Quark-hadron duality in inelastic scattering

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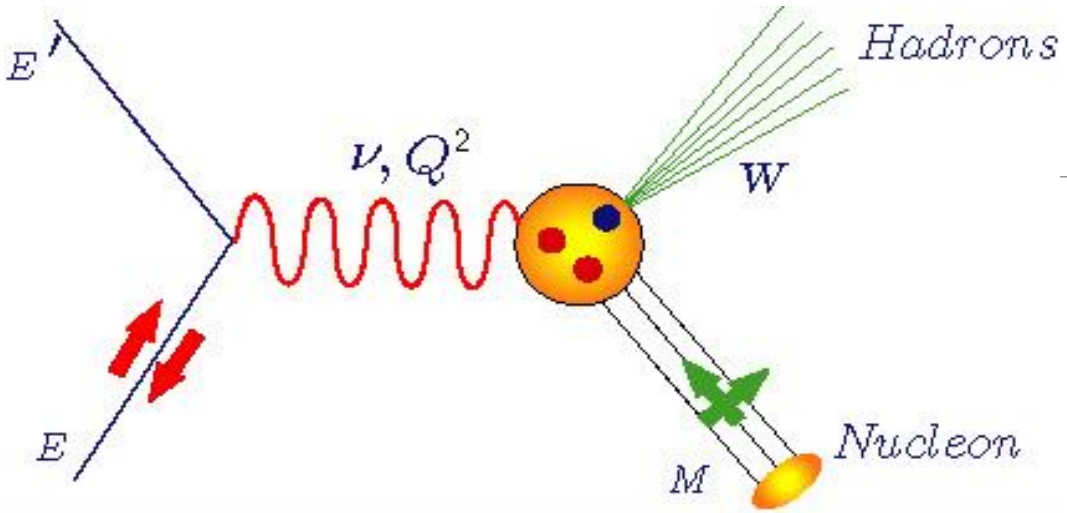
Inclusive Electron Scattering – Formalism



Q^2 : Four-momentum transfer
x : Bjorken variable (=Q^2/2Mn)
ν : Energy transfer
M : Nucleon mass
W : Final state hadronic mass

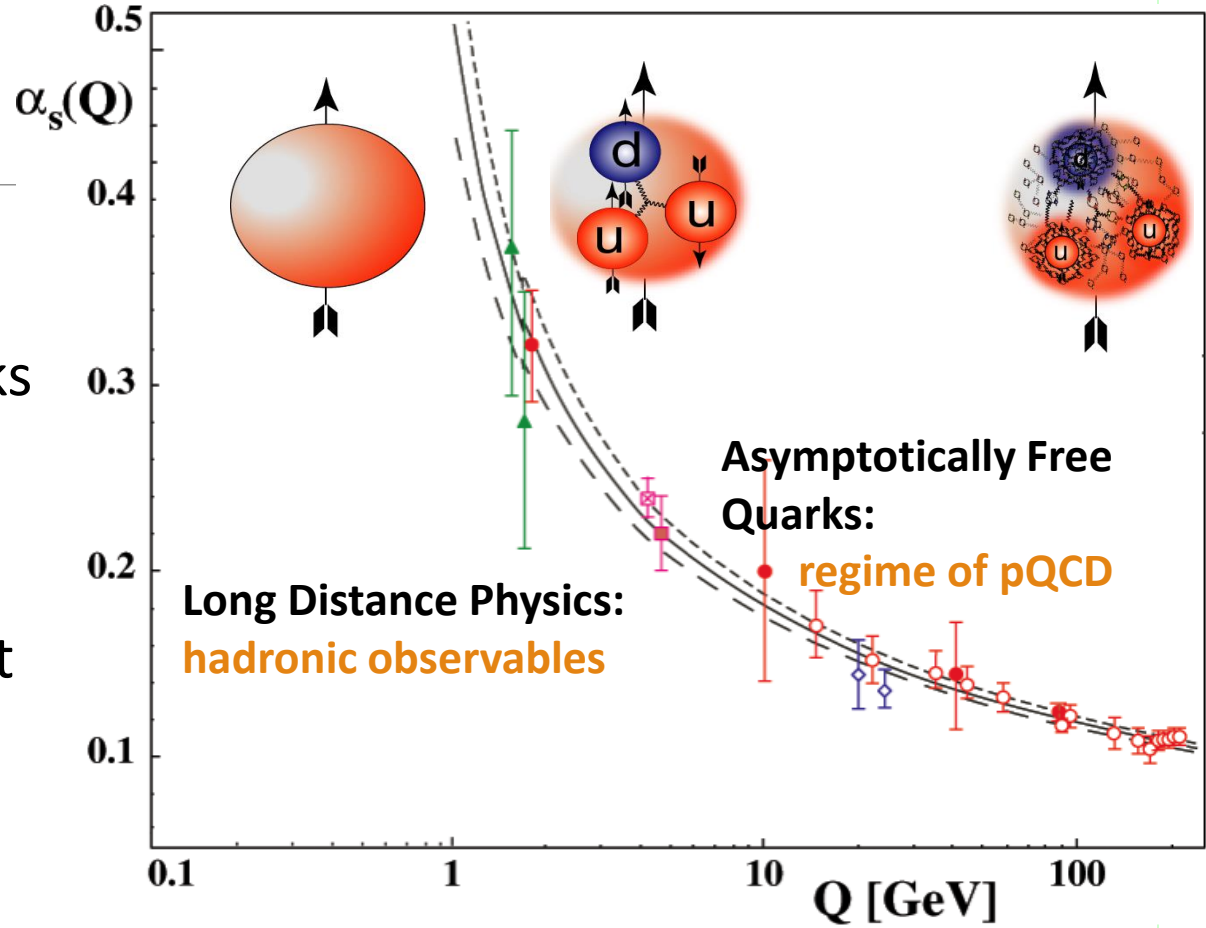
$$\frac{d^2\sigma}{dE'd\Omega}(\downarrow\Uparrow + \uparrow\Uparrow) = \frac{8\alpha^2\cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

- Unpolarized structure functions $F_1(x,Q^2)$ and $F_2(x,Q^2)$, or $F_T(x,Q^2)$ [$=2xF_1(x,Q^2)$] and $F_L(x,Q^2)$, separated by measuring $R = \sigma_L/\sigma_T$

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 one, under certain circumstances, to bridge the gap between the theoretical predictions and experimentally observable quantities." [M.A.Shifman, QCD@Work2003]

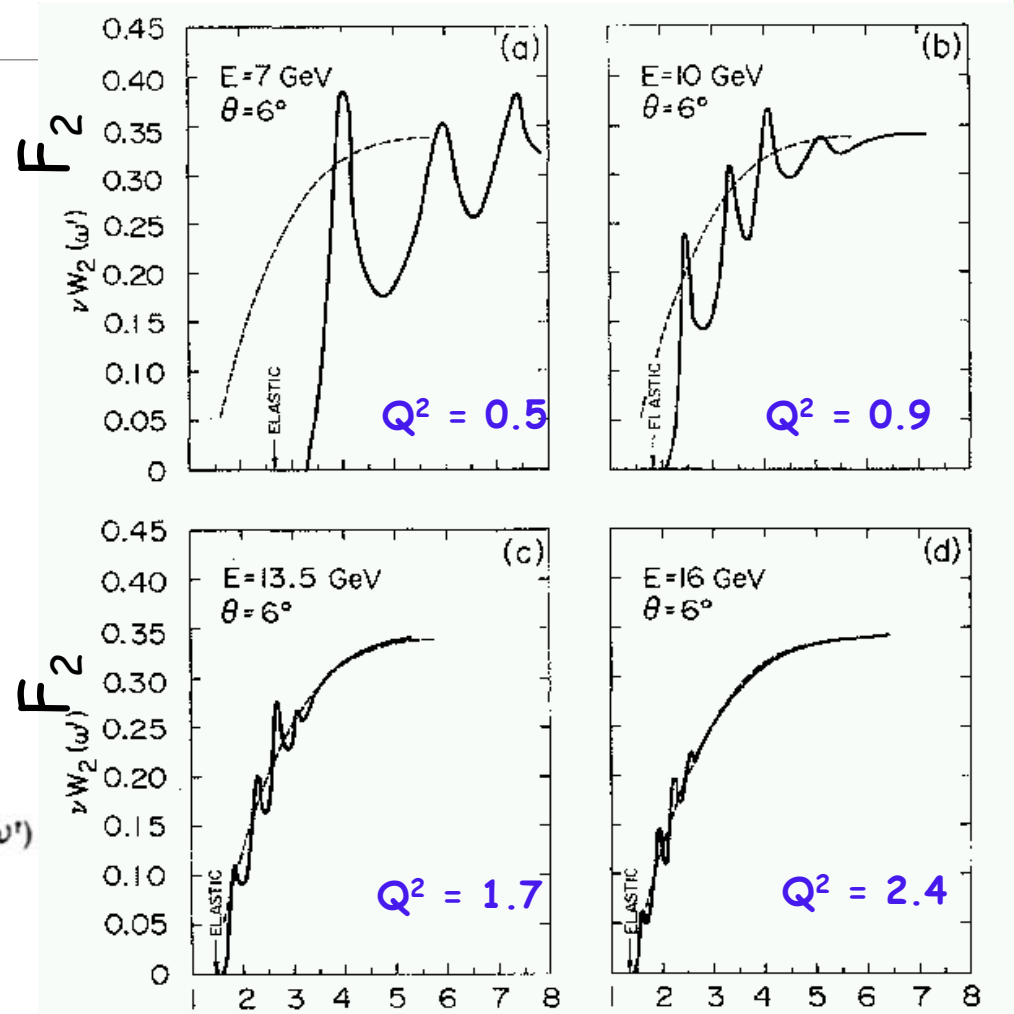
“Bloom-Gilman” Duality: Inclusive Electron Scattering

E.D. Bloom, F.J. Gilman, Phys. Rev. Lett. 25 (1970) 1140.
E.D. Bloom, F.J. Gilman, Phys. Rev. D 4 (1971) 2901.

- Resonance region data oscillate around “scaling curve”.
- Resonance data are equivalent to the scaling curve on “average”
- Resonance region data “slide” along the scaling curve when Q^2 increases.

- Finite energy sum rule:

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



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

Duality is described in the Operator Product Expansion

as higher twist effects being small or canceling

DeRujula, Georgi, Politzer (1977)

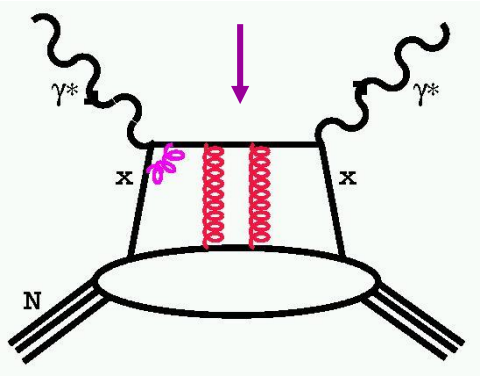
$$M_n(Q^2) = \int_0^1 x^{n-2} F(x, Q^2) dx$$

Cornwall-Norton moments

$$M_n(Q^2) = A_n(Q^2) + \sum_k \left(\frac{n M_0^2}{Q^2} \right)^k B_{n,k}(Q^2)$$

Logarithmic dependence

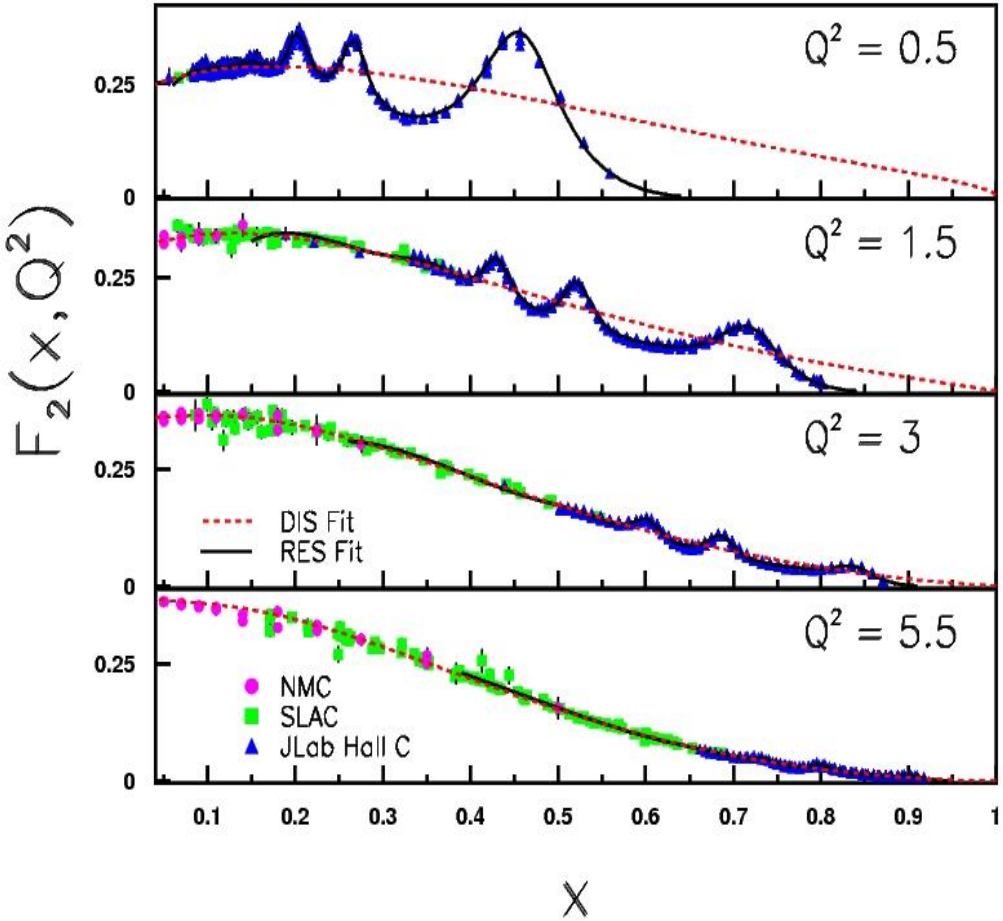
Higher twists



To study duality:

- need data
- need "scaling curve"

DIS fit – 'F2ALLM' H.Abramowicz and A.Levy, hep-ph/9712415
Res fit - E.Christy and P.E. Bosted, PRC 81,055213



