Quark-Hadron Duality in Structure Functions

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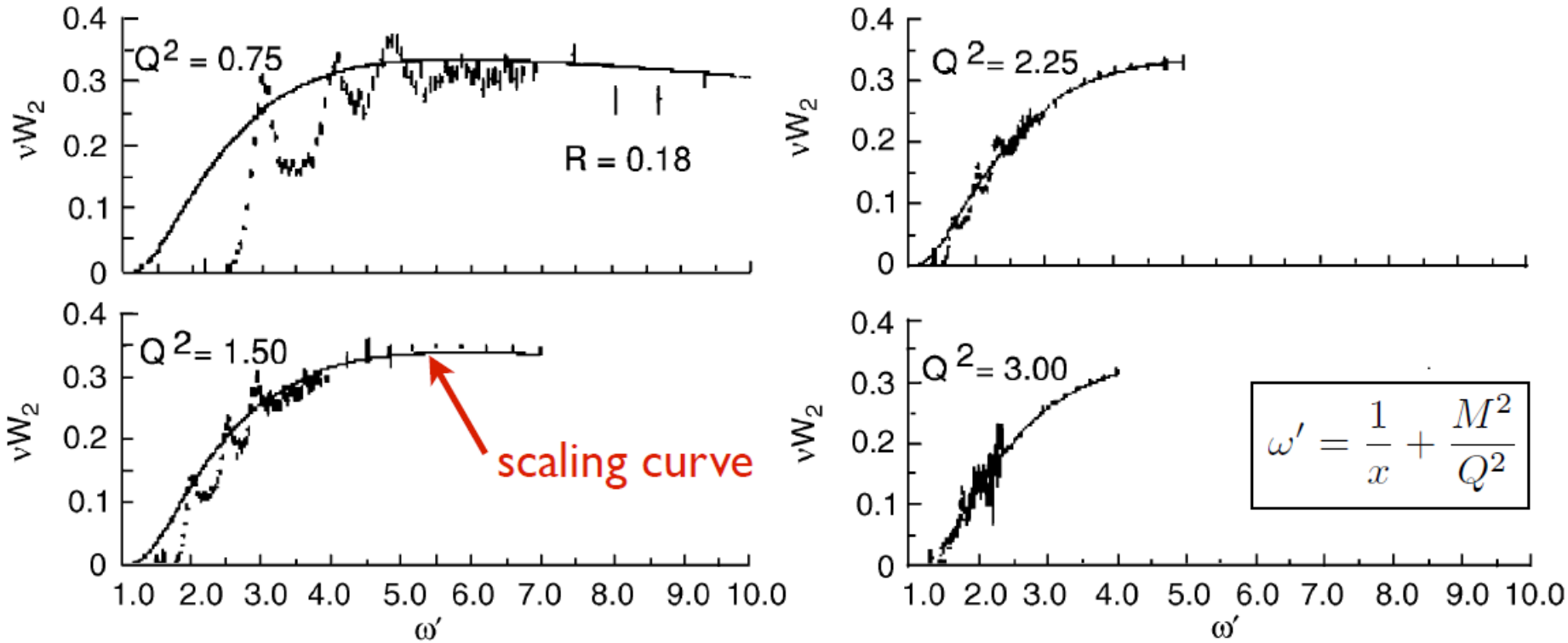
Overview

- Introduction, historical perspective
  - Bloom-Gilman Duality
  - Duality in QCD
- Verification of Quark-Hadron Duality and its possible applications
  - Procedure
  - Results: spin-averaged proton and neutron F_2 structure function
  - Spin sector: duality in proton helicity structure function
- Summary

Duality in Electron-Hadron Scattering

- Bloom-Gilman Duality Phys. Rev. Lett. 25, 1140 (1970)



$$\omega' = \frac{1}{x} + \frac{M^2}{Q^2}$$

$$\frac{2M}{Q^2}\int_0^{\nu_m} \nu W_2(\nu, Q^2)\, d\nu = \int_1^{\omega'_m} \nu W_2(\omega')\, d\omega'$$

- Description in terms of quarks or hadrons are equivalent

QCD Interpretation

- Operator Product Expansion

De Rujula, Georgi, Politzer, Phys. Lett. B 64, 428 (1976)

"The most intriguing aspects of SLAC data on inclusive electroproduction are precocious scaling and local duality"

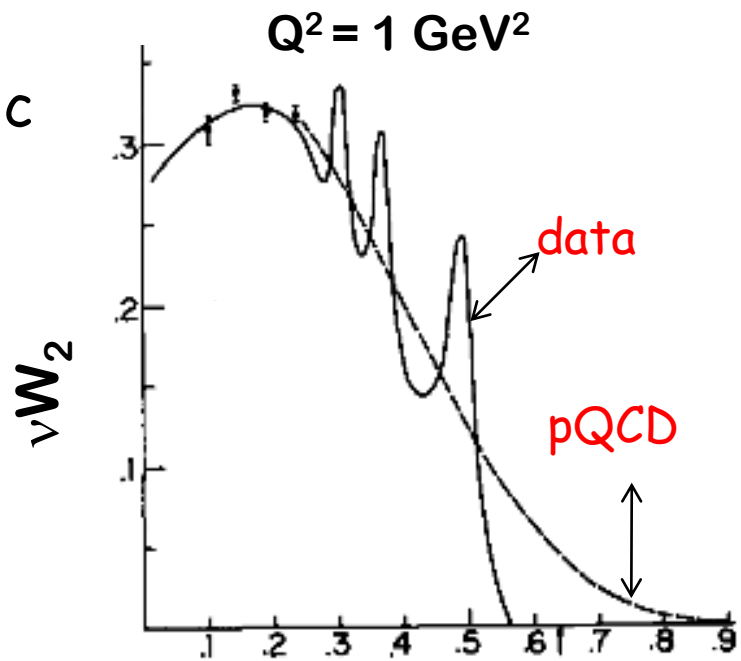
$$\int_0^1 \xi^n F(\xi, Q^2) d\xi = \underbrace{A_n(Q^2)}_{\text{twist-2}} + \text{higher twists}$$

$$\upsilon W_2(Q^2, x) = \frac{x^2}{k^3} F_2^S(\xi, Q^2) + 6\frac{m^2}{Q^2}\frac{x^3}{k^4}\int_\xi^1 d\xi' F_2^S(\xi', Q^2) + 12\frac{m^2}{Q^4}\frac{x^4}{k^5}\int_\xi^1 d\xi' \int_{\xi'}^1 d\xi'' F_2^S(\xi'', Q^2)$$

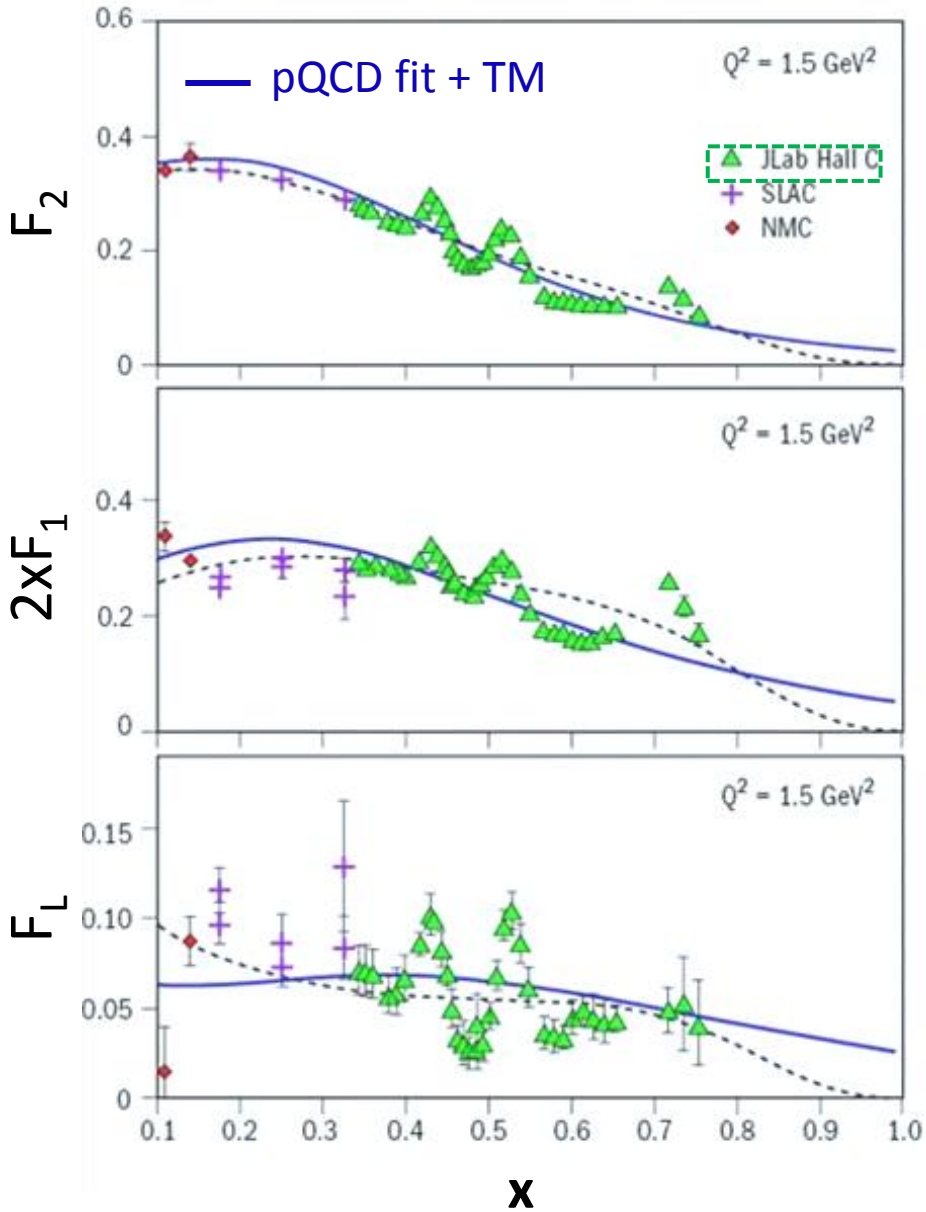
- On average, the resonance data mimic the twist-2 pQCD calculation

