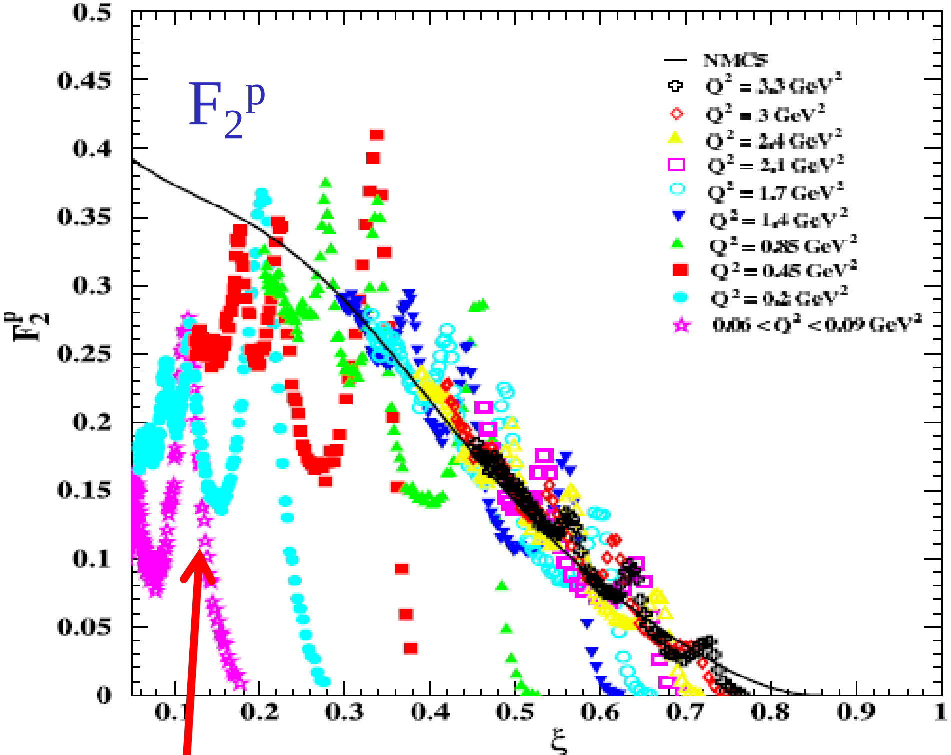
$$\frac{2M}{q^2}\int_0^{\nu_m} d\nu\ \nu W_2(\nu,q^2) = \int_1^{(2M\nu_m+m^2)/q^2} d\omega'\ \nu W_2(\omega')$$

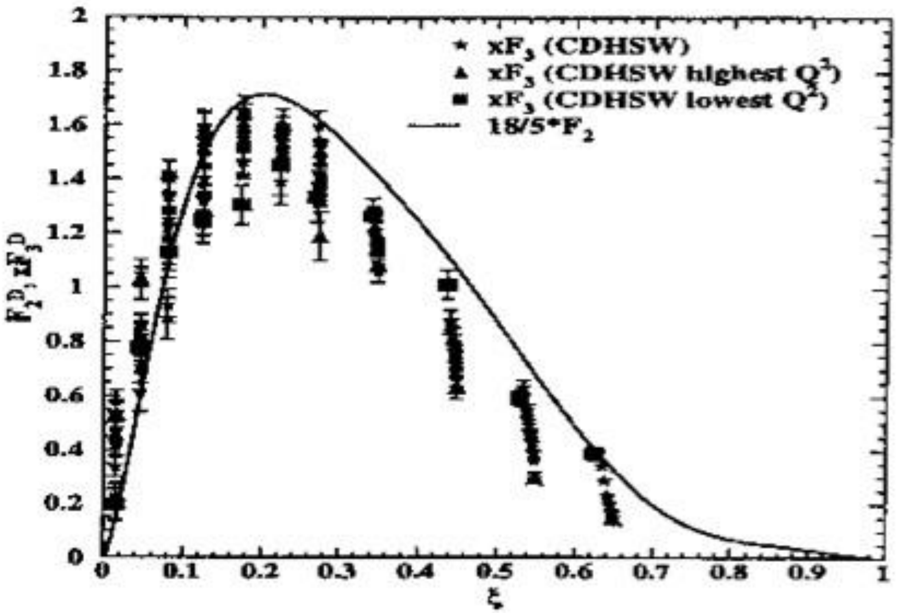
- Resonances oscillate around curve *at all Q^2*



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

What is the average curve? Is it the pure valence distribution?