"DIS" fit to larger W data all the way down to $Q^2 = 0$

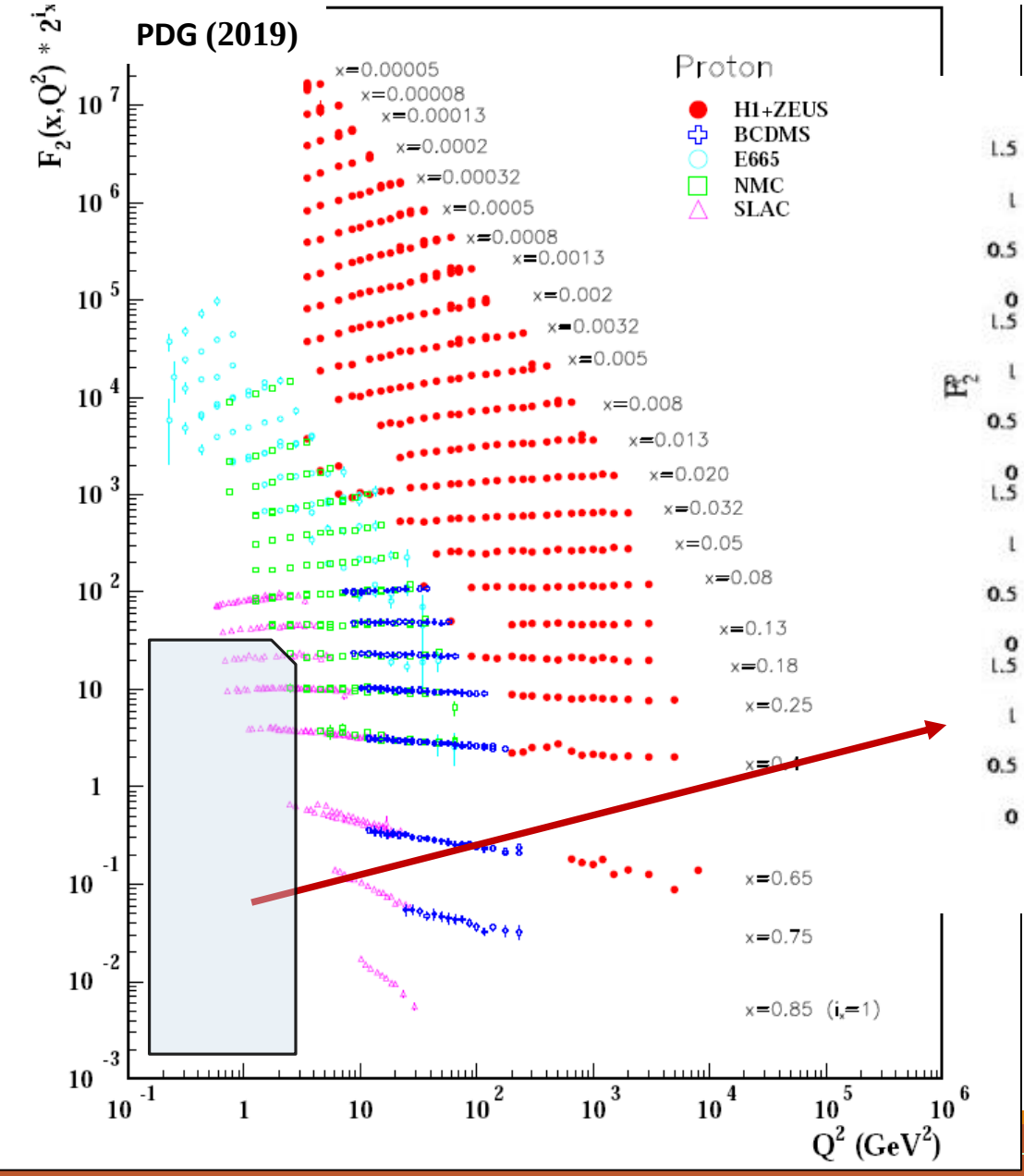
→ Curve necessarily includes contributions beyond massless limit perturbative QCD:

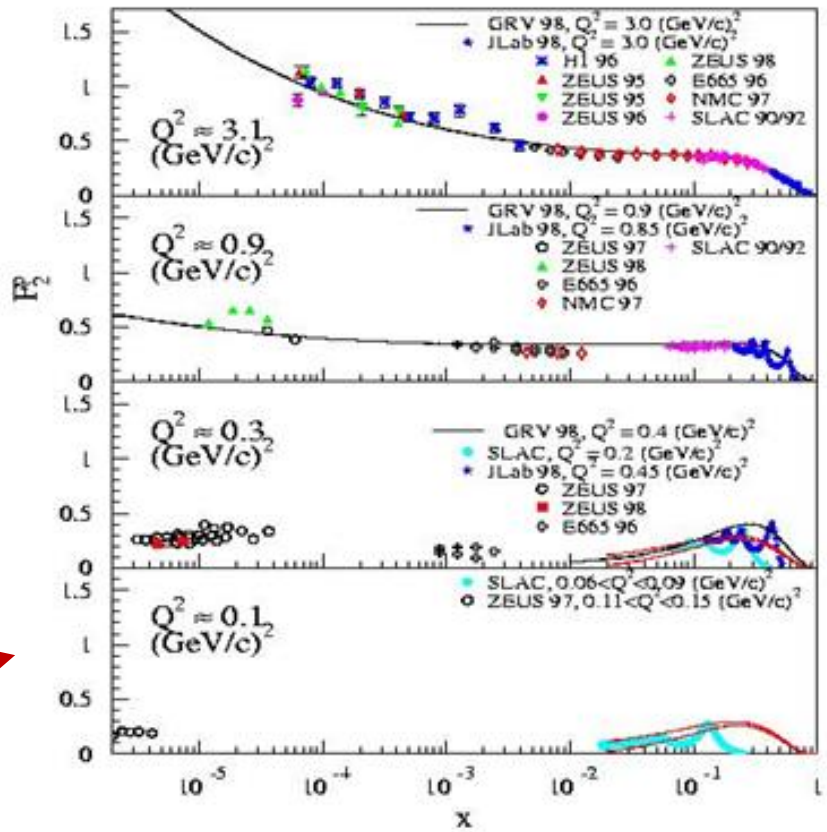
I) Target Mass (TM)

II) Higher-Twist (HT)

The Proton Structure Function

$$M_n(Q^2) = \int_0^1 x^{n-2} F(x, Q^2)\, dx$$



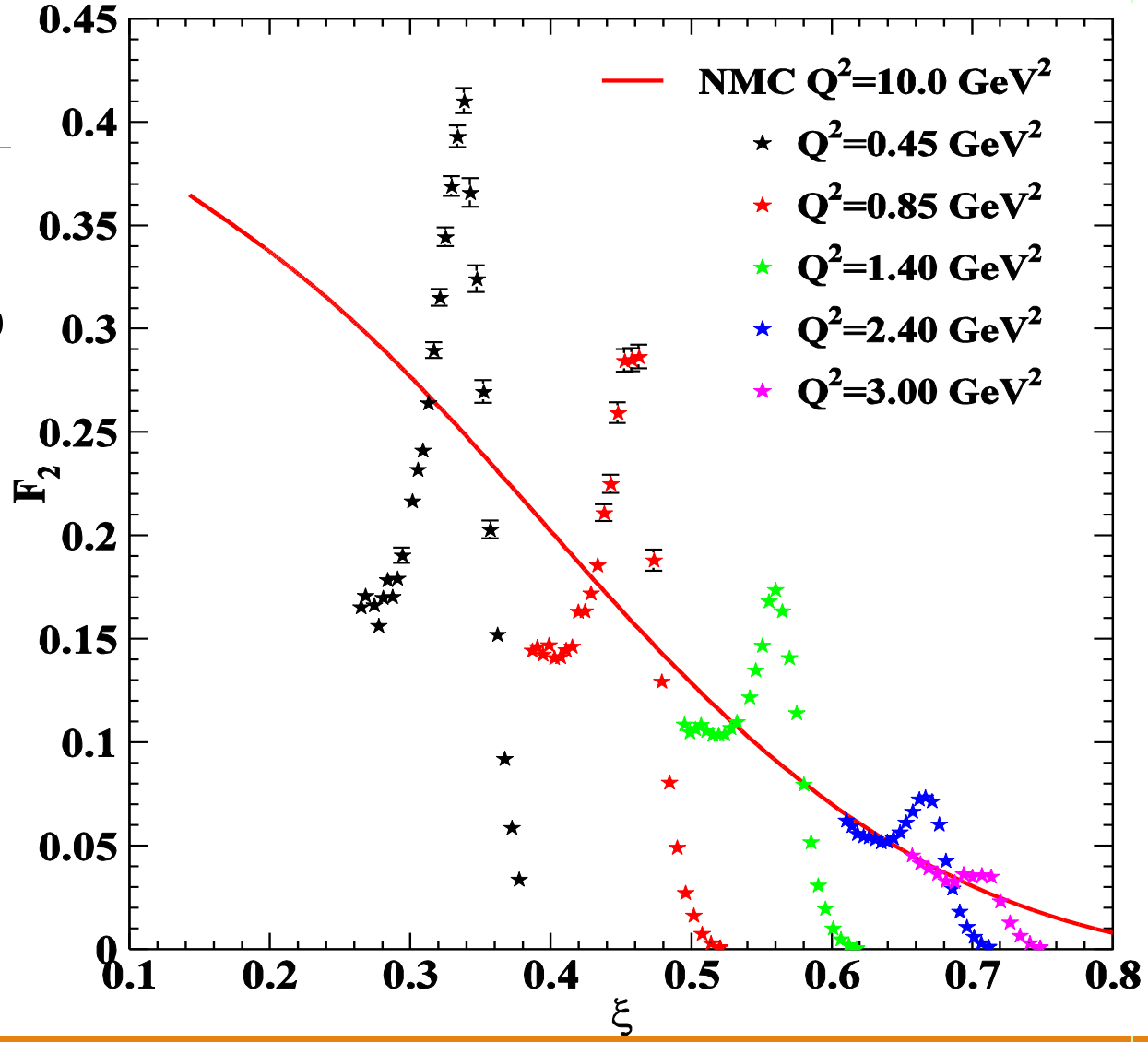


Can we limit the x range?

Local Duality in the F_2 Structure Function

Define N-Δ region as
$1.2 < W^2 < 1.9\ GeV^2$

- Obviously, duality does not hold on top of peak!
- However, for F_2 the defined N-Δ region mimics the DIS parameterization
- Note that one does not expect much Q^2 evolution at these values of x (or ξ)

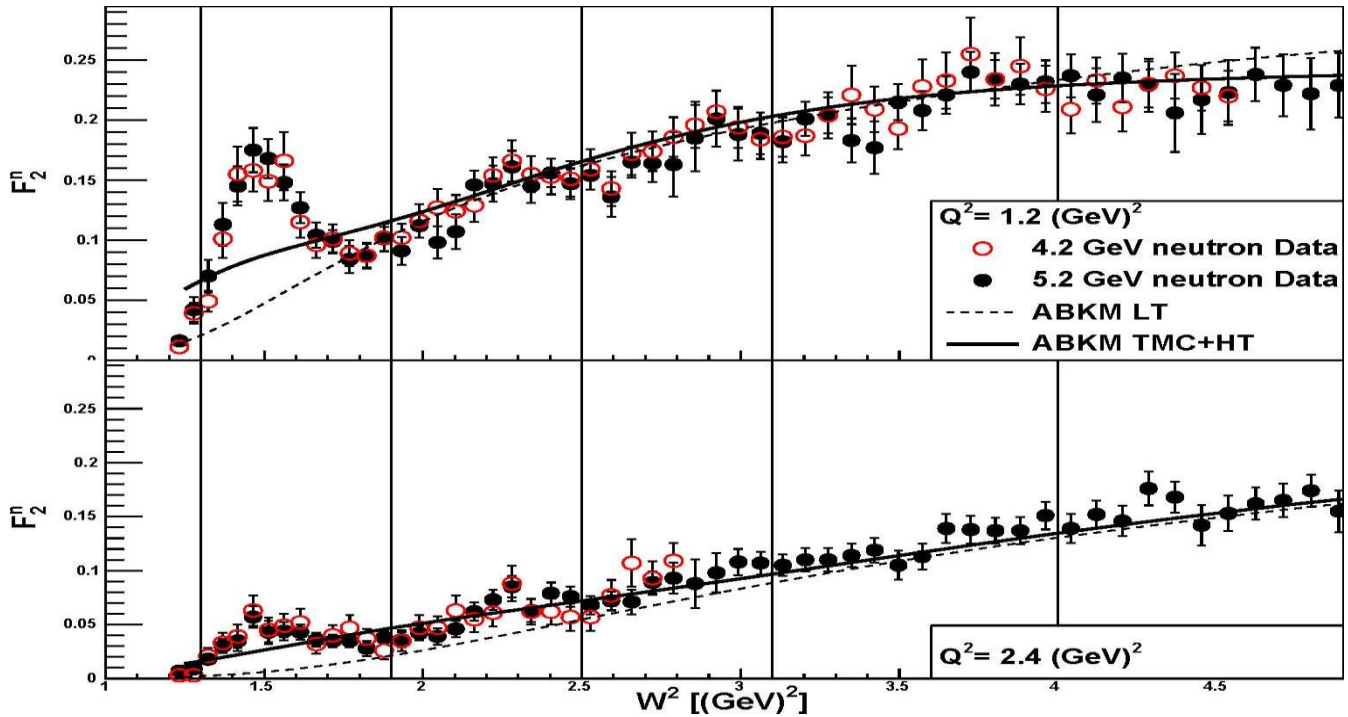


Truncated Moments and Local Duality

$$M_n(x\min, x\max, Q^2) = \int_{x\min}^{x\max} x^{n-2} F(x, Q^2)\,dx$$

Truncated moments follow ***DGLAP-like evolution*** equations.

