George Washington University
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Quarks or hadrons?
Duality in electron-nucleon scattering

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Outline

- Introduction: *Bloom-Gilman duality*
- Duality in QCD
  - → OPE and higher twists
- Local duality & truncated moments
- Duality in the neutron
  - → is duality in proton an accident?
  - → extraction of neutron resonance structure from deuterium data
- Duality in pion electroproduction
- Conclusions

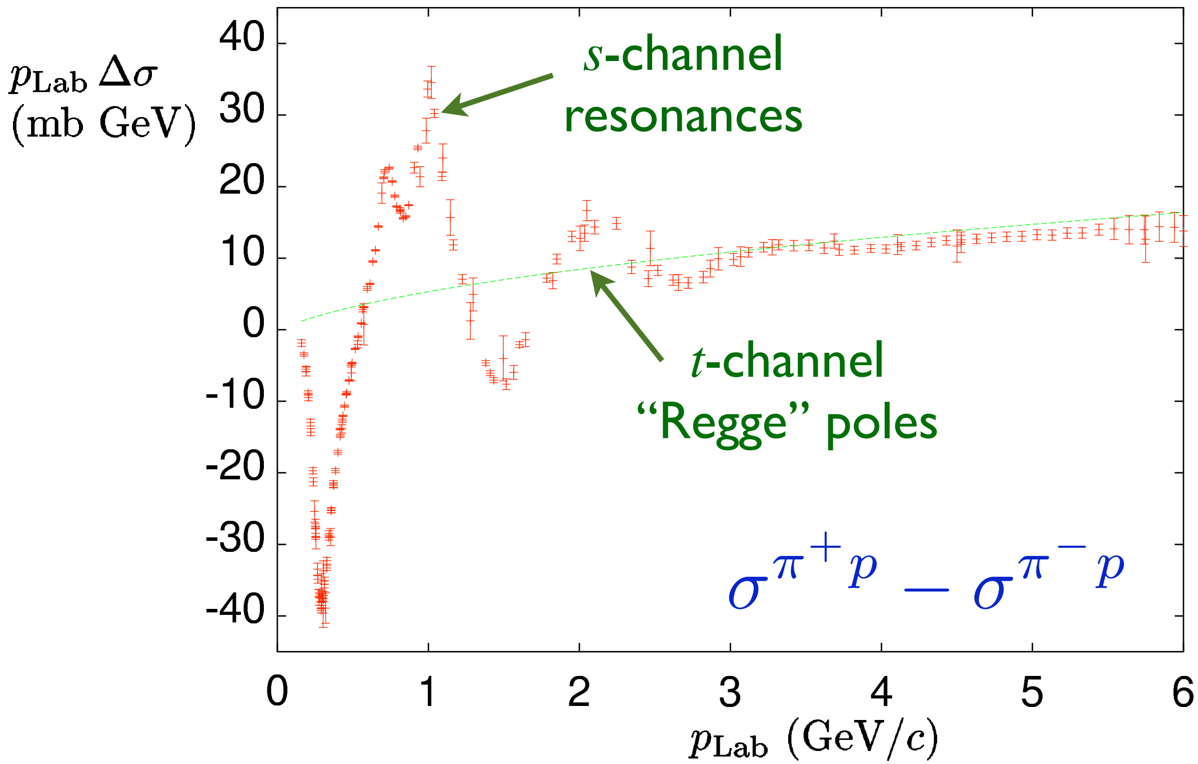
Quark-hadron duality

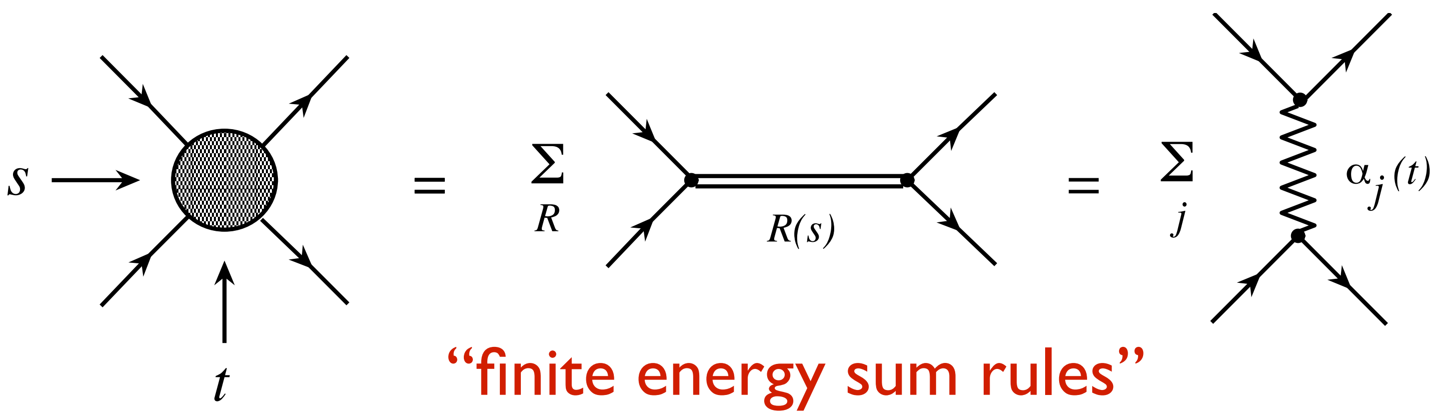
Complementarity between *quark* and *hadron* descriptions of observables