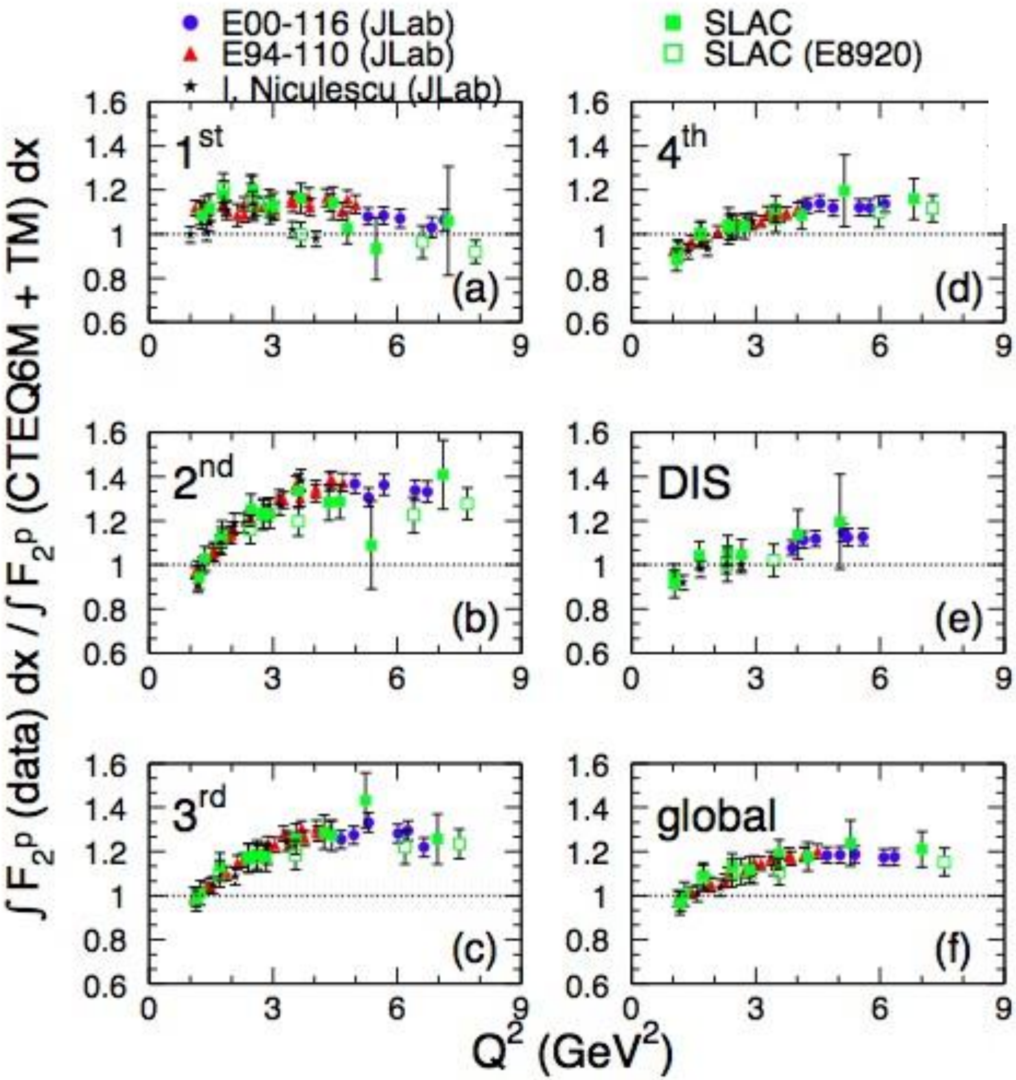


Low Q^2 – while low x, perhaps wavelength such that sea quarks "invisible"??

Curve = average electron scattering D data * 18/5

Data = DIS neutrino xF_3 (nuclear averaged to D), valence sensitive only

Too much focus on the integral value? – what about Q^2 dependence?