↕

Duality = higher twists are either small or cancel, on average



Quark-Hadron Duality: Confirmation at JLab



Duality in spin-averaged structure functions:

Y. Liang *et al.*, nucl-ex/0410027 (2004)

Resonances average to QCD curve down to a surprisingly low Q^2

↓

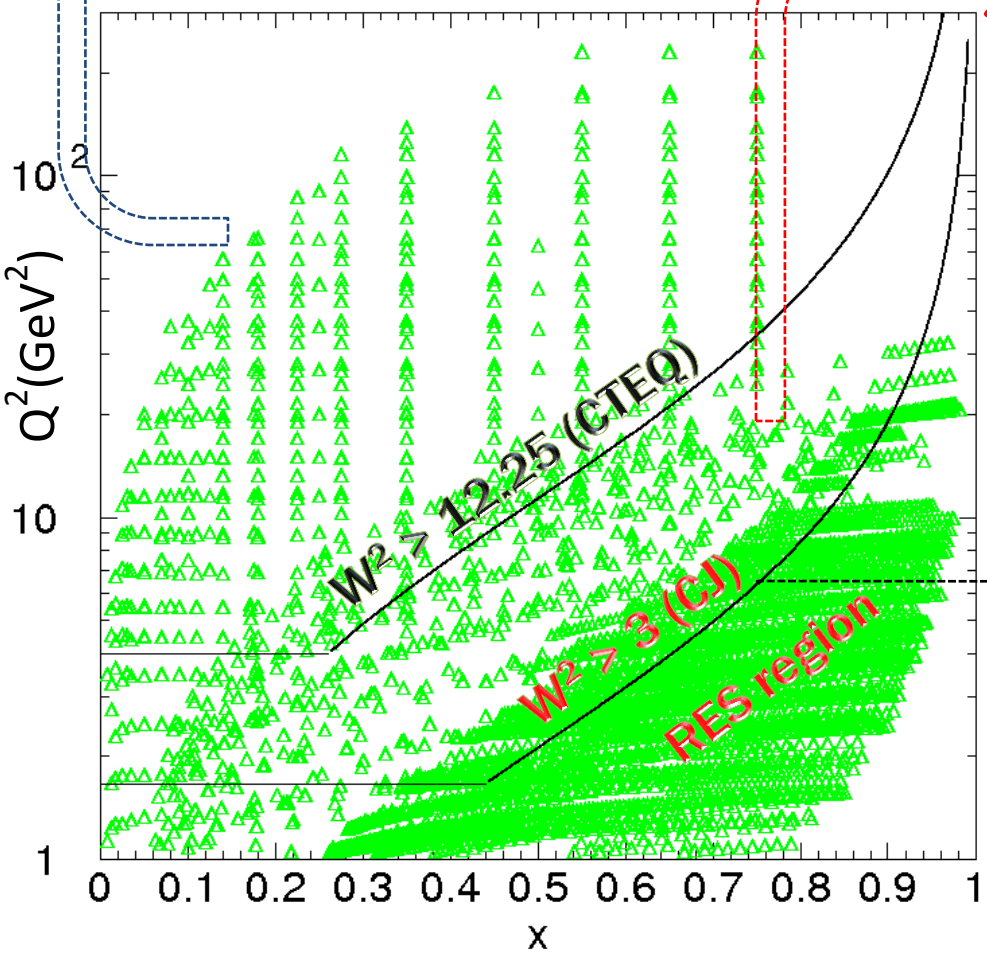
"The successful application of duality to extract known quantities suggests that it should also be possible to use it to extract quantities that are otherwise kinematically inaccessible."

(CERN Courier, 2004)

couldn't agree more…

Quark-Hadron Duality: Practical Application

- PDFs constrained up to **x ~ 0.65-0.7**: CTEQ, MRST (MSTW)…



- PDFs constrained up to **x ~ 0.8-0.9**

S. Alekhin, Phys. Rev. D 63, 094022 (2001)
…
S. Alekhin, J. Blumlein, S. Klein, S. Moch, Phys. Rev. D 81, 014032 (2010)

Accardi *et al.*, Phys. Rev. D 81, 034016 (2010)

Accardi *et al.*, arXiv:1102.3686

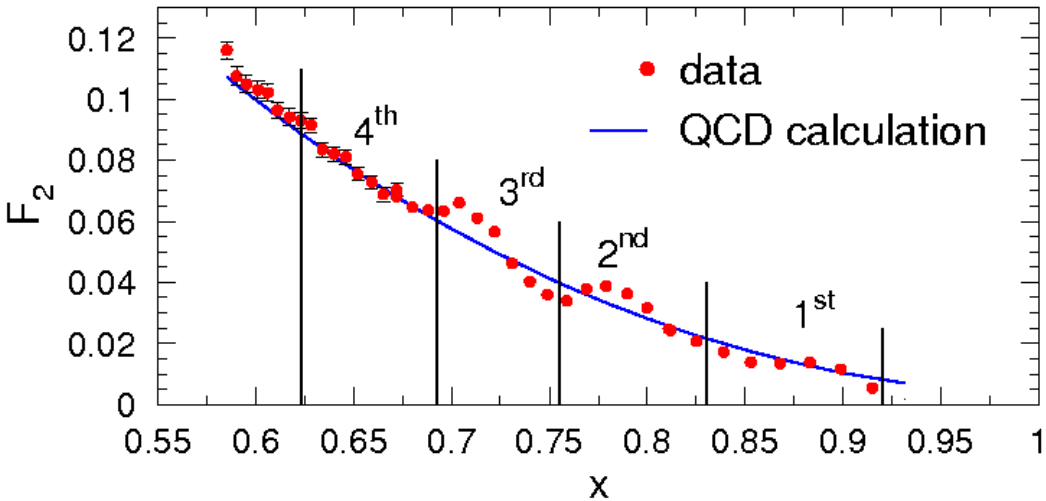
If duality works, why stop here?

Why not use averaged RES region data as additional constraints for PDFs at large x?