As defined in A. Psaker, W. Melnitchouk, E. Christy, C. Keppel, PRC 78 (2008) 025206

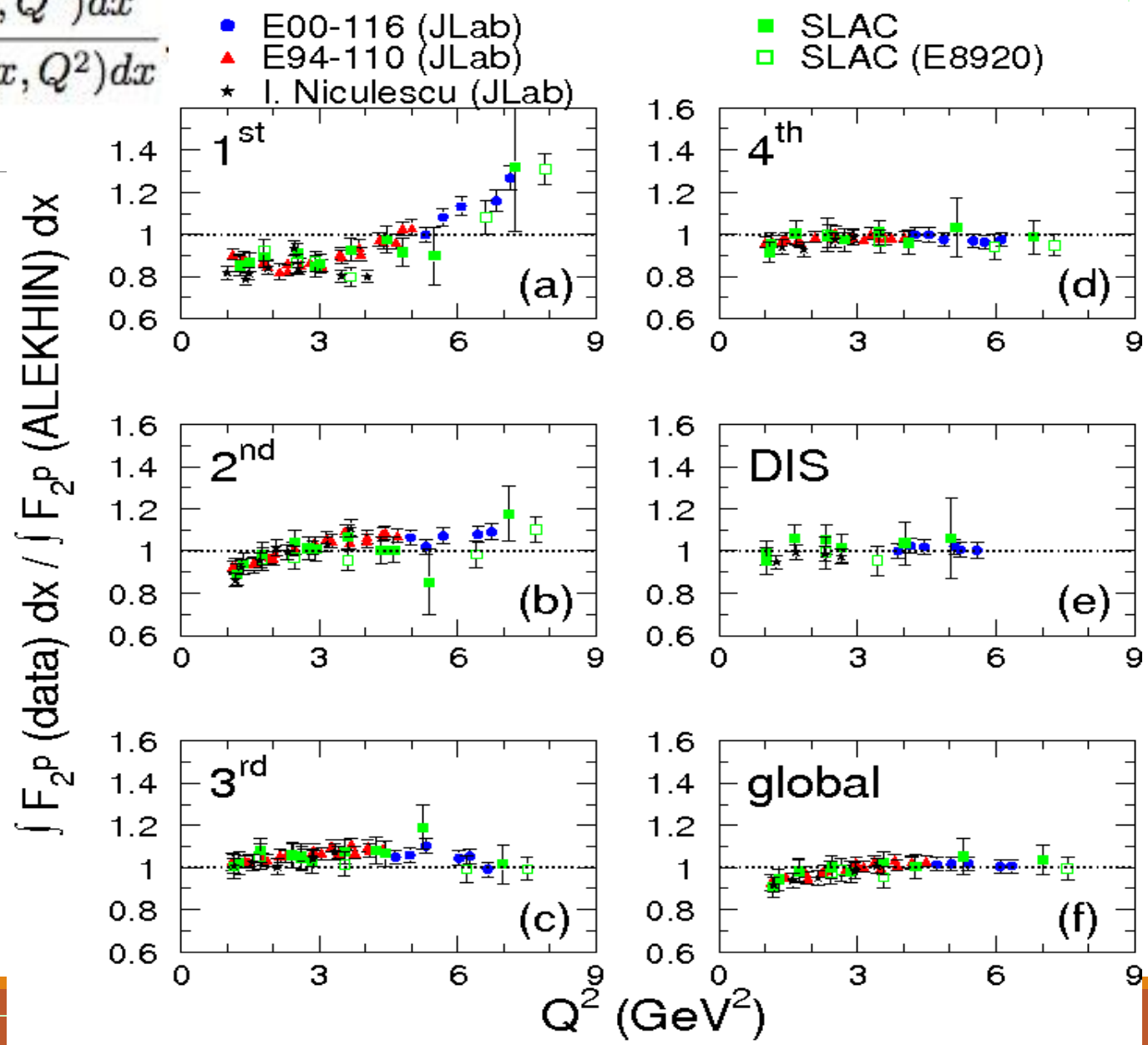


I.N *et al* PRC91 (2015) 055206

$1.3 \le W^2 \le 1.9$ GeV^2 [1st (or Δ) region],
$1.9 \le W^2 \le 2.5$ GeV^2 [2nd region],
$2.5 \le W^2 \le 3.1$ GeV^2 [3rd region],
$1.3 \le W^2 \le 4.0$ GeV^2 [total resonance].

Local Quark Hadron Duality – Proton

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



S. Malace *et al.*, PRC 80, 035207 (2009)

Does it work for the Neutron?

Frank E. Close, Nathan Isgur PLB 509 (2001) 81

- **"for the proton duality may be satisfied by *W* <1.*6 GeV*"**
- **"For neutron targets […] we anticipate systematic deviations from local duality"**
- **"the *S11*(1530) […] and the *F15*(1680) are enhanced relative to the deep inelastic scaling curve for proton targets"**
- **for neutron targets, the *S11*(1530) region will fall below the scaling curve**

For simple (toy) quark model with spin-flavor symmetric wave function

low energy

→ *coherent* scattering from quarks $d\sigma \sim \left(\sum_i e_i\right)^2$

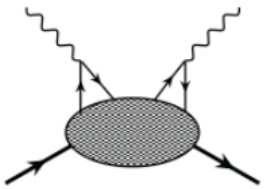
high energy

→ *incoherent* scattering from quarks $d\sigma \sim \sum_i e_i^2$

For duality, these must be equal...

→ how can *square of a sum* become *sum of squares*?

Wally Melnitchouk at
Open Questions in Parton-Hadron Duality
University of Virginia, March 13, 2015



cat's ears diagram (4-fermion higher twist $\sim 1/Q^2$)

$$\propto \sum_{i \neq j} e_i\, e_j \sim \Big(\underbrace{\sum_i e_i}_{\text{coherent}}\Big)^2 - \underbrace{\sum_i e_i^2}_{\text{incoherent}}$$

proton $\quad \mathrm{HT} \sim 1 - \left(2 \times \frac{4}{9} + \frac{1}{9}\right) = 0\,!$

neutron $\quad \mathrm{HT} \sim 0 - \left(\frac{4}{9} + 2 \times \frac{1}{9}\right) \neq 0$

→ here duality in proton is a coincidence

→ should *not* hold for neutron!

S. Brodsky (2000)

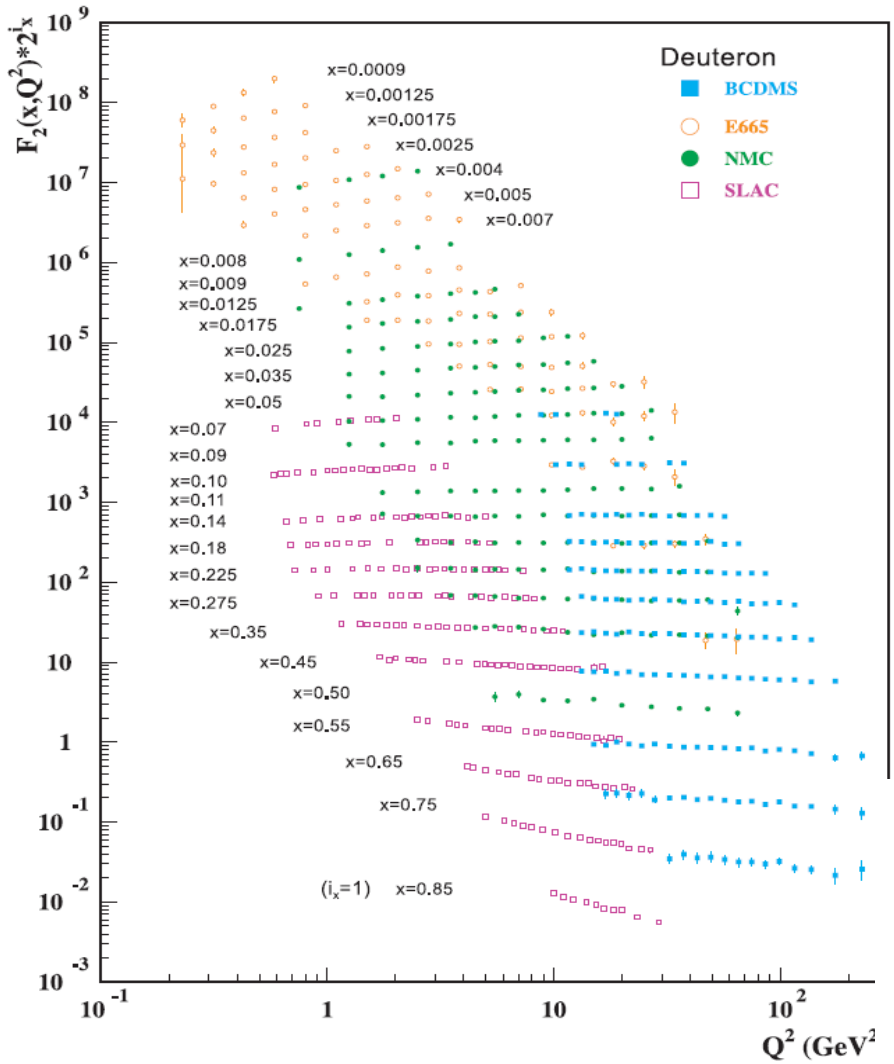
Close & Isgur, PLB ***509****, 81 (2001)*

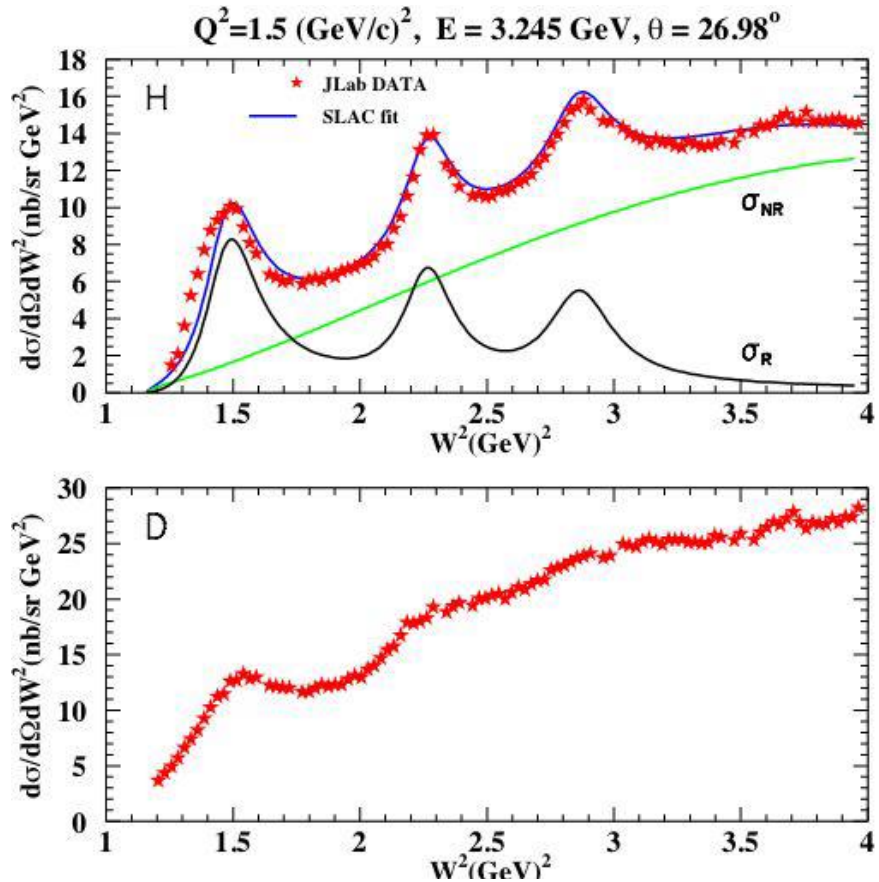
Close & WM, PRC ***68****, 035210 (2003)*
PRC ***79****, 055202 (2009)*

S. Brodsky (2000)

The Deuteron (neutron+proton+…)

PDG (2019)

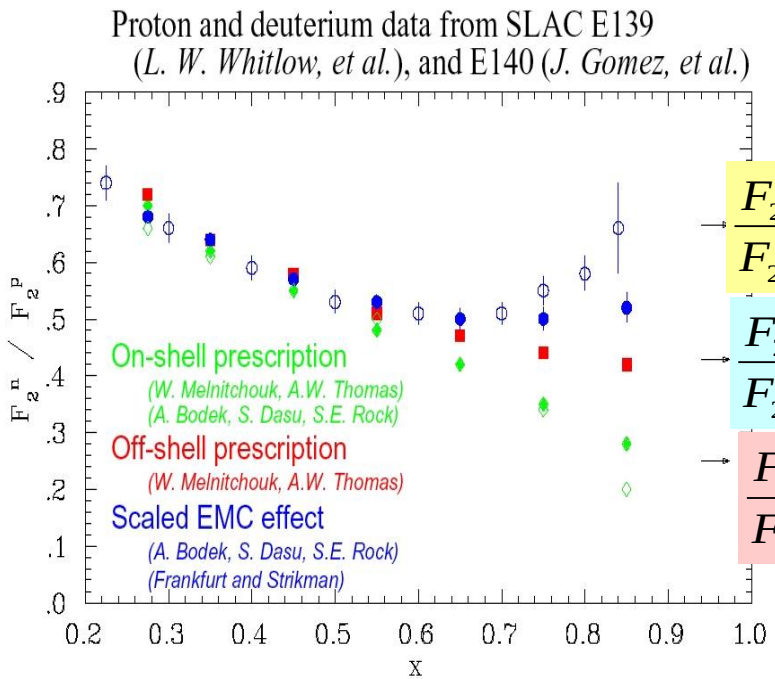




Extraction of neutron requires modeling of (non-)resonant components, including Fermi motion, nuclear binding effects, etc.