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

Integral ratio flattens in Q^2

- Q^2 behavior of scaling curve should be known
- **Q^2 behavior is hallmark of pQCD**
- Resonances displaying same
- Another critical test of duality
- Seems to exhibit an onset at $Q^2 \sim 3$ GeV^2

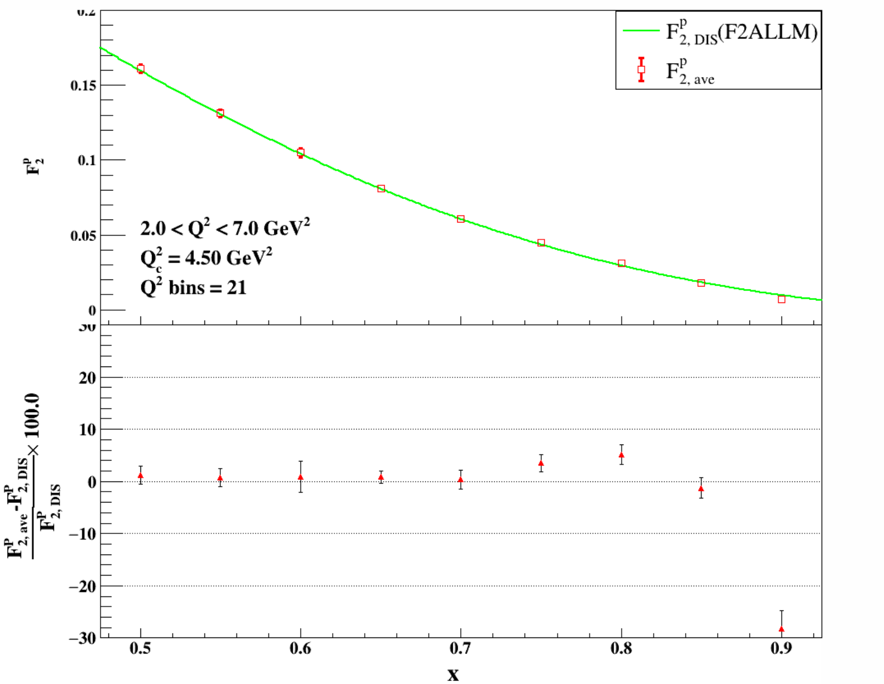
S. Malace, et al., Phys.Rev. C80 (2009) 035207

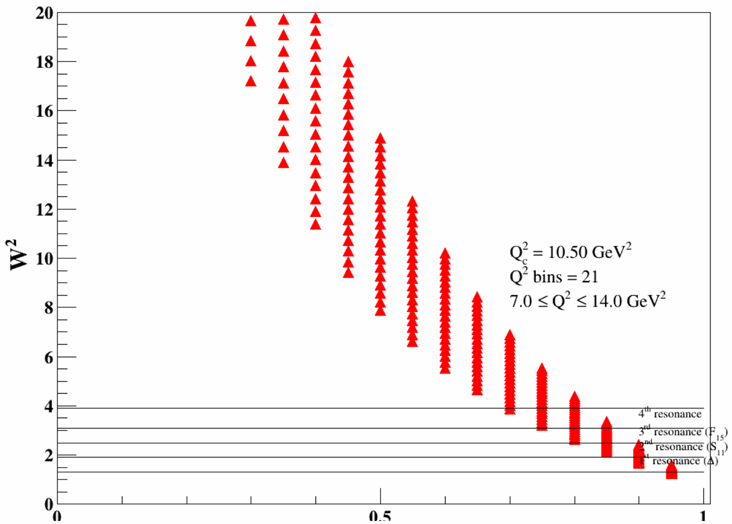
Should work even better at high Q^2….

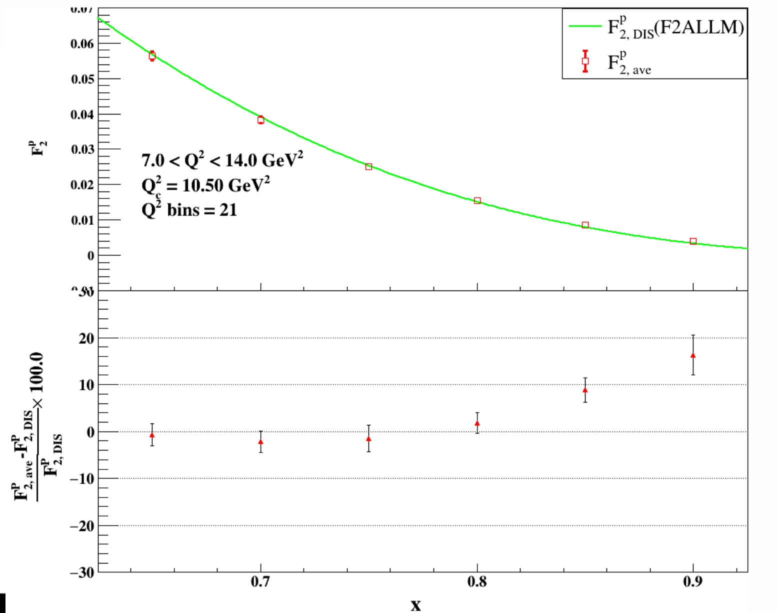
Debaditya Biswas, *PhD Thesis (publication in progress)*