First Step: Verify Quark-Hadron Duality

- Simple procedure:

  1) Pick structure function from data and QCD calculation and delimit resonance regions for duality tests



Region	W^2_{min}	W^2_{max}
1st	1.3	1.9
2nd	1.9	2.5
3rd	2.5	3.1
4th	3.1	3.9
DIS	3.9	4.5

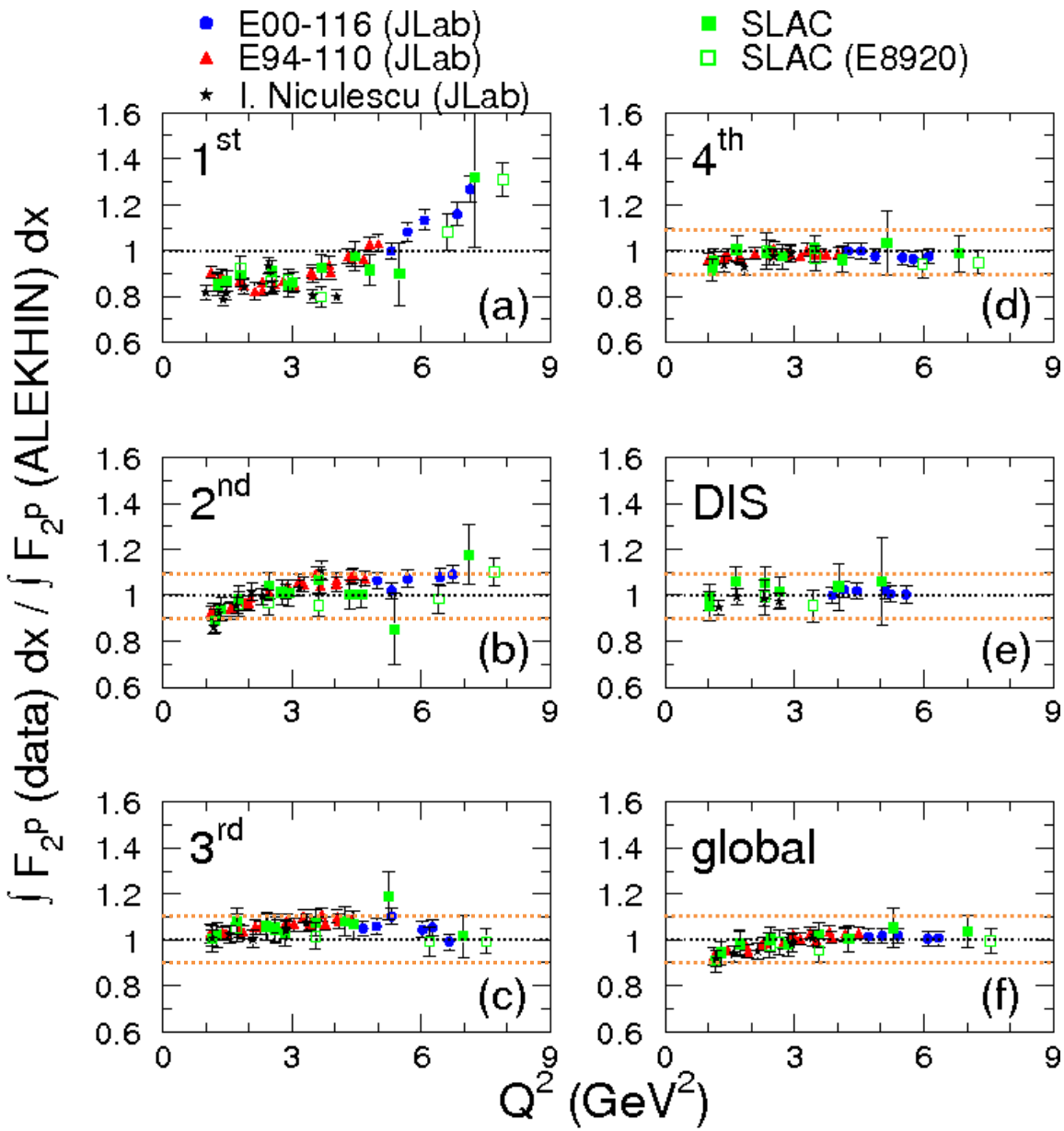
$$x = Q^2 / (W^2 + Q^2 - M^2)$$

2) Calculate:

$$\frac{\int_{x_m}^{x_M} F_2^{data}(x,Q^2)\,dx}{\int_{x_m}^{x_M} F_2^{QCD\ calc.}(x,Q^2)\,dx}$$

If ratio ~ 1 -> duality works

Duality in Proton F_2^p Structure Function



Ratio within 10% : globally, 4th, 3rd, 2nd

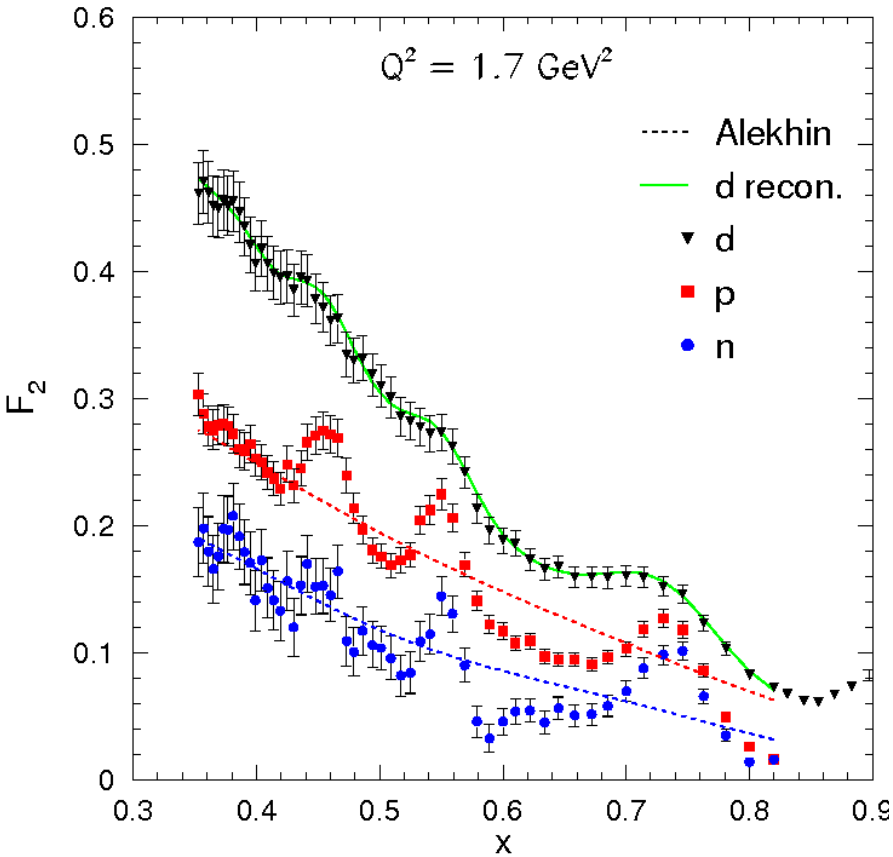
1st : special case

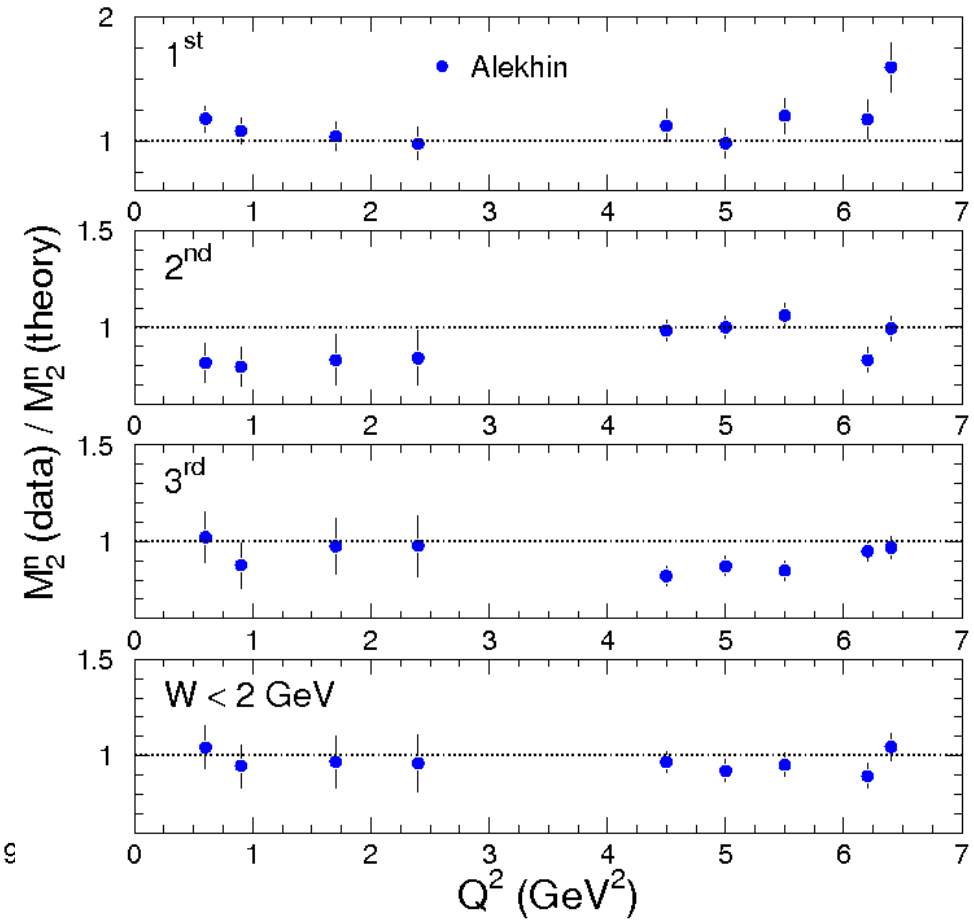
- models predict stronger violations of duality
- calculation based on handbag diagram may break at such low W
- at the largest x, QCD fits poorly constrained -> difficult to test duality