Extract neutron from deuteron data

Large uncertainties due to nuclear effects



$$\frac{F_2^n}{F_2^p} = \frac{2}{3} \Rightarrow \frac{d}{u} = \frac{1}{2}$$

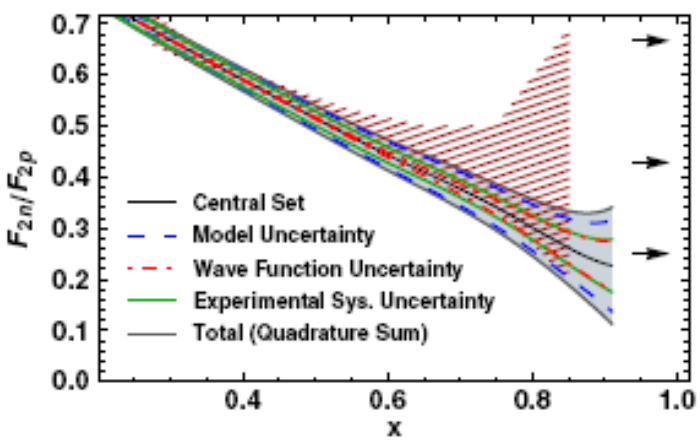
$$\frac{F_2^n}{F_2^p} = \frac{3}{7} \Rightarrow \frac{d}{u} \to \frac{1}{5}$$

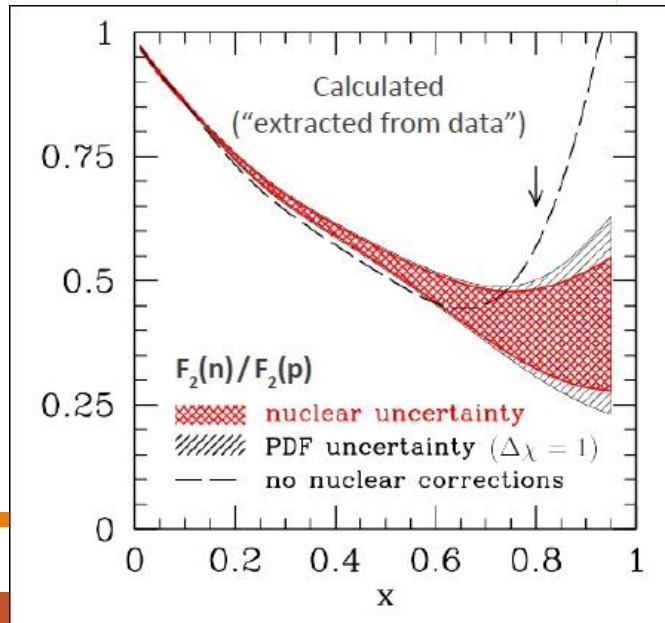
$$\frac{F_2^n}{F_2^p} = \frac{1}{4} \Rightarrow \frac{d}{u} \to 0$$

$$\frac{F_2^n}{F_2^p} \approx \frac{1+4d/u}{4+d/u}$$

$$\frac{d}{u} \approx \frac{4F_2^n/F_2^p - 1}{4 - F_2^n/F_2^p}$$

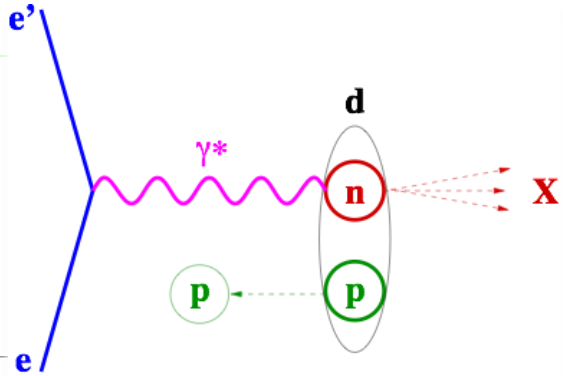
A. Accardi *et al.*, PRD 84 014008 (2011)

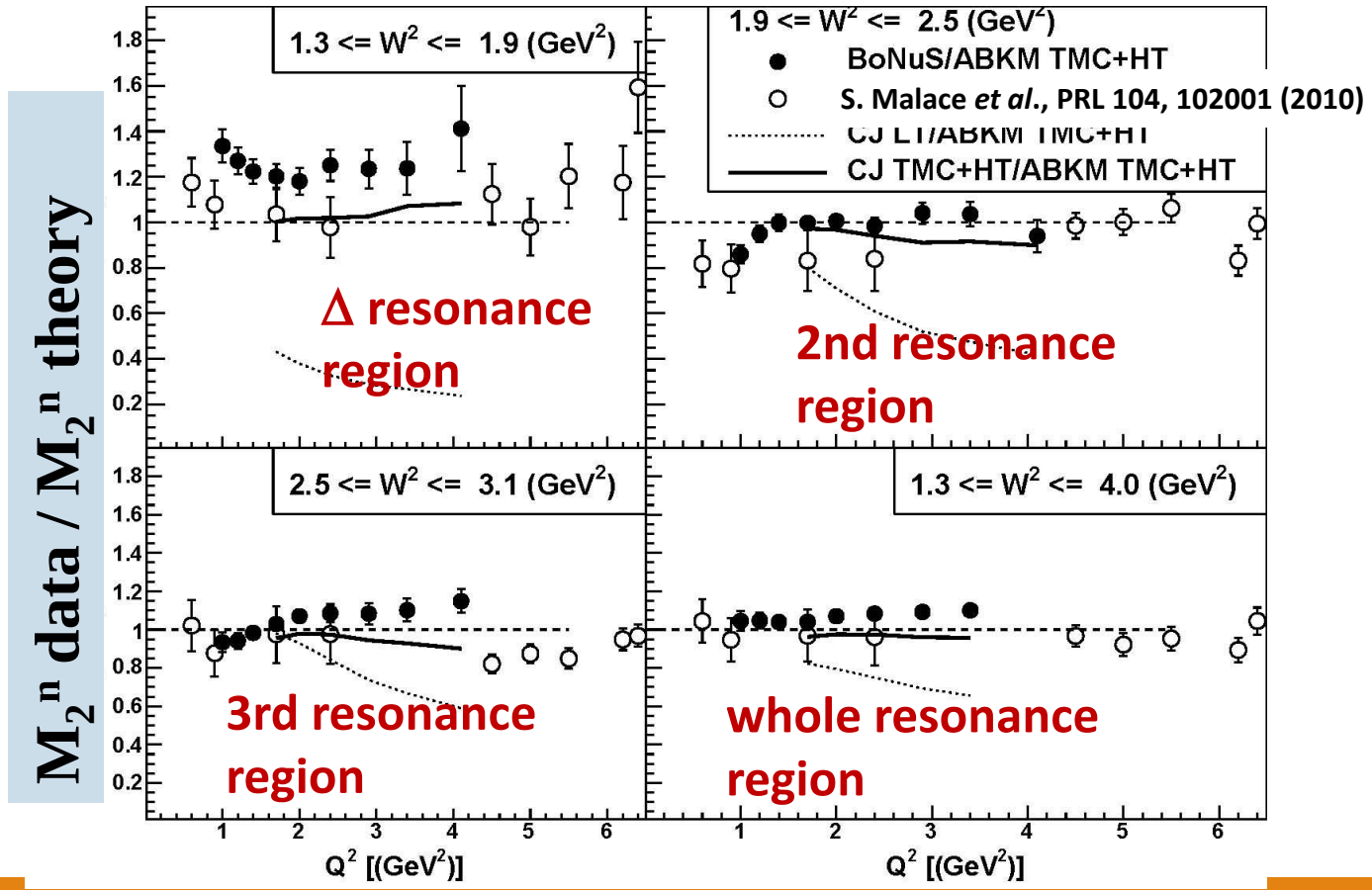




J. Arrington, J.G. Rubin,W.Melnitchouk PRL 108, 252001 (2012)

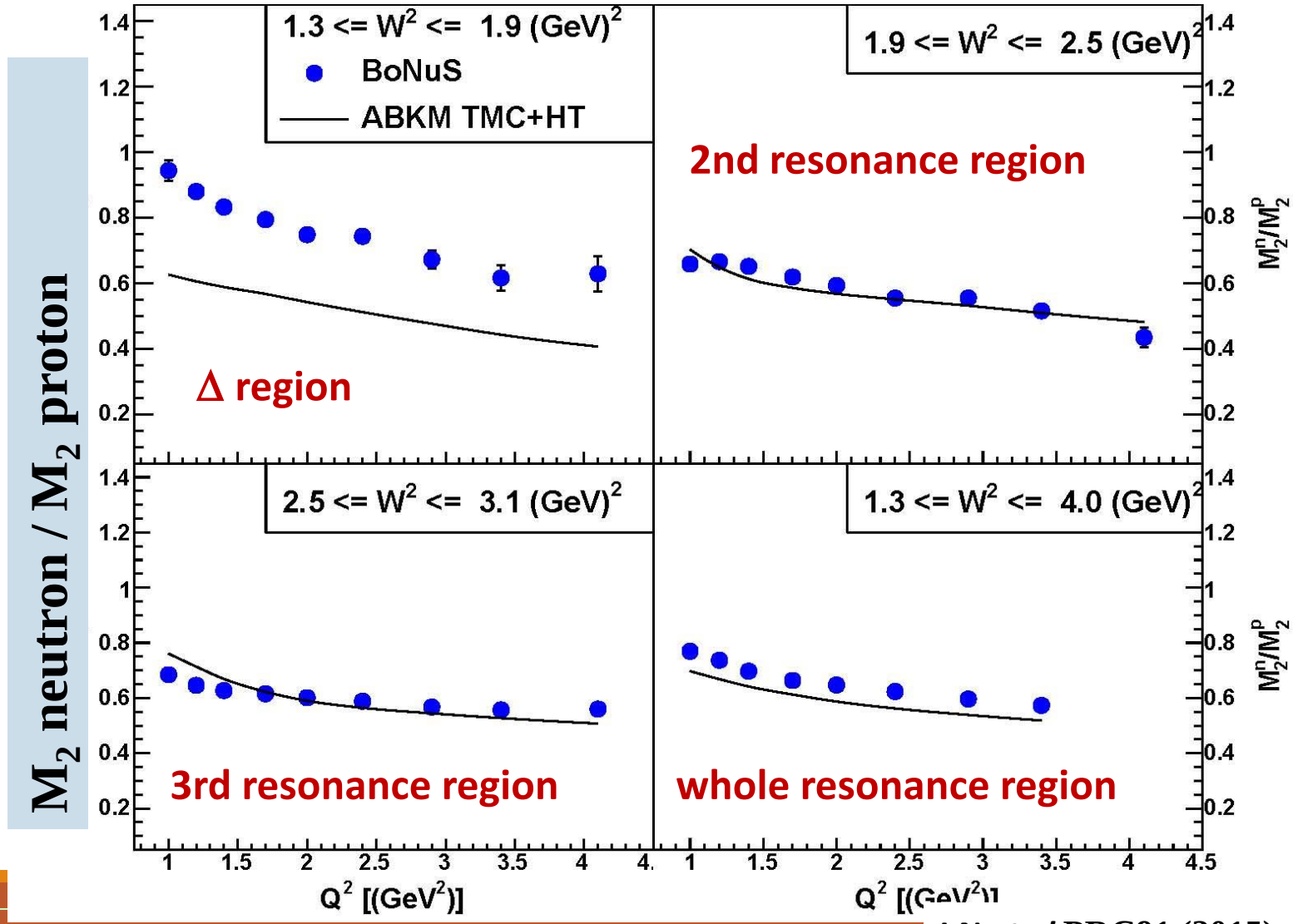
Local Quark Hadron Duality – Neutron (BoNuS Experiment)