12 GeV data (see W. Henry talk today)!

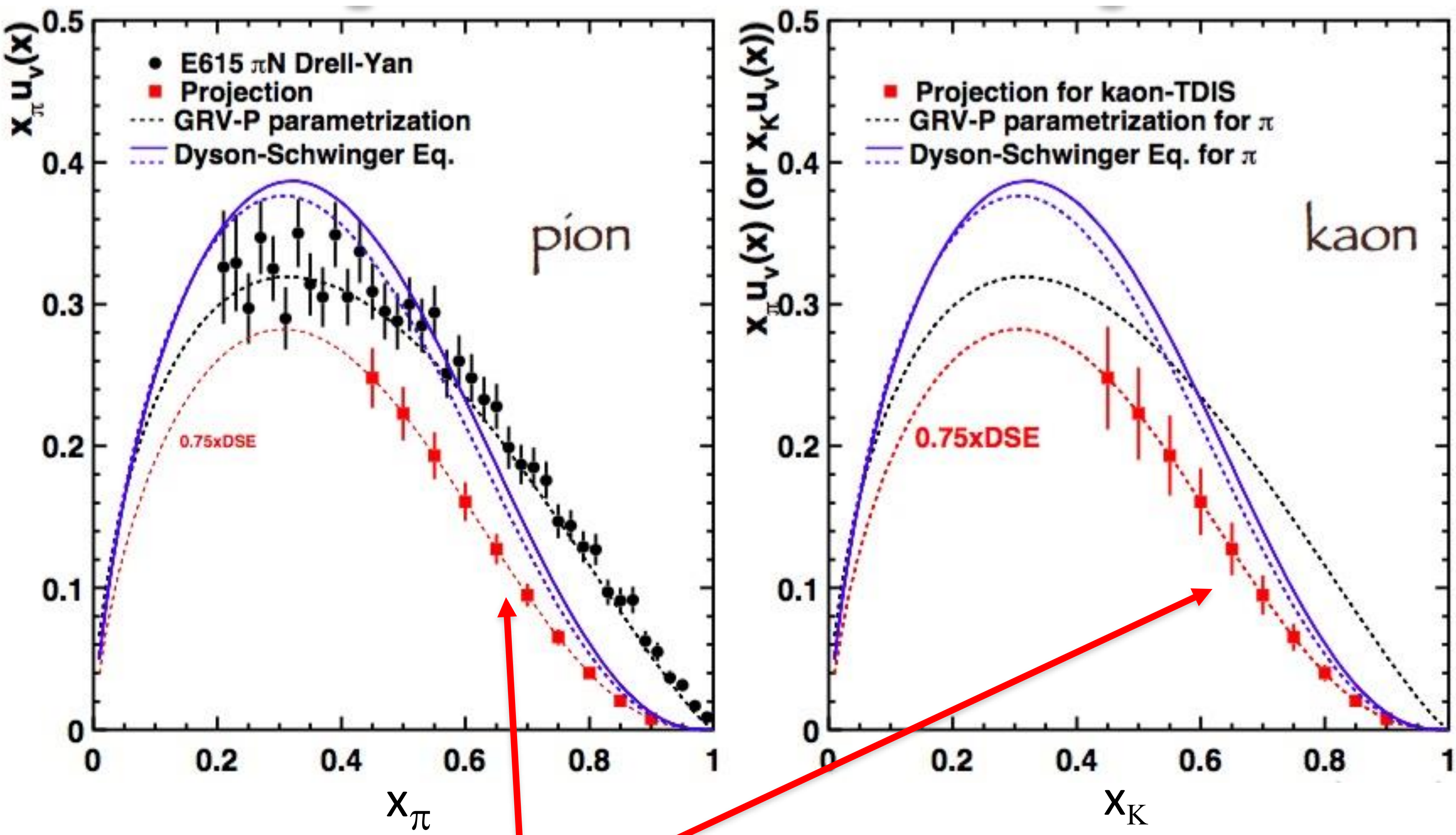
Duality averaging approach







In the 12 GeV future… Will duality hold also for meson structure functions?