S.P. Malace *et al.*, Phys. Rev. C 80 035207 (2009)

Duality in Neutron F_2^n Structure Function

- F_2^n extracted from proton F_2^p and deuteron F_2^d structure functions



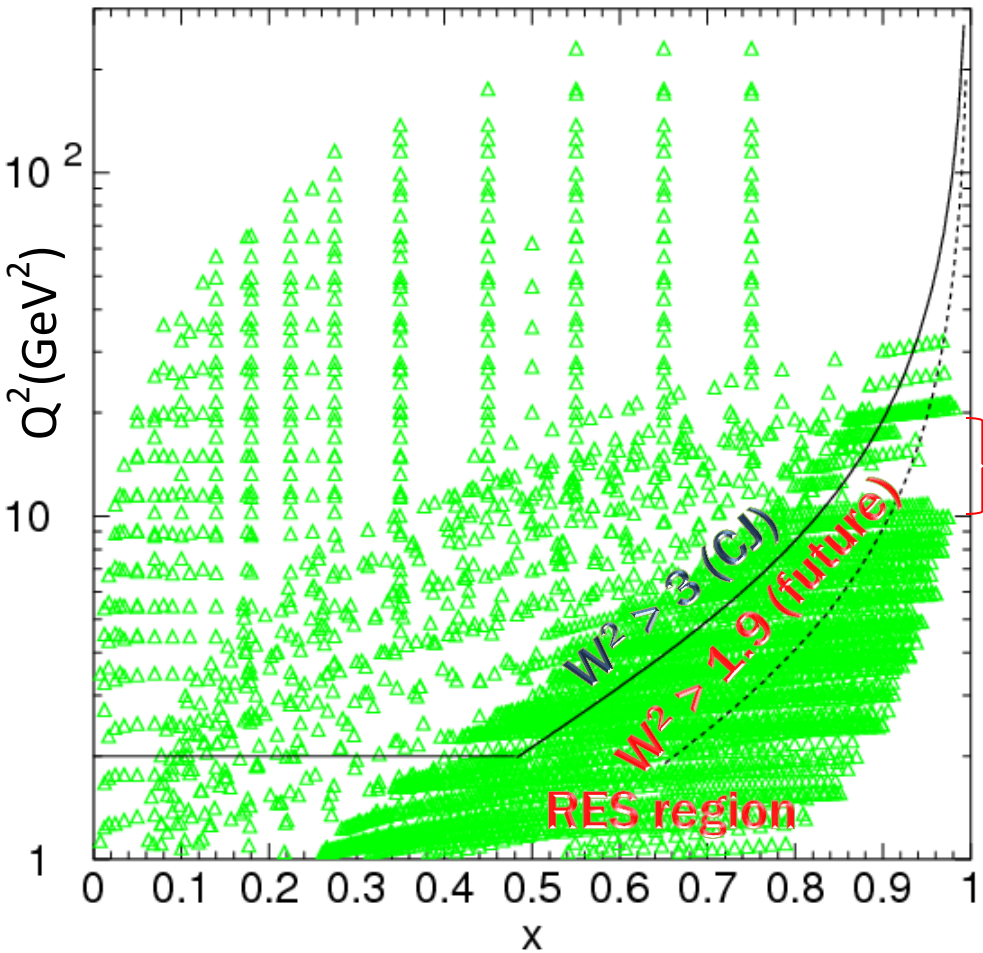


Ratio within 10% globally and 15%-20% for 3rd, 2nd

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

Quark-Hadron Duality: Practical Application

- Confirmation of duality in both proton and neutron F_2: globally, and locally down to the second resonance region ($W^2 > 1.9\ GeV^2$)



- Extend the pool of constraints for PDF fits to larger x by using averaged RES Region data

Future:

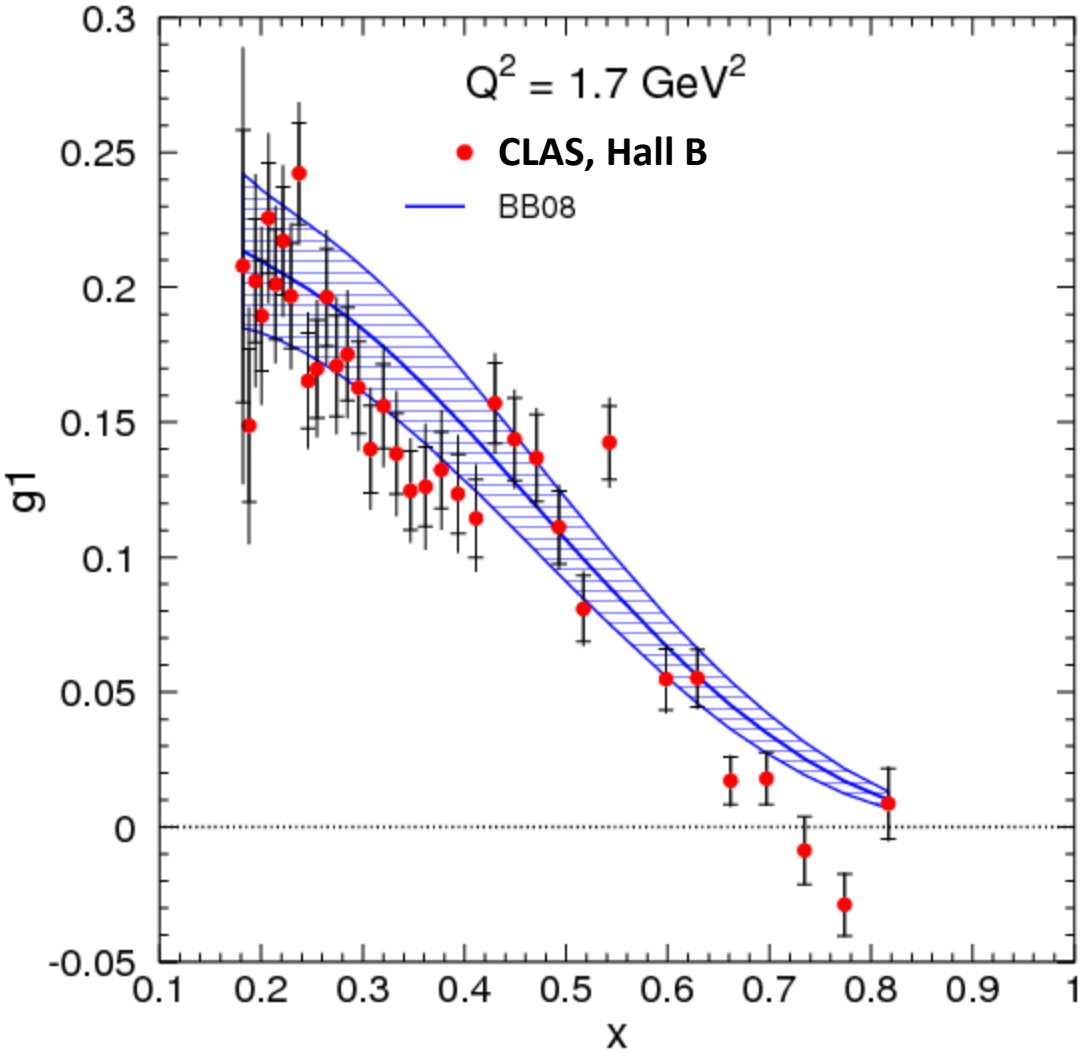
- E12-10-002 approved to run at JLab 12 GeV -> more data in RES and DIS regions at large x

- CJ collaboration: plans to explore this avenue

Could this be extended to the polarized sector?