I.N *et al* PRC91 (2015) 055206

Proton/Neutron Comparison

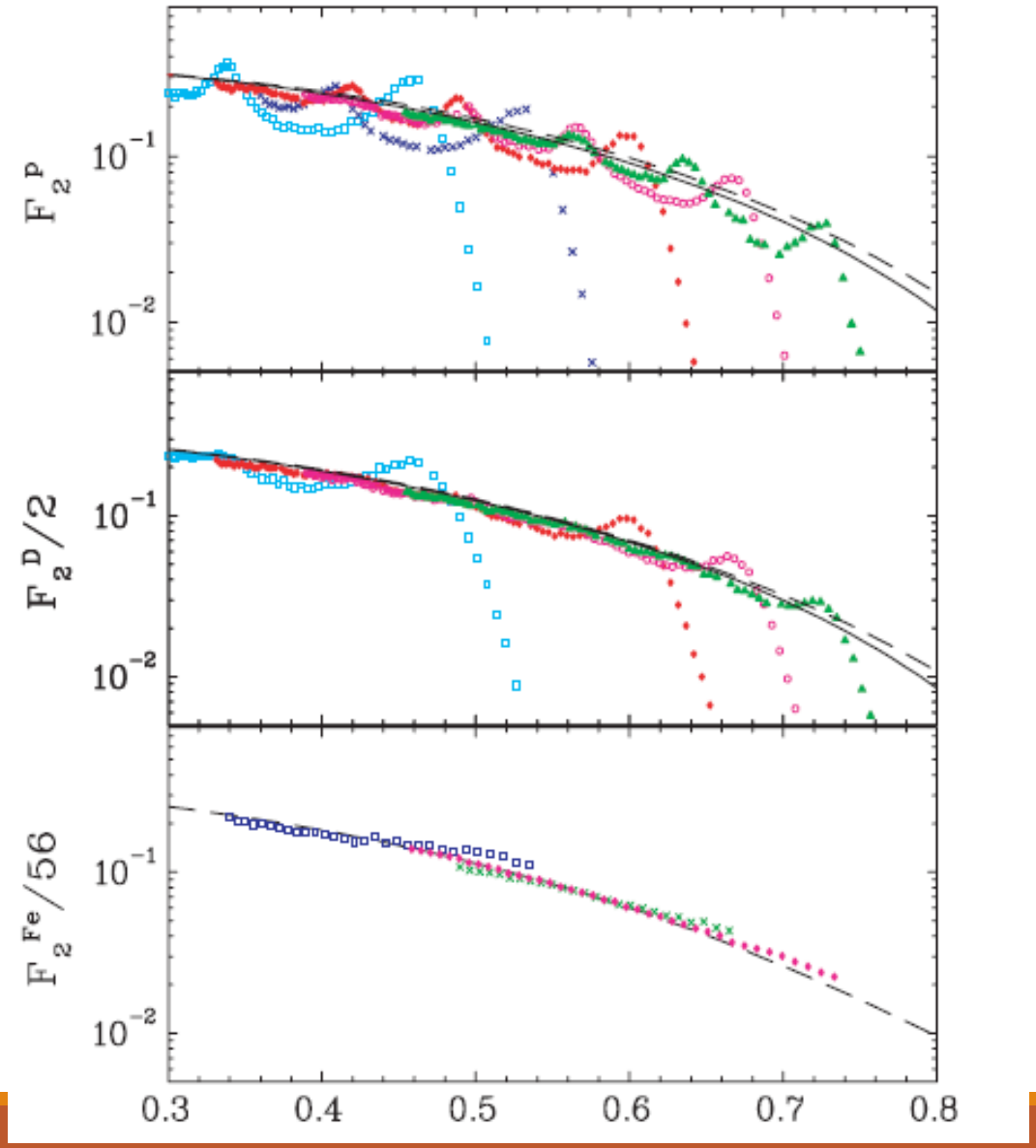


I.N *et al* PRC91 (2015) 055206

Duality is observed in a variety of structure functions

- ✓ F_2^p
- ✓ F_1^p
- ✓ F_L^p
- ✓ F_2^n
- ✓ F_2^d
- ✓ F_2^{nuclei}

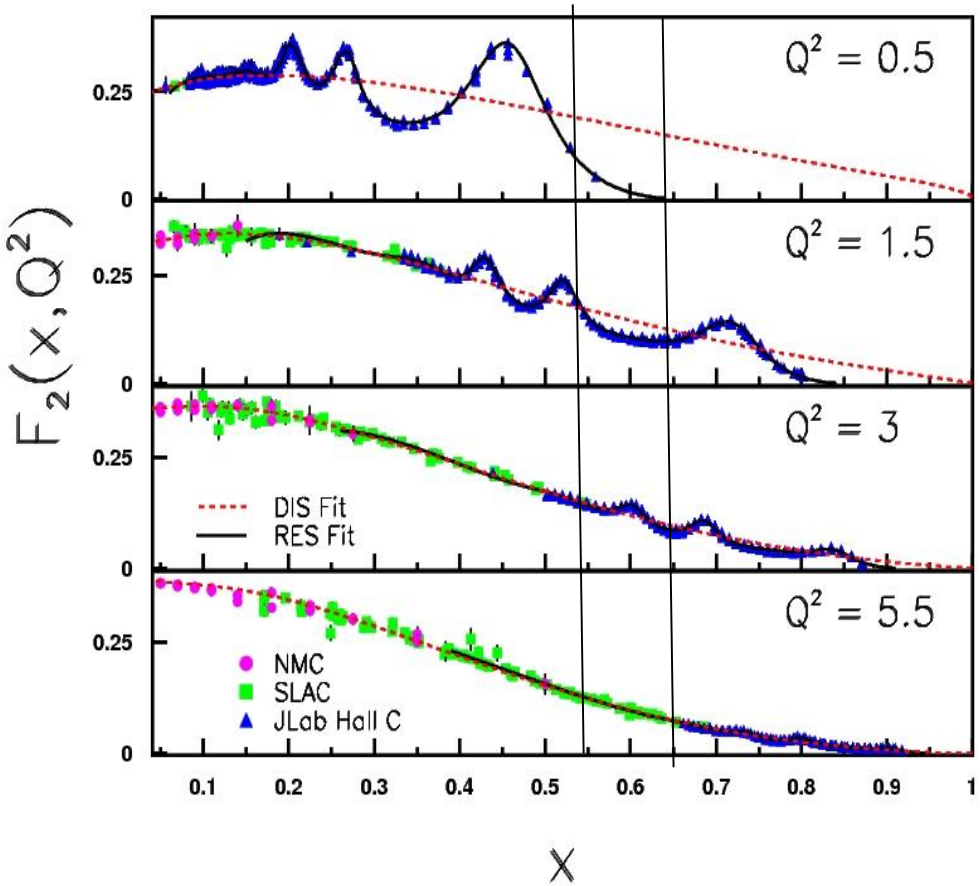
Duality appears to be a fundamental, non-trivial property of nucleon structure



What scaling curve to use?

- **Each resonance slides to higher x along the DIS fit**
- **Averaging over a Q^2 range at fixed x effectively averages over a number of resonances including peaks and valleys.**
- **Take out Q^2 dependence using DIS curve then average over range in Q^2**

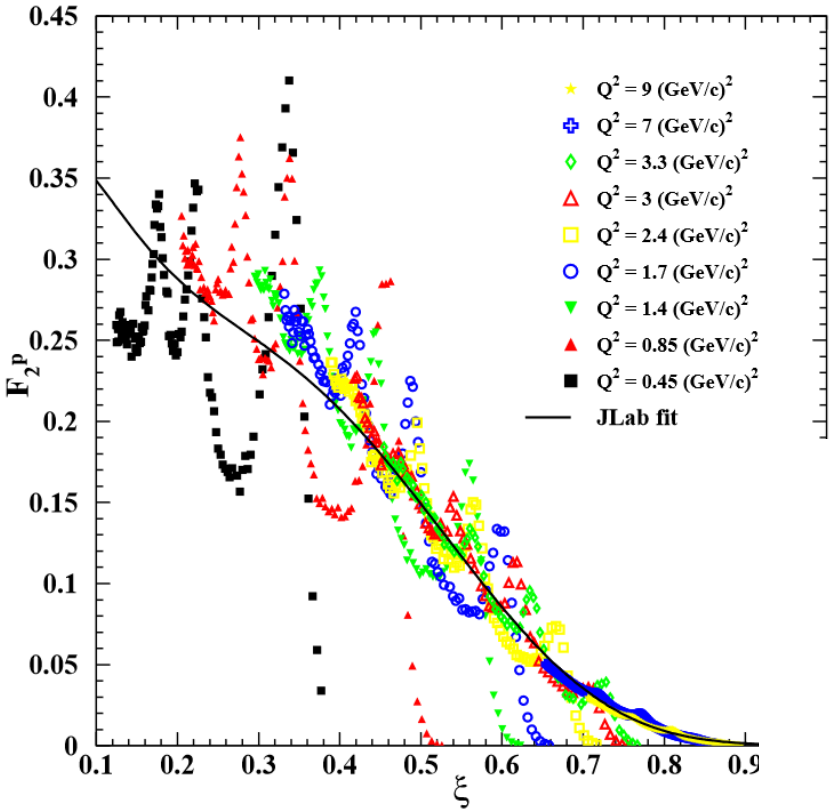
DIS fit – 'F2ALLM' H.Abramowicz and A.Levy, hep-ph/9712415
Res fit - E.C. and P.E. Bosted, PRC 81,055213