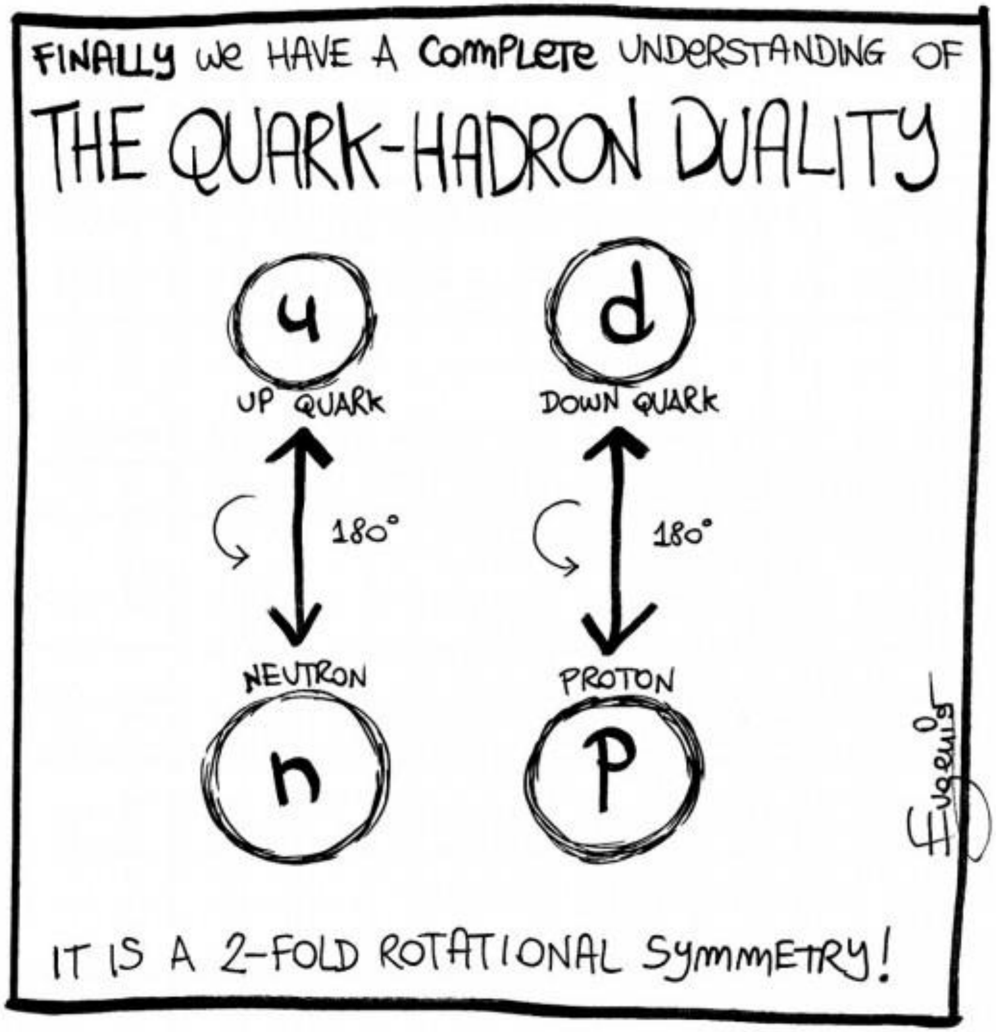
Projected TDIS results

Essentially no data currently

Summary

- Quark-hadron duality is somehow a fundamental property of nucleon structure
  - **Works generally in every process studied**
  - Studies now *quite* numerous!
- Seems to need >1 state for averaging
  - Elastic add to moments
  - Delta alone a problem
  - But, how many?
- Challenges to quantifying experimentally
  - pQCD predictions for large x, low Q have large uncertainties
- Integral OR Q^2-dependence or both?
  - what is the average curve?
- Can we use duality as a tool to probe large x?

- If understood better, a powerful tool to understand confinement
  - Hadronic observables determined by pQCD calculations



From CP^3 Danish National Research Foundation

Open Questions

What is the fundamental, underlying mechanism for duality?

Can we test in 3D and, if so, what quantities to measure?

Are there any missing measurements that should be made?