Duality in Spin Structure Functions

- Fewer data in the polarized sector -> quark-hadron duality in g_1 and g_2 not established to the same precision as in F_1 and F_2



<u>Additional complication</u>: spin-dependent quantities not restricted to be positive

Example:

- proton g_1 negative in the 1st RES region (low Q2)
- neutron g_1 changes sign as a function of x

Go back to (more) basic quantities…

Duality in Proton Spin Structure Functions

- Inclusive scattering of a longitudinally polarized electron from a longitudinally polarized proton (P_z along the γ^* direction)

$$\frac{d\sigma}{d\Omega dE'} = \Gamma(\sigma_T + \varepsilon\sigma_L + hP_z\sqrt{1-\varepsilon^2}\,\sigma'_{TT})$$

$$\frac{1}{2}(\sigma_{1/2} + \sigma_{3/2}) \qquad \frac{1}{2}(\sigma_{3/2} - \sigma_{1/2})$$

$\sigma_{1/2}$, $\sigma_{3/2}$ -> helicity cross sections

- correspond to the spin of γ^* and proton antialigned (1/2) and aligned (3/2)
- in the Bjorken limit proportional to the positive and negative helicity PDFs
- defined to be positive

Duality in Proton Spin Structure Functions

- Define helicity structure functions $H_{1/2}$ and $H_{3/2}$

$$H_{1/2} = \frac{MK}{4\pi^2\alpha}\sigma_{1/2} \qquad H_{3/2} = \frac{MK}{4\pi^2\alpha}\sigma_{3/2}$$

S.P. Malace, W. Melnitchouk, A. Psaker, Phys. Rev. C 83, 035203 (2011)

$$H_{1/2} = F_1 + g_1 - \frac{Q^2}{\nu^2} g_2 \qquad H_{3/2} = F_1 - g_1 + \frac{Q^2}{\nu^2} g_2$$

- Choice of F_1, g_1, g_2
  - "Data" -> g_1 from E91-023 (CLAS, JLab) K.V. Dharmawardane *et al.*, Phys. Lett. B 641, 11 (2006)

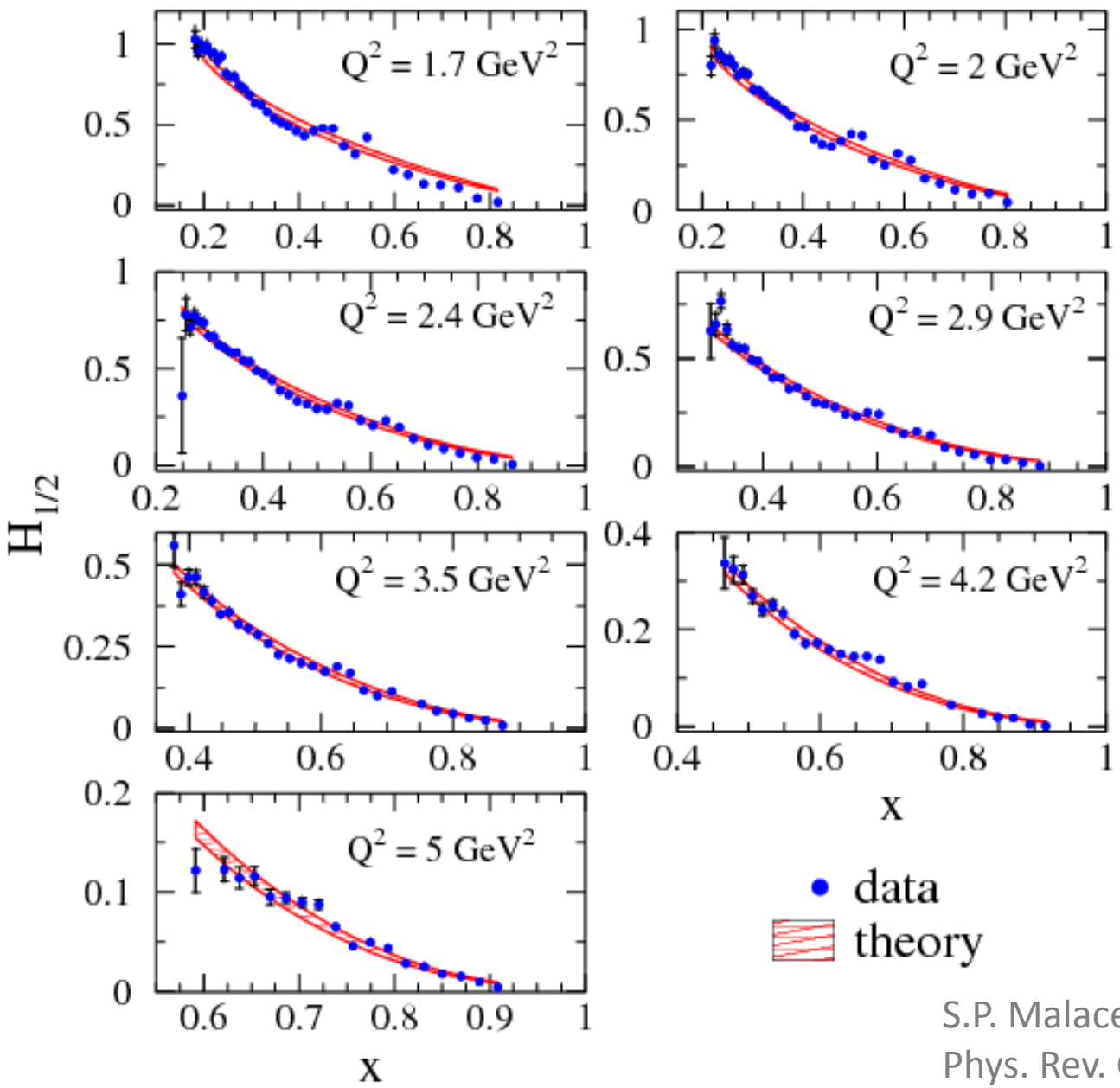
    -> F_1 from Christy-Bosted fit Phys. Rev. C 81, 055213 (2010)

    -> g_2 from Simula *et al.* S. Simula *et al.*, Phys. Rev. D 65, 034017 (2002)
  - "Theory" -> g_1 from Blümlein and Böttcher Nucl. Phys. B 841, 205 (2010)

    -> F_1 from ABKM Phys. Rev. D 81, 014032 (2010)