E. Christy, 2018 Duality workshop

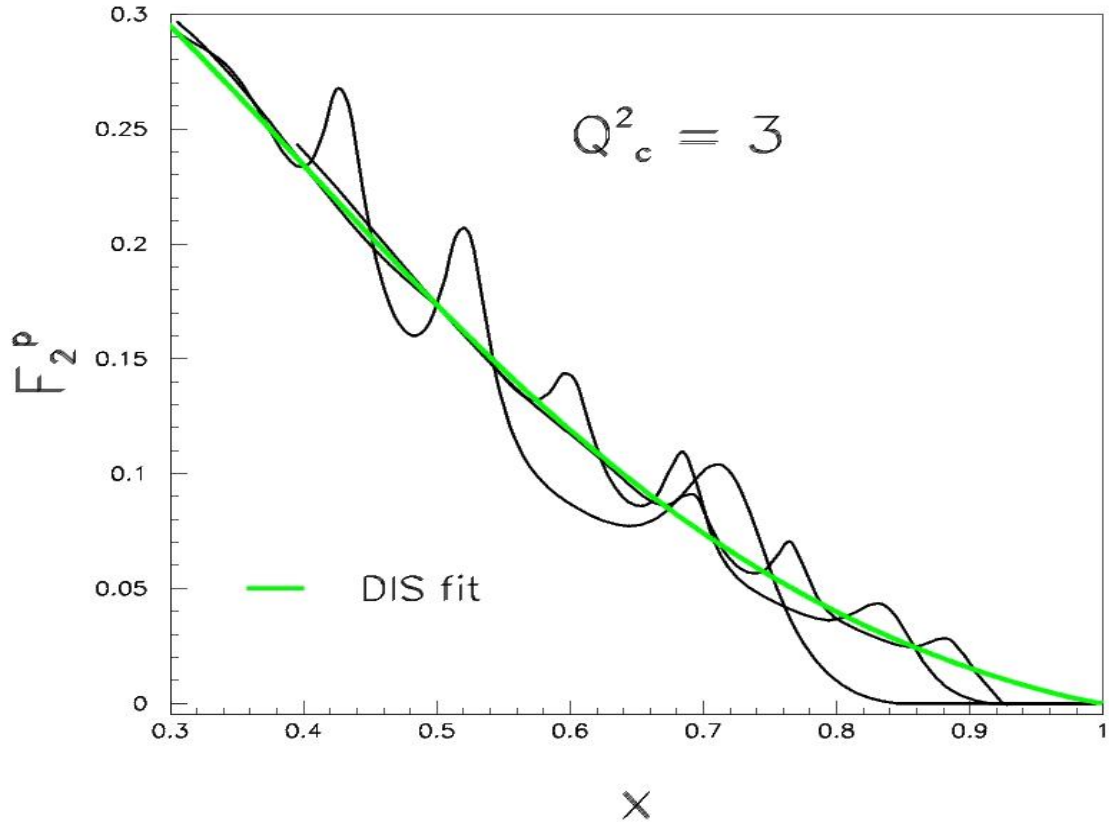
Duality-based averaging procedure

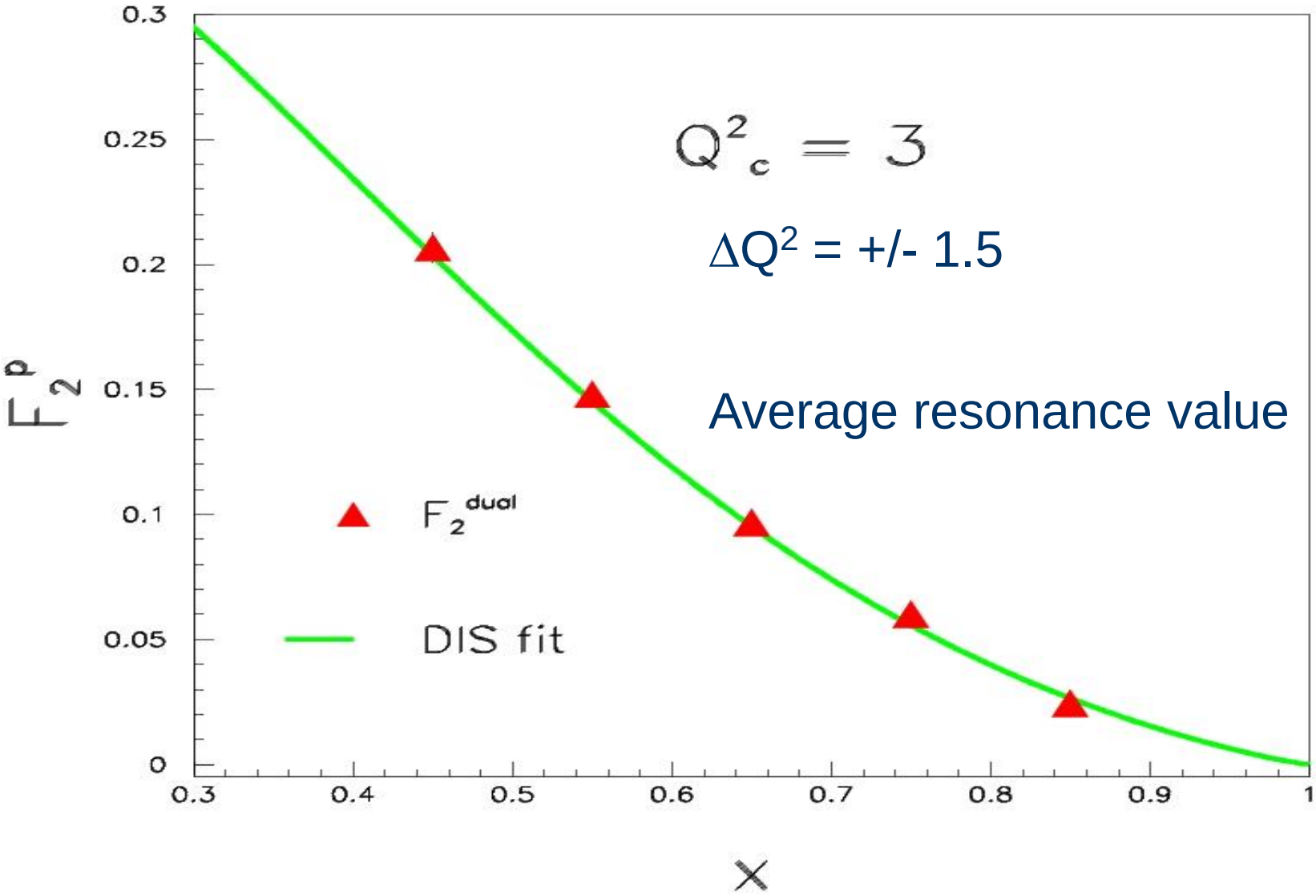
E. Christy, Duality workshop JMU 2018



Q^2 dependence removed with DIS fit

$F_2^{res}(x,Q^2_c) = F_2^{res}(x,Q^2) * F_2^{dis}(x,Q^2_c)/F_2^{dis}(x,Q^2)$





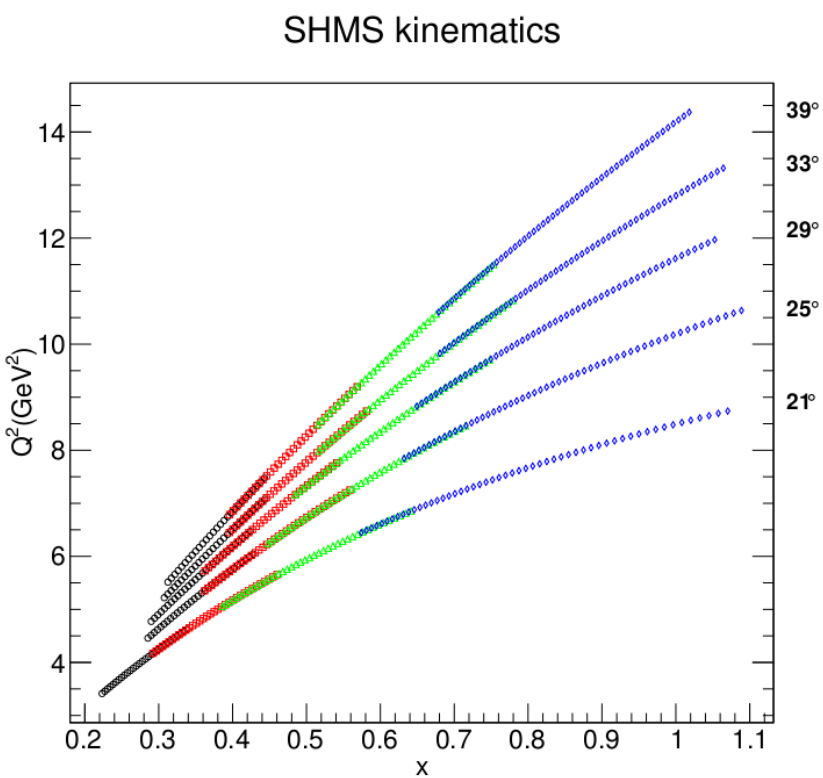
ΔQ^2 = +/- 1.5

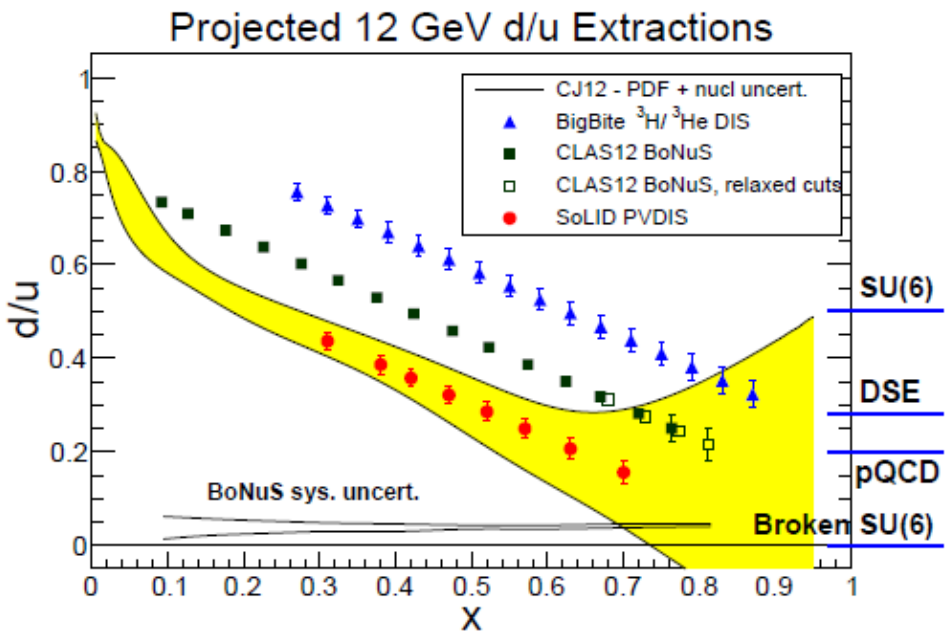
Average resonance value

Future studies: JLab at 12 GeV

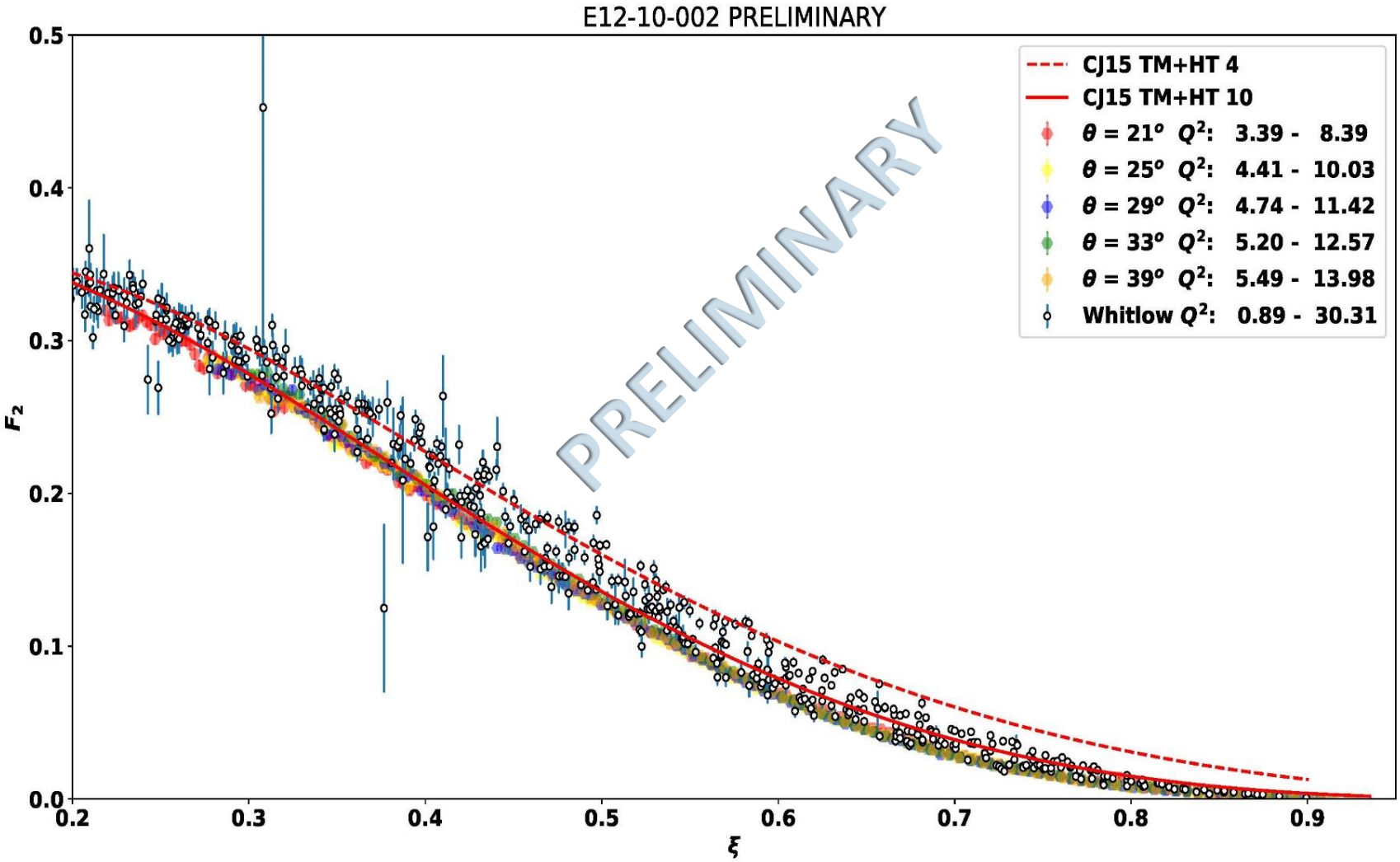
E12-10-002: Spring 2018
Proton and deuteron

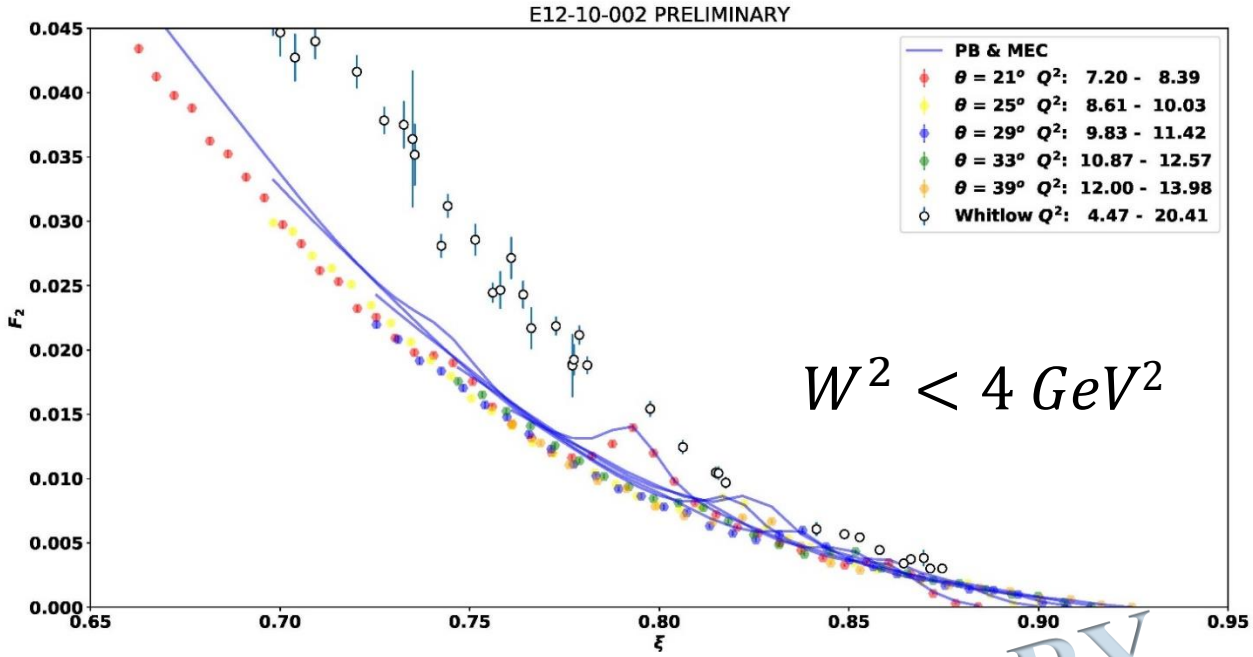
E12-06-113: Spring 2020
neutron

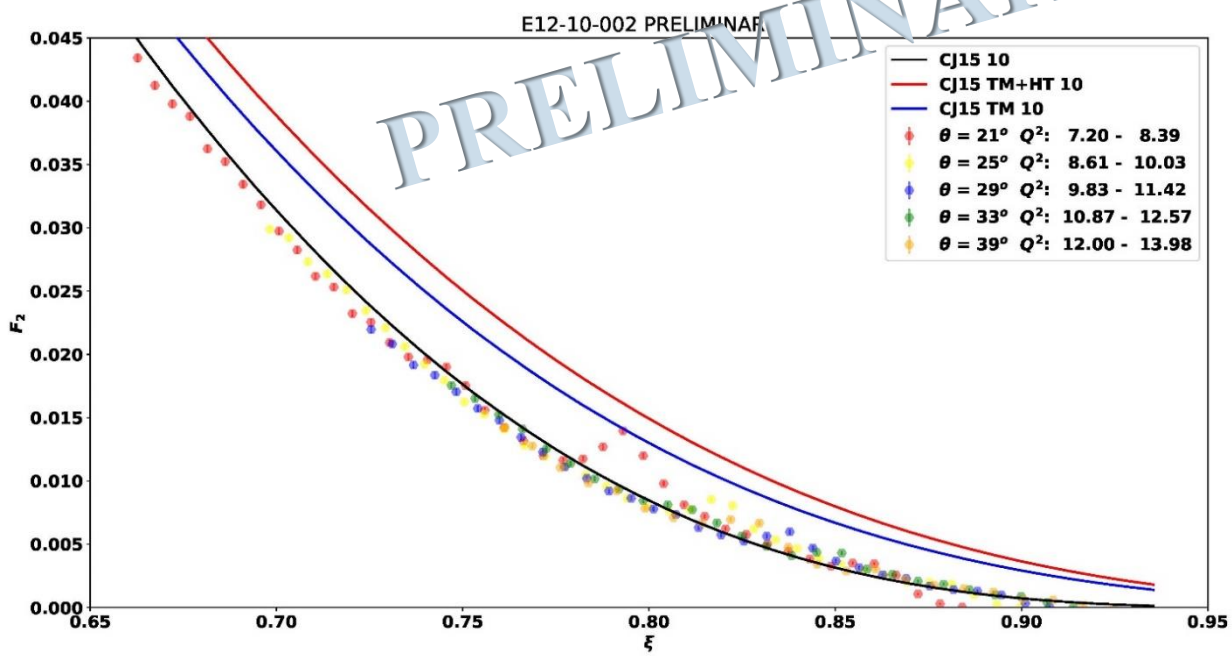




Preliminary Results (E12-10-002): proton




E12-10-002 PRELIMINARY
PB & MEC
θ = 21° Q²: 7.20 - 8.39
θ = 25° Q²: 8.61 - 10.03
θ = 29° Q²: 9.83 - 11.42
θ = 33° Q²: 10.87 - 12.57
θ = 39° Q²: 12.00 - 13.98
Whitlow Q²: 4.47 - 20.41
$W^2 < 4\ GeV^2$
F₂
ξ


E12-10-002 PRELIMINARY
PRELIMINARY
CJ15 10
CJ15 TM+HT 10
CJ15 TM 10
θ = 21° Q²: 7.20 - 8.39
θ = 25° Q²: 8.61 - 10.03
θ = 29° Q²: 9.83 - 11.42
θ = 33° Q²: 10.87 - 12.57
θ = 39° Q²: 12.00 - 13.98
F₂
ξ

Conclusion

Quark-hadron duality is somehow a fundamental property of nucleon structure

- Works generally in every process studied
- Studies now quite numerous

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?

Extra Slides

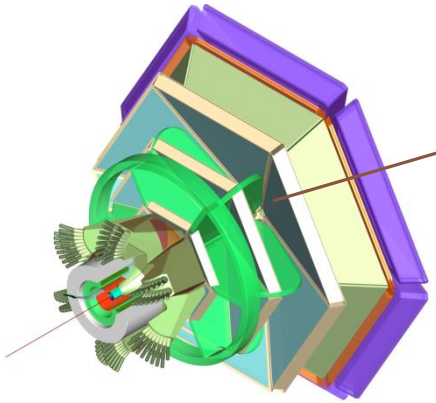
For the new data and duality, you will also want to make the argument why the high Q2 resonance region is duality interesting - here, I would make the points

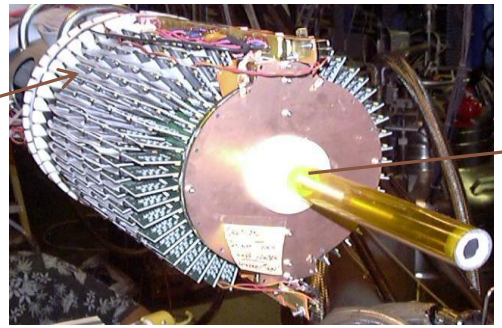
(a) that most explanations center around cancelling or minimal higher twist.. and so the prediction should be that duality is only better at higher Q, need to test!