$$\sum_{hadrons} = \sum_{quarks}$$

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

Duality in hadron-hadron scattering



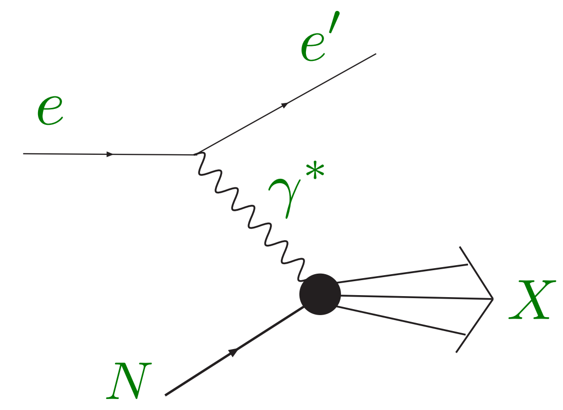


“finite energy sum rules”

Igi (1962), Dolen, Horn, Schmidt (1968)

Electron-nucleon scattering

- Inclusive cross section for $eN \to eX$



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

$$\left.\begin{aligned} \nu &= E - E' \\ Q^2 &= \vec{q}^{\,2} - \nu^2 = 4EE'\sin^2\frac{\theta}{2} \end{aligned}\right\} \quad x = \frac{Q^2}{2M\nu}$$

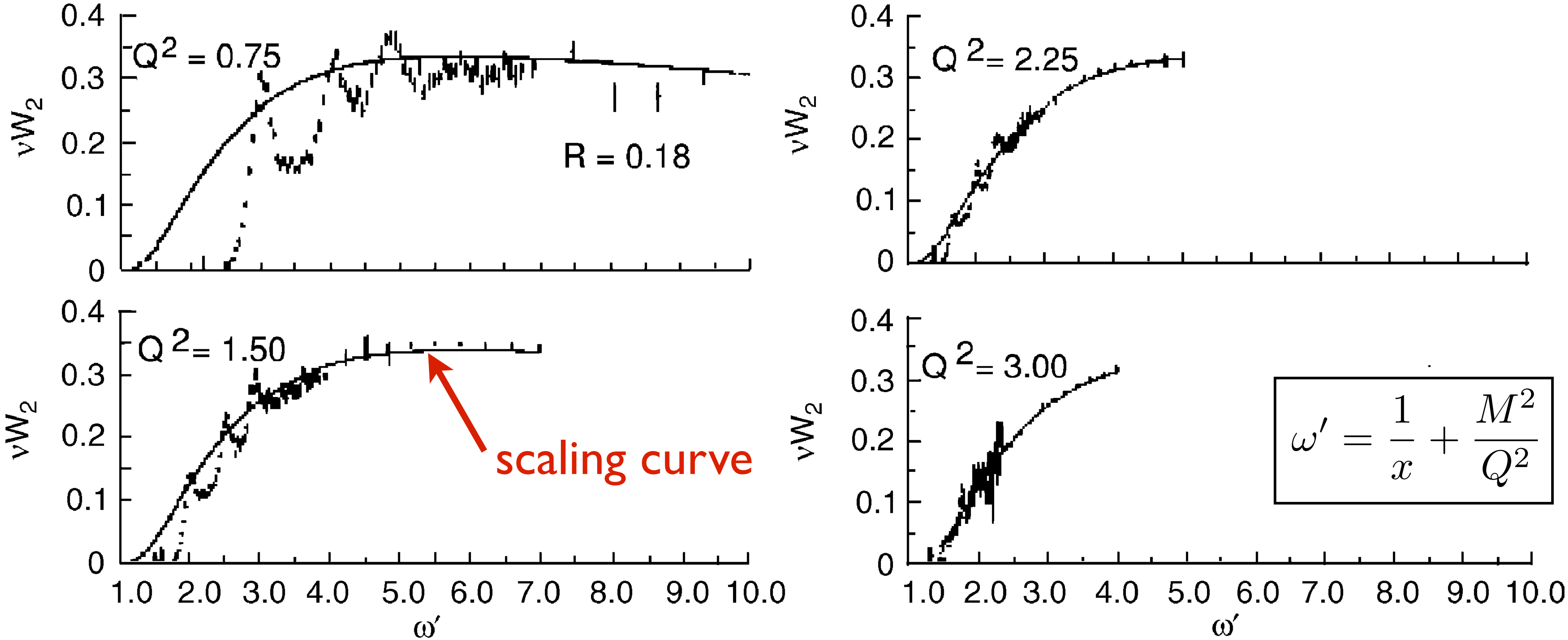
"Bjorken scaling variable"