    -> g_2 from Wandzura-Wilczek relation with g1 from BB08

$H_{1/2}$ Structure Function

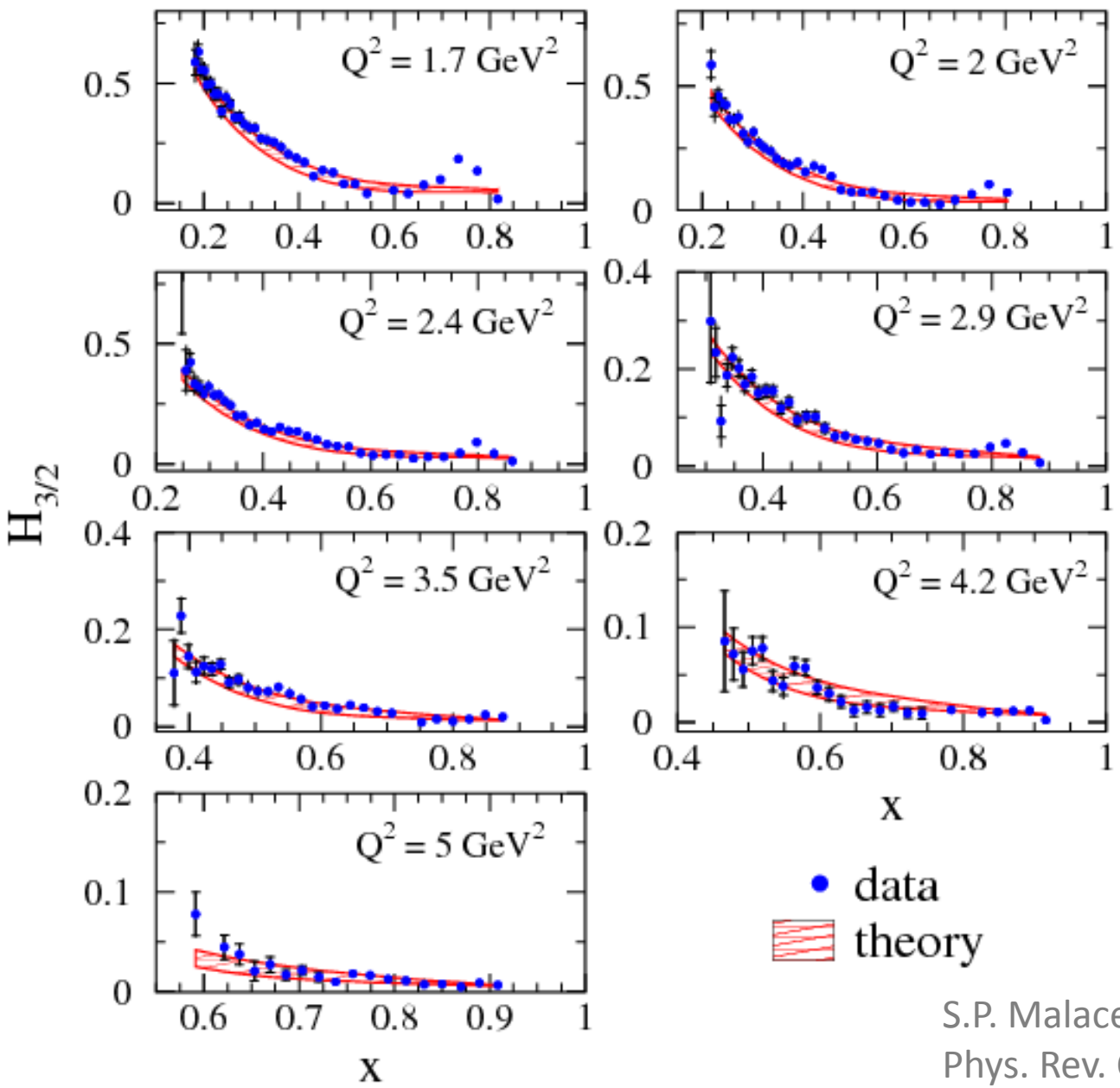


Data in good agreement with global fit for both DIS and RES region

Global fit overestimates data at low Q^2 and largest x (1st RES region)

S.P. Malace, W. Melnitchouk, A. Psaker, Phys. Rev. C 83, 035203 (2011)

$H_{3/2}$ Structure Function



Data in good agreement with global fit for both DIS and RES region

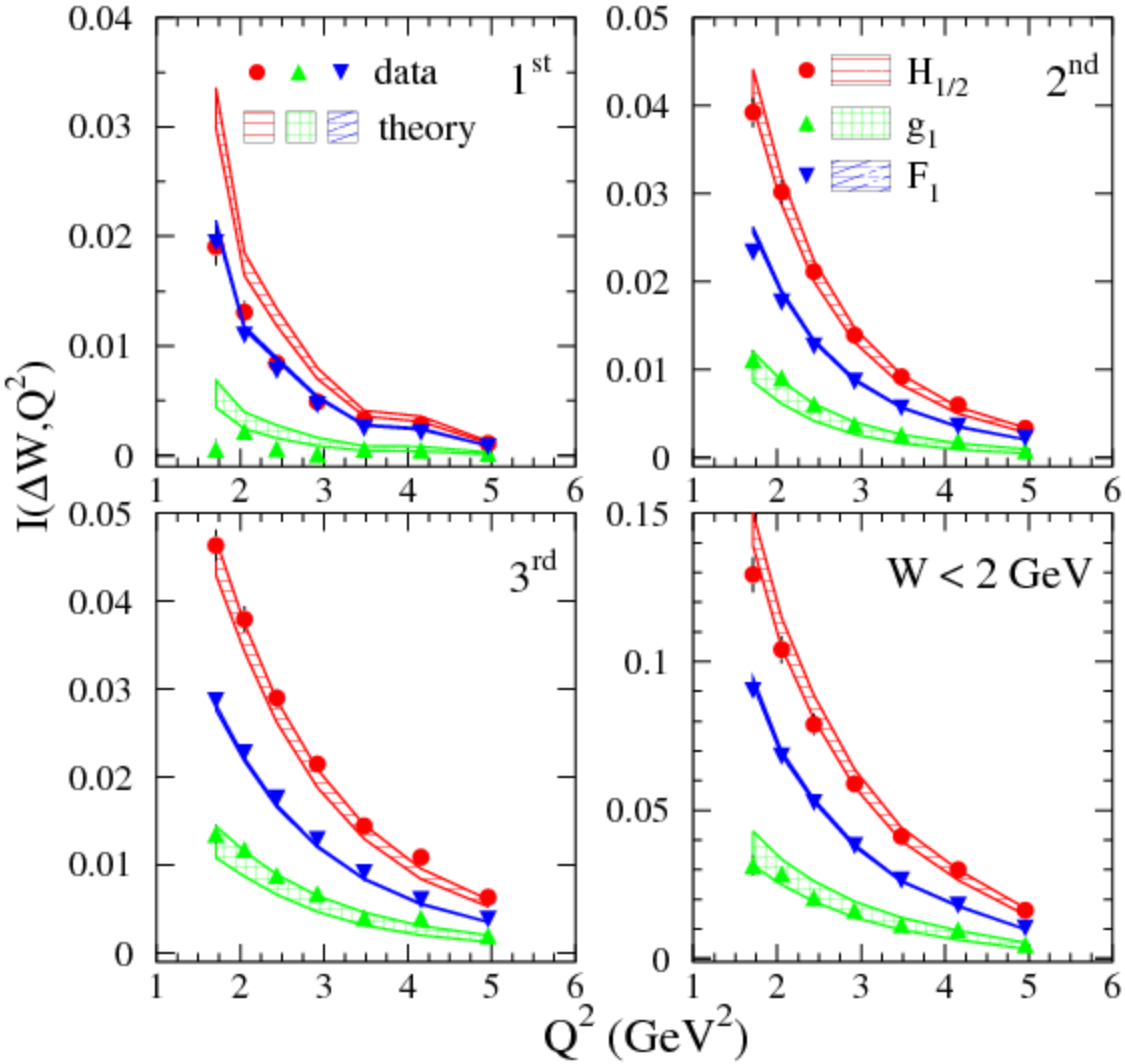
Global fit underestimates data at low Q^2 and largest x (1st RES region)

↓

prominent peak stands out

S.P. Malace, W. Melnitchouk, A. Psaker, Phys. Rev. C 83, 035203 (2011)

Duality in $H_{1/2}$



$$I(\Delta W, Q^2) = \int_{\Delta W} dx H_{1/2}(x, Q^2)$$

<u>Duality ratio</u>:

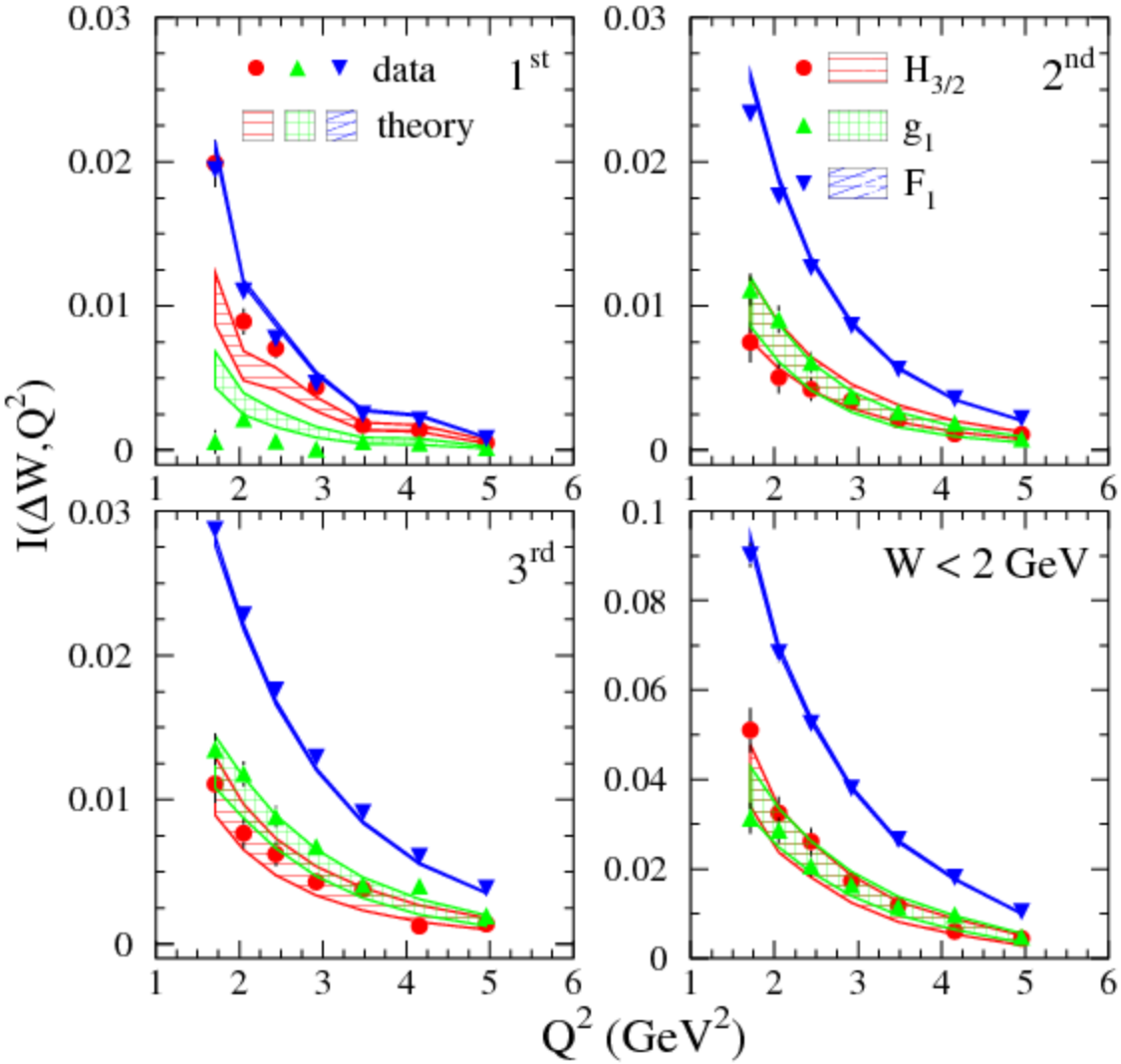
- globally within 10%
- 2nd and 3rd within 15%
- 1st : stronger violations at low Q^2, up to 50%; for Q^2 > 3 GeV2 within 20%