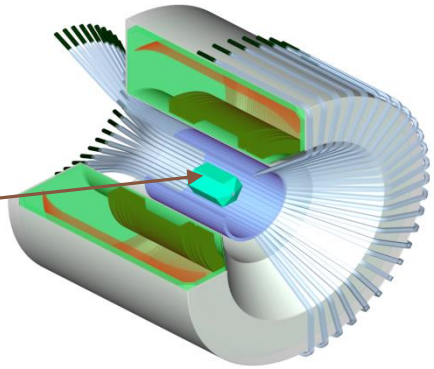
(b) the curves we compare to should be better at higher Q, lending themselves to better testing

(c) it's really the Q2 dependence and not the integral that's most fascinating... we get the scaling curve Q2 dependence from DGLAP, well understood and not a bound object... do the resonances really pick up this Q2 dependence on average - again, can test best with high Q [my personal favorite point]

Future neutron studies: BONUS at 12 GeV (E12-06-113)

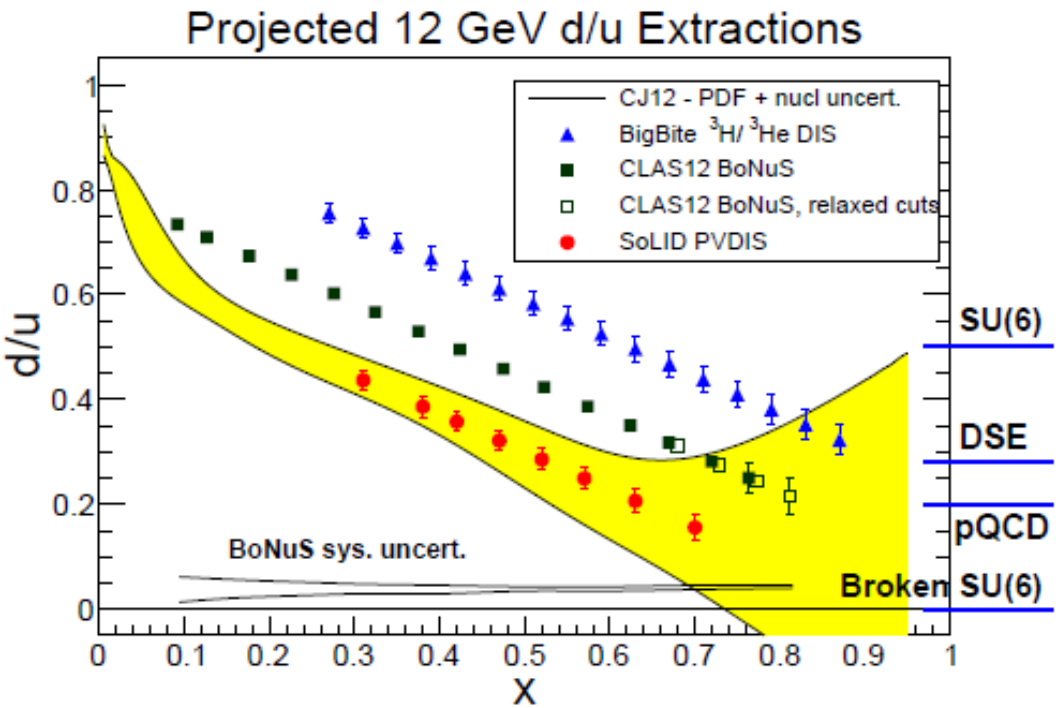




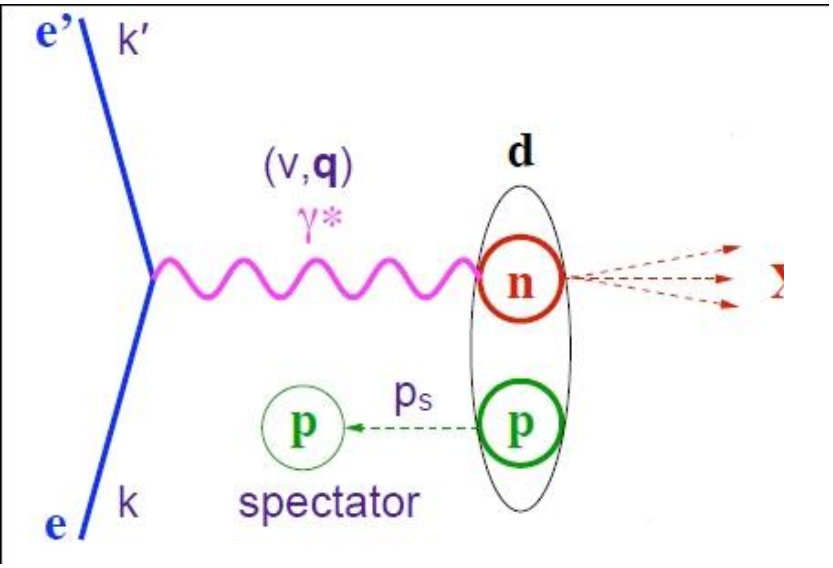


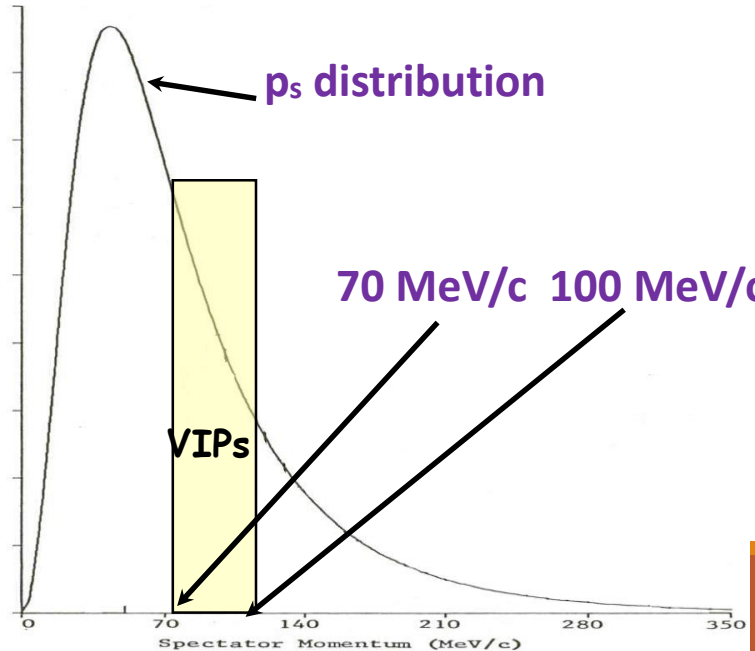
Data in early 2020

- **DIS region with**
  - $Q^2 > 1\ \mathrm{GeV}^2/c^2$
  - $W^* > 2$ GeV

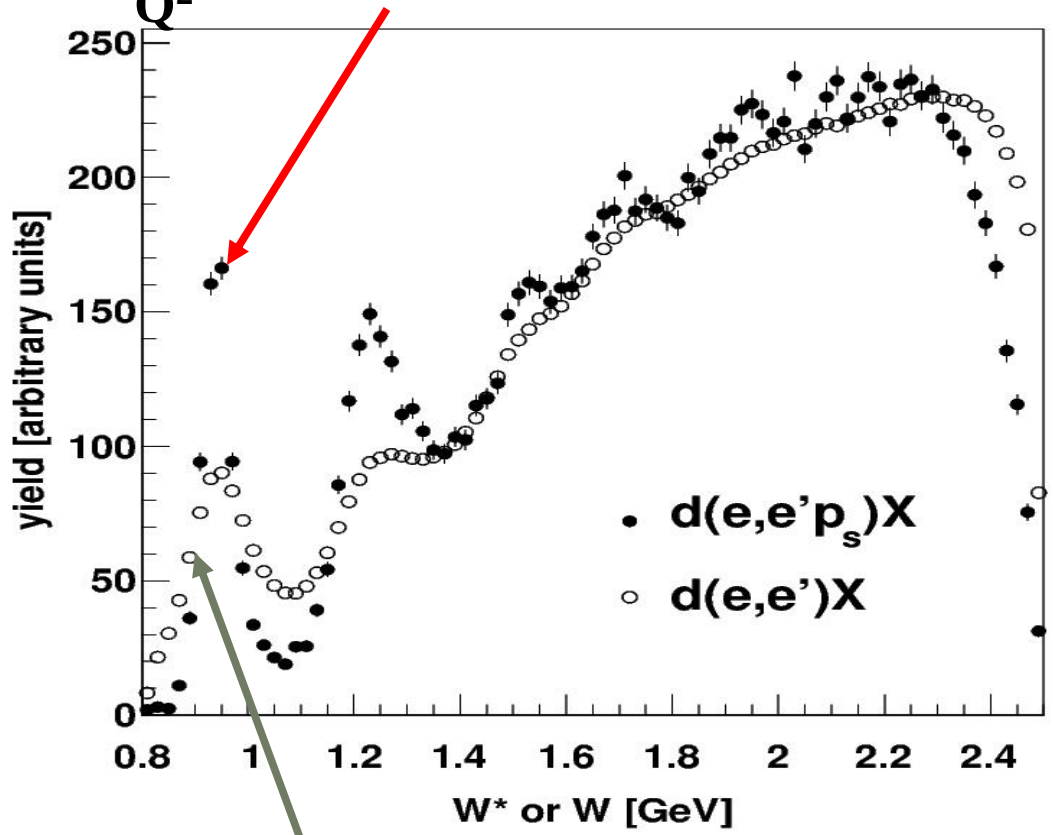


Kinematic reconstruction with tagged protons





$$W^{*2} = (p_n + q)^2 \approx M^{*2} + 2M\nu(2 - \alpha_s) - Q^2$$



$$W^2 = M^2 + 2M\nu - Q^2$$

Ratio Method

N. Baillie *et al.*, PRL108, 199902 (2012)
S. Tkachenko *et al.*, PRC 89, 045206 (2014)

VIP (Very Important Protons)

P_s < 100 MeV/c, θ_{pq} ≥ 100 deg

Experimental ratio

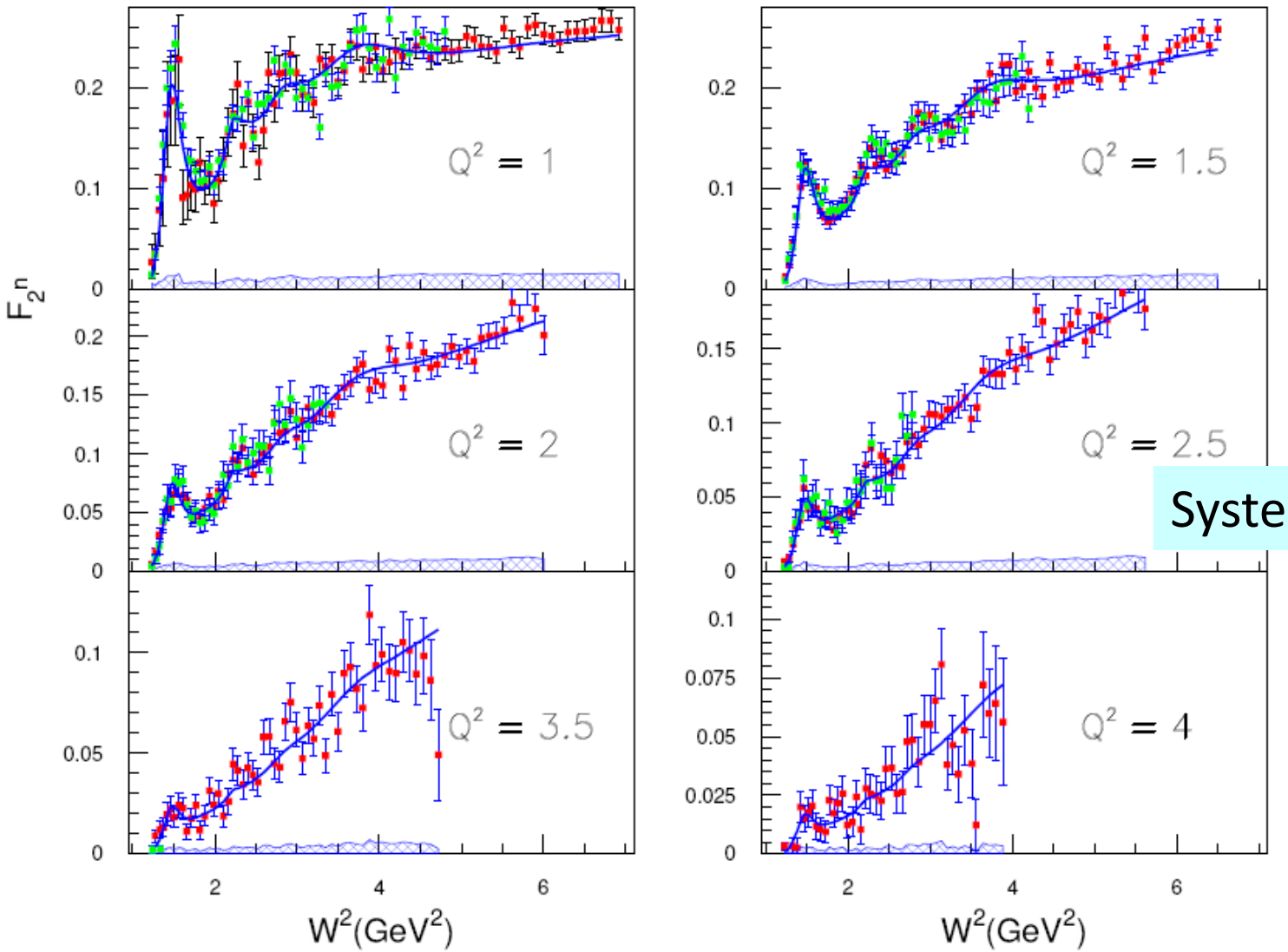
$$R_{exp} = \frac{N_{d(e,e'p_s)}(W^*, Q^2)}{N_{d(e,e')}(W, Q^2)} C(E_b, W^*, W, Q^2) =$$

$$\frac{F_2^n(W^*, Q^2)}{F_2^d(W, Q^2)} \int_{VIP} d\alpha_s dp_s^{\perp} A_p(\alpha_s, p_s^{\perp}) S(\alpha_s, p_s^{\perp}).$$

$$F_2^n = F_2^d \times R_{\exp}$$

Results

E=4.2 and 5.3 GeV



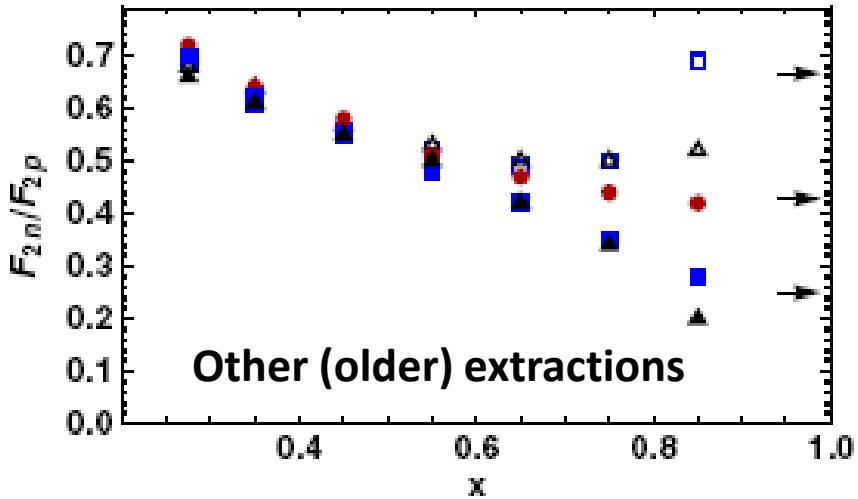
Systematic unc.