↓

origin: strong duality violation in g_1

S.P. Malace, W. Melnitchouk, A. Psaker, Phys. Rev. C 83, 035203 (2011)

Duality in $H_{3/2}$



$$I(\Delta W, Q^2) = \int_{\Delta W} dx H_{3/2}(x, Q^2)$$

<u>Duality ratio</u>:

- globally within 20%
- 2nd and 3rd within 20-25%

↓

duality realized more clearly in $H_{1/2}$ than in $H_{3/2}$

- 1st : stronger violations at low Q^2, up to 90%; for Q^2 > 3 GeV2 within 20%

S.P. Malace, W. Melnitchouk, A. Psaker, Phys. Rev. C 83, 035203 (2011)

Summary

- Quark-Hadron Duality observed by Bloom and Gilman more than 40 years ago has been confirmed by precise data from JLab

- JLab quantitatively mapped quark-hadron duality in spin-averaged structure functions in a Q^2 range from ~1 to ~7 GeV^2; 12 GeV will push this to Q^2 of ~20 GeV^2

- Studies have shown that duality appears to be realized in spin structure functions as well

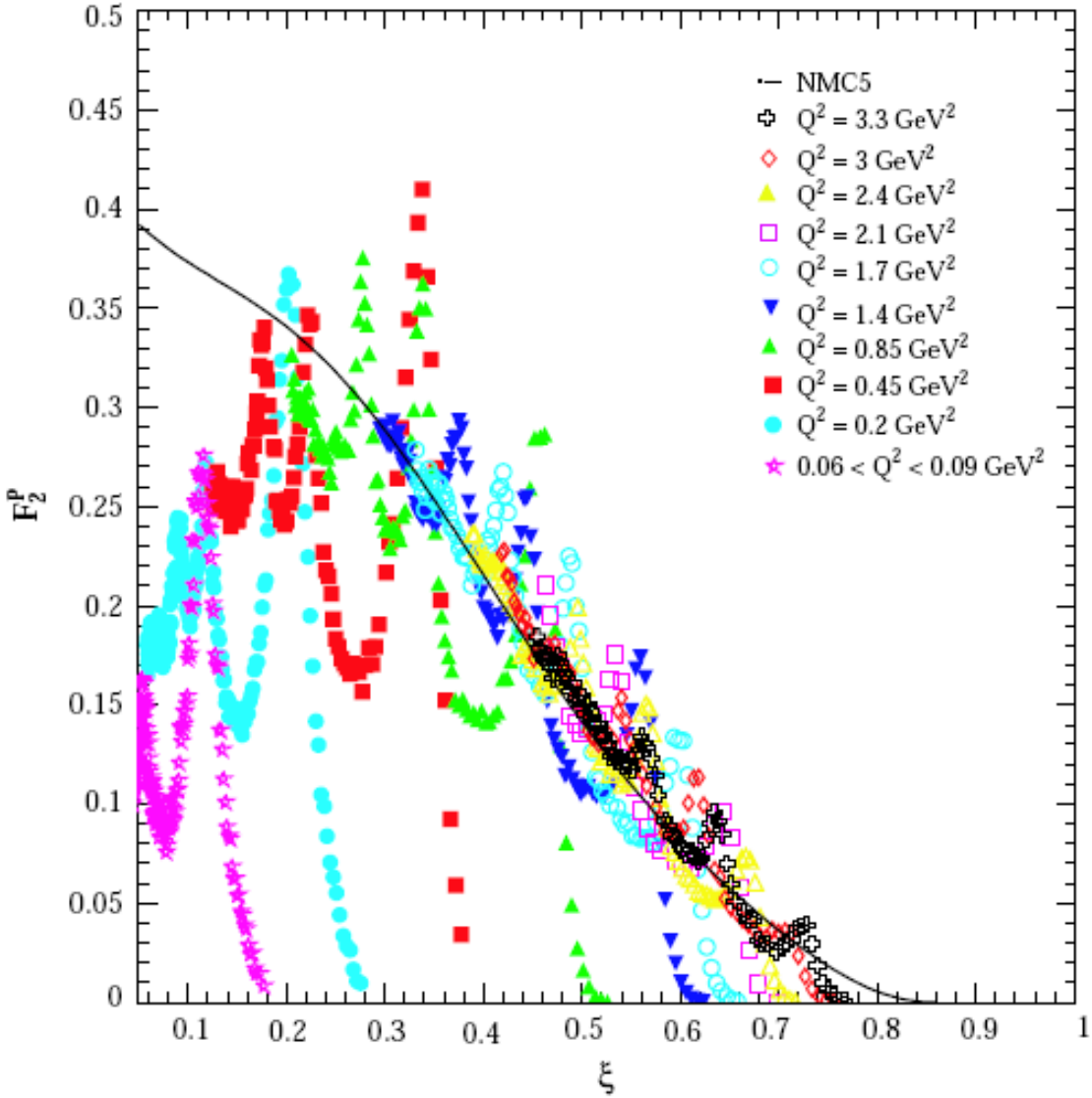
- Recent global fits (CJ, ABKM) yield stable LT PDFs using low W^2 (> 3 GeV^2) data

- Suggests exploring the possibility of using averaged RES data (W^2 > 1.9 GeV^2) as constraints for PDF fits at very large x

Backup Slides

Bloom-Gilman Duality: JLab

- The observation of Bloom and Gilman confirmed by JLab data



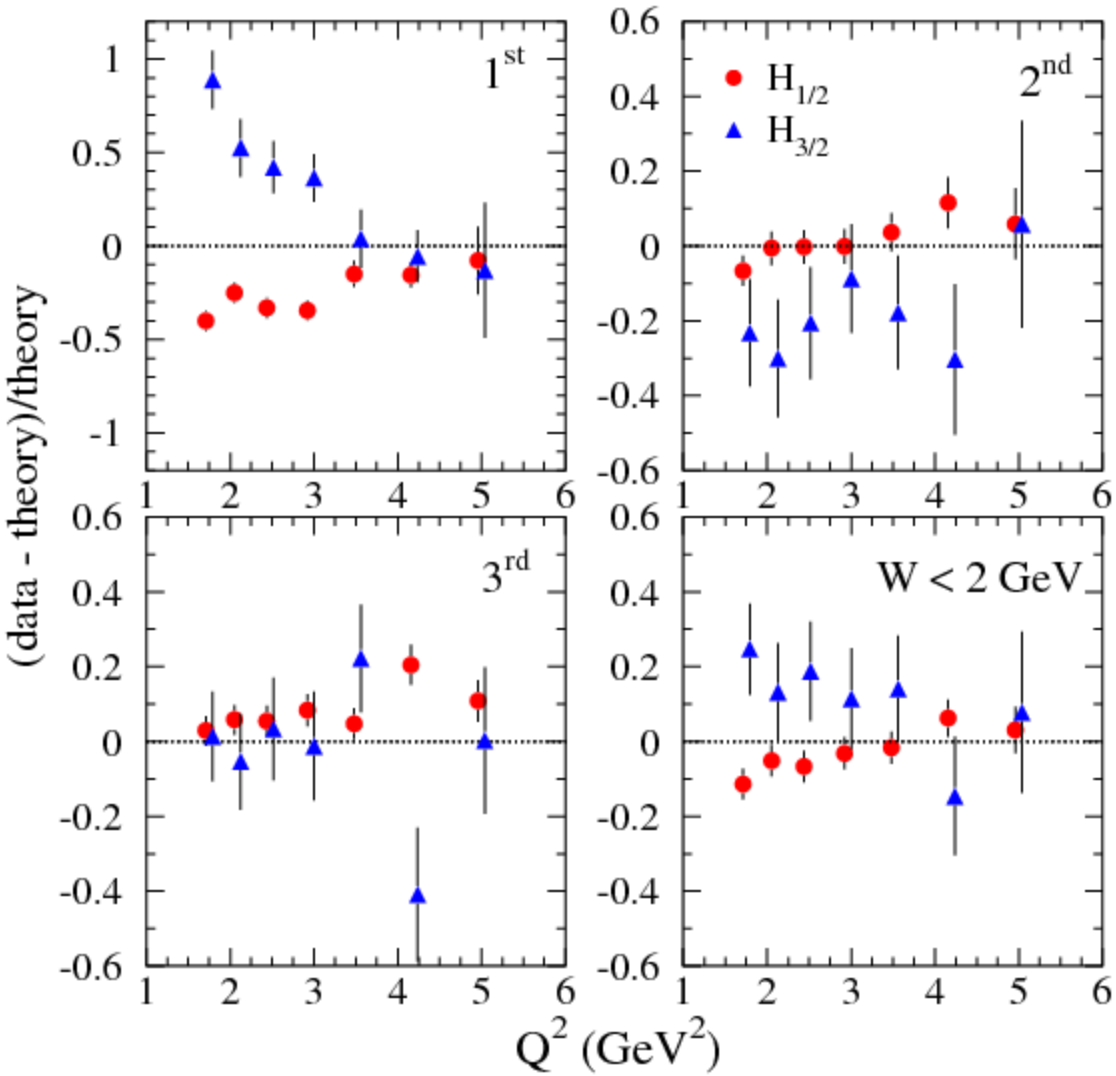
Strongly Q^2 dependent resonances average to scaling curve

Nachtmann scaling variable

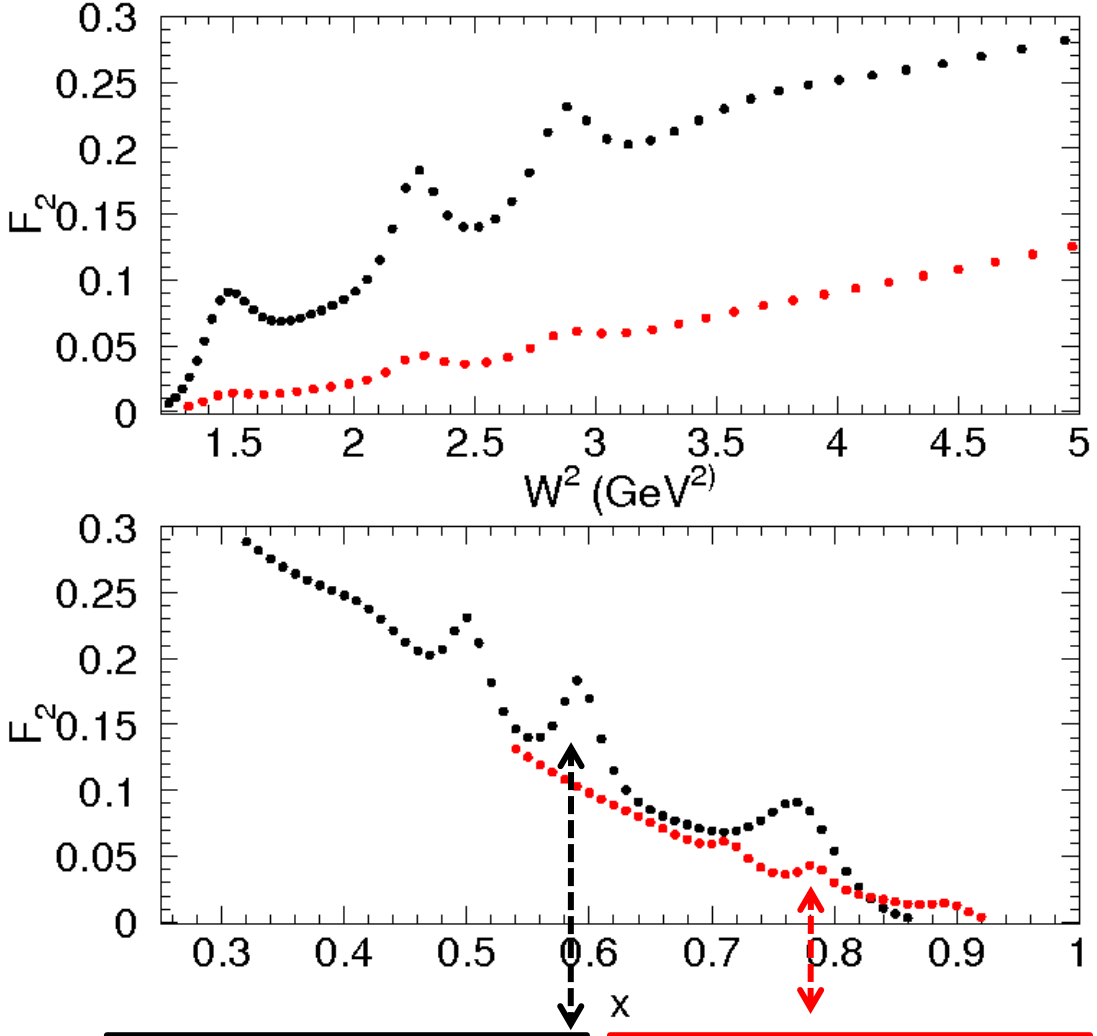
$$\xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$$

I. Niculescu *et al.*, Phys. Rev. Lett. 85, 1182 (2000)

Ratio



Resonances Slide…



2nd resonance region at $Q^2 = 2$ GeV^2

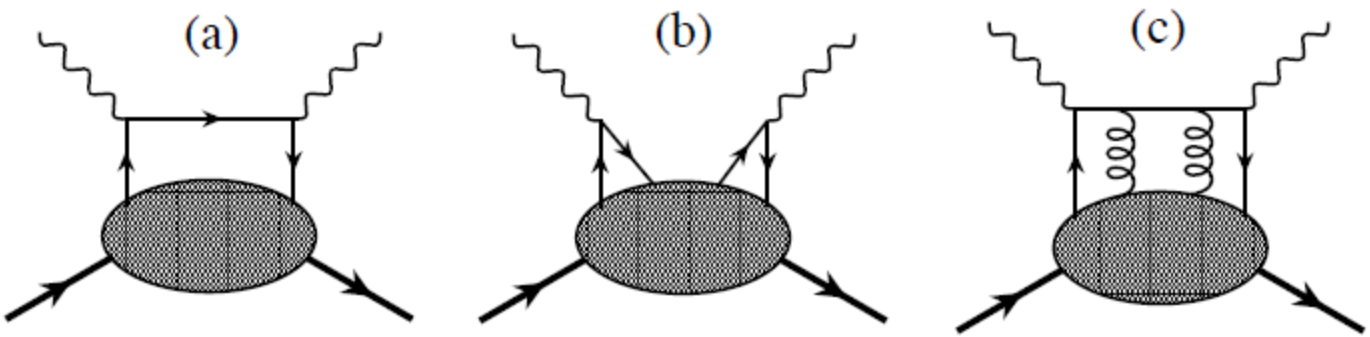
2nd resonance region at $Q^2 = 5$ GeV^2

QCD Interpretation

- Operator Product Expansion

W. Melnitchouk, R. Ent, C. Keppel, Phys. Rep. 428, 127 (2005)

$$M_n(Q^2) = \int_0^1 dx\, x^{n-2} F_2(x, Q^2) = A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \ldots$$



$\tau = 2$ $\tau > 2$

single quark scattering

qq and qg correlations

Duality = suppression of higher twist, on average