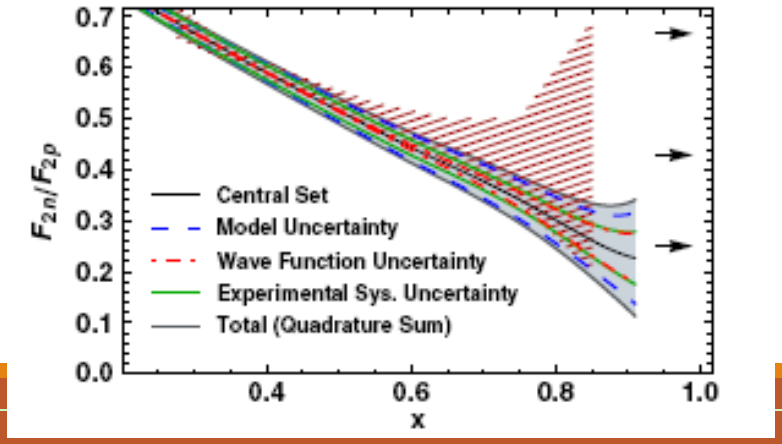
S. Tkachenko *et al.*, PRC 89, 045206 (2014)

Extract neutron from deuteron data

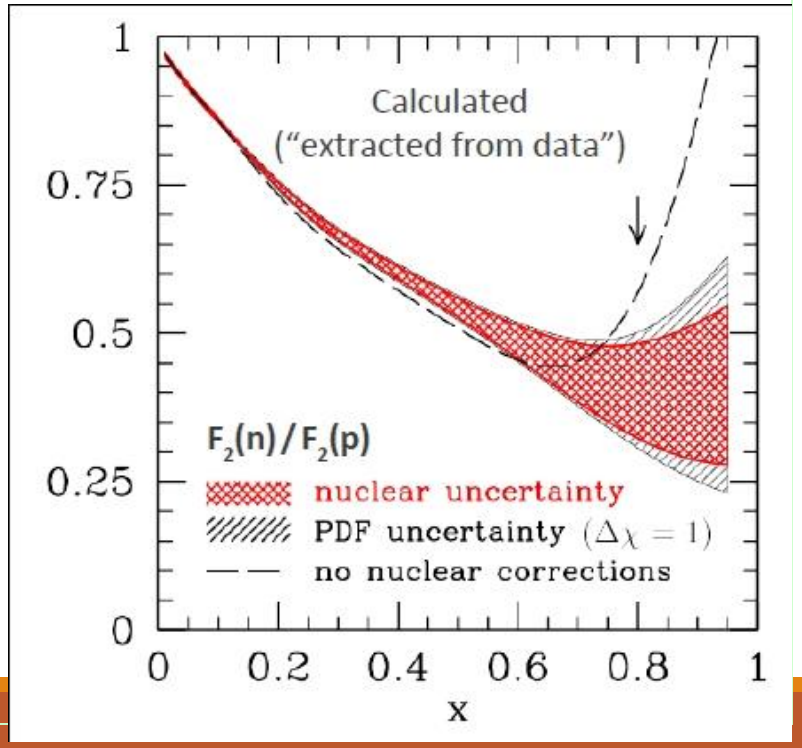
Large uncertainties due to nuclear effects

J. Arrington, J.G. Rubin, W. Melnitchouk PRL 108, 252001 (2012)

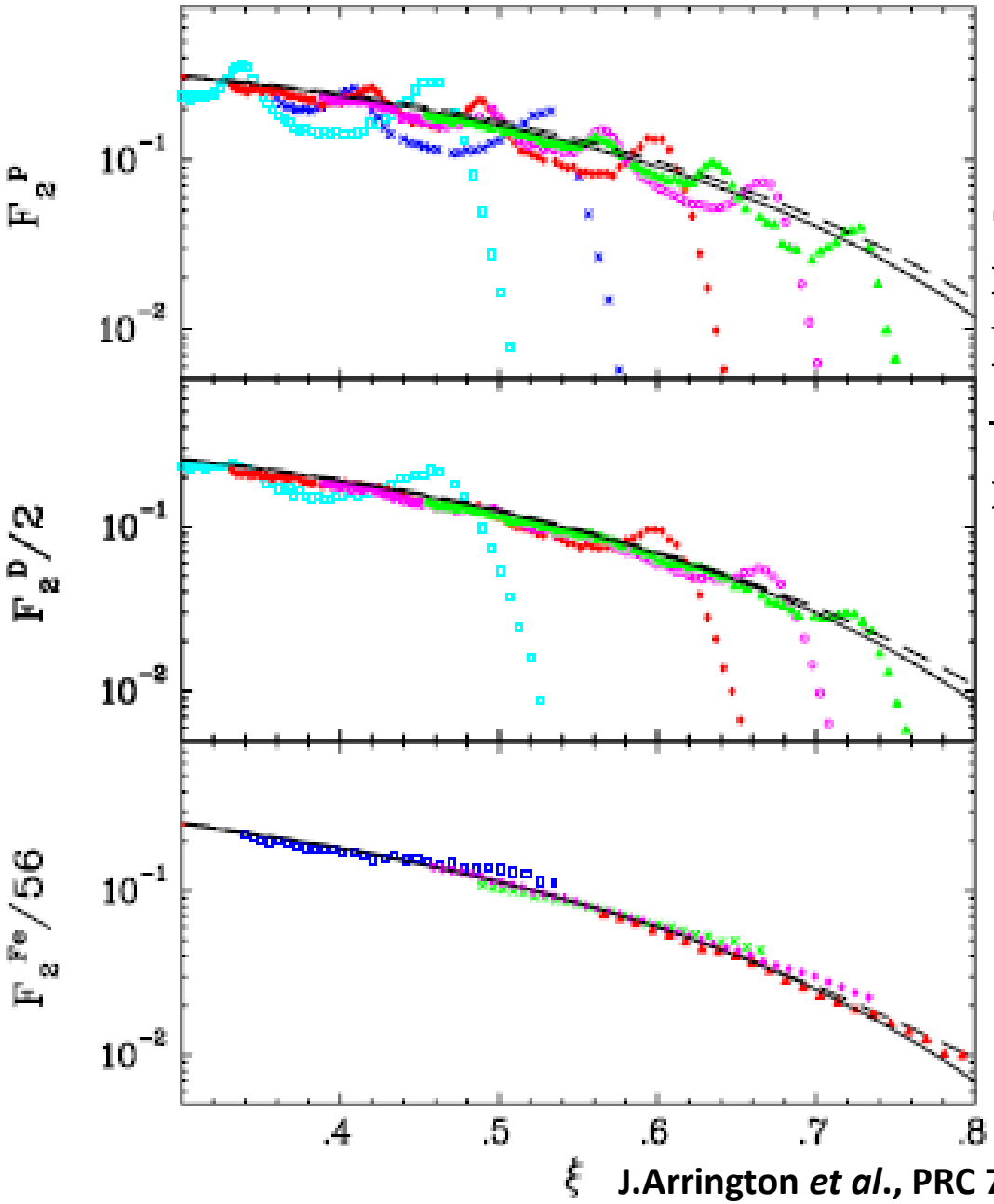




A. Accardi *et al.*, PRD 84 014008 (2011)



The Proton and the Deuteron



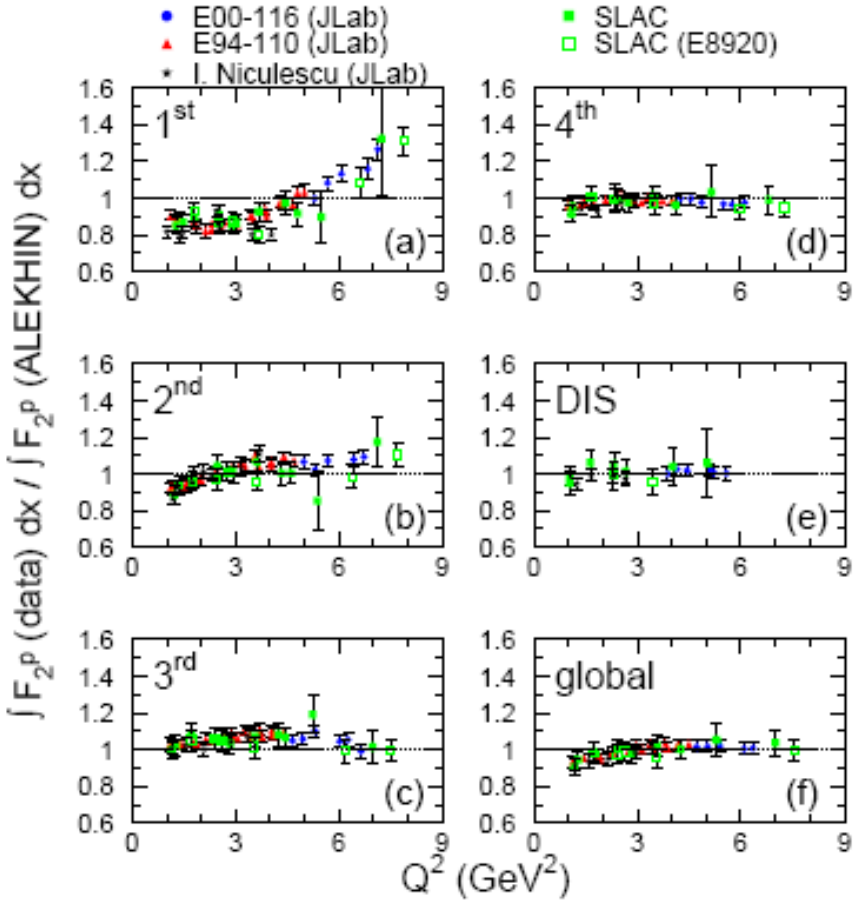
Scaling (duality) is observed in nuclei

Resonances less pronounced – washed out by Fermi motion

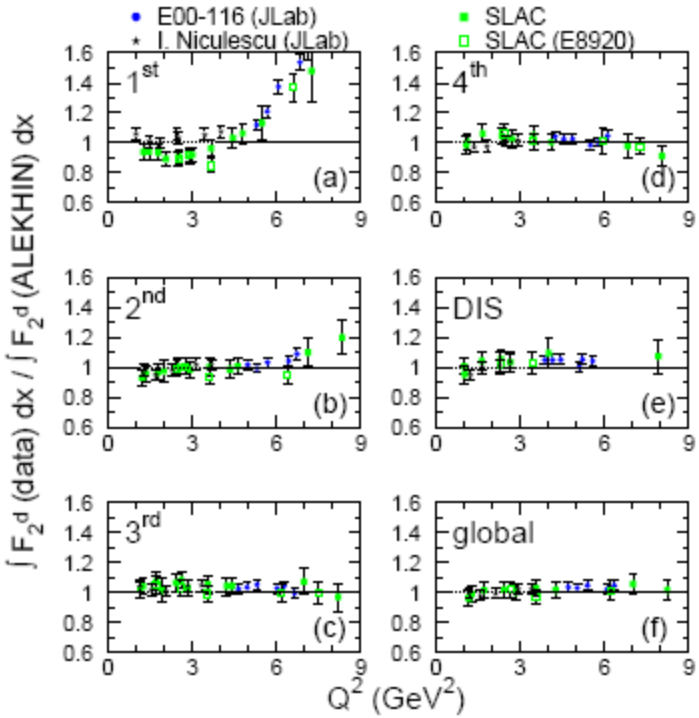
J.Arrington *et al.*, PRC 73 (2006) 035205

Local duality

The proton



The deuteron

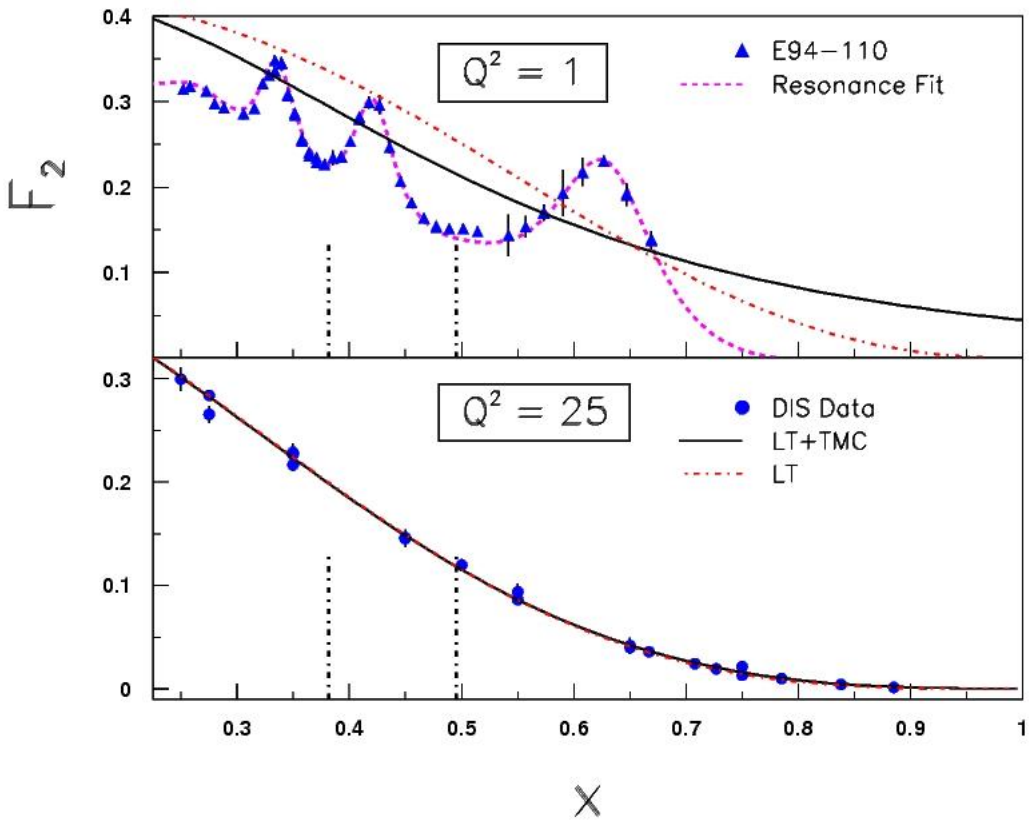


S. Malace *et al.*, PRC 80, 035207 (2009)

Truncated Moments and Local Duality

A. Psaker, W. Melnitchouk, MEC, C. Keppel

Phys.Rev.C. 78, 025206



⟶ Compare integral over select resonance regions to evolved scaling curve + TM

→ Scaling curve is empirical Fit to data at $Q^2 = 25$, where TM contribution has been separated from leading-twist via an unfolding procedure.

→ Scaling curve is then evolved to lower Q^2 via non-singlet evolution before recalculating the TM contributions at the lower Q^2.