- F_1 , F_2 "structure functions"

  ⟶ contain all information about structure of nucleon

  ⟶ functions of $x,\ Q^2$ in general

Bloom-Gilman duality



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

Bloom, Gilman, PRL ***85****, 1185 (1970)*

⇨ resonance – scaling duality in proton $\nu W_2 = F_2$ structure function

Bloom-Gilman duality

- Average over (strongly Q^2 dependent) resonances $\approx Q^2$ independent scaling function

- Finite energy sum rule for eN scattering

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

measured structure function (function of ν and Q^2)

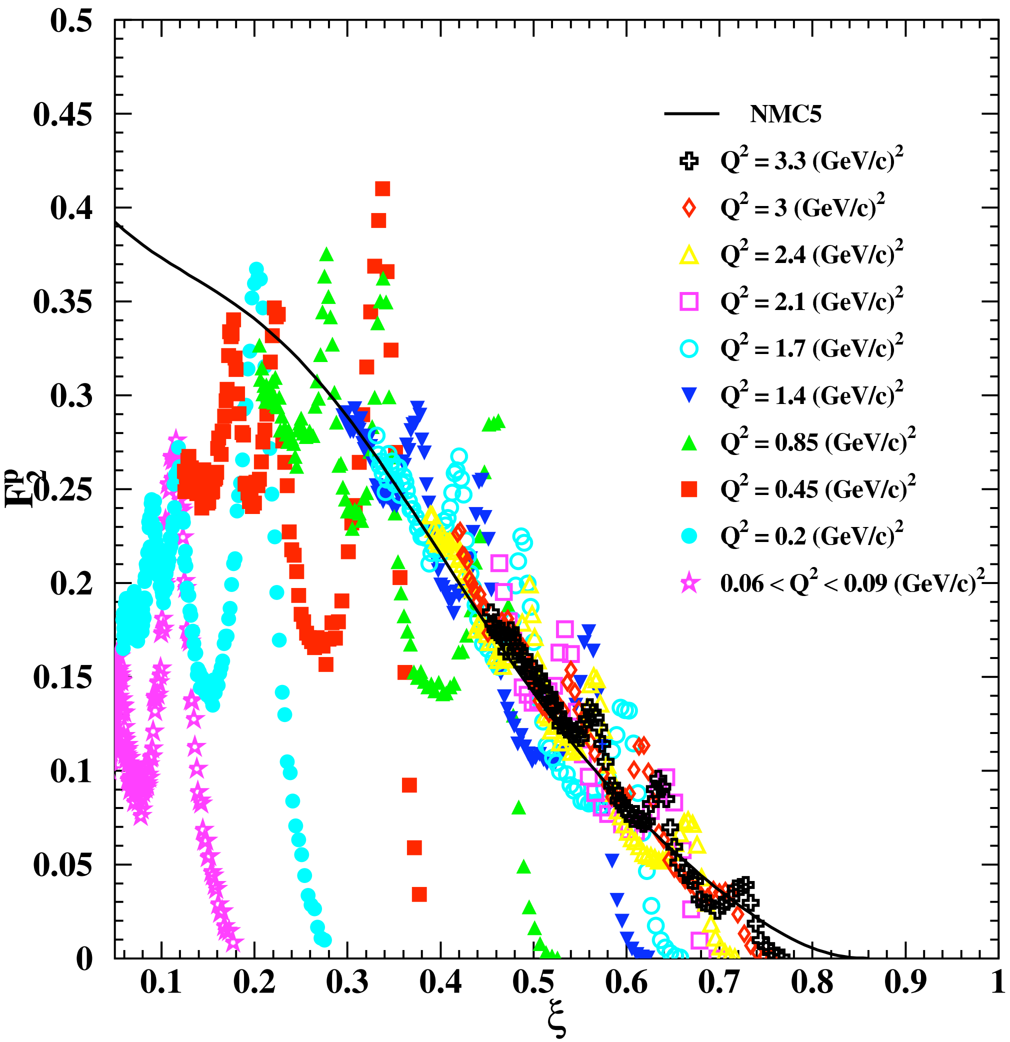
"hadrons"

scaling function (function of ω' only)

"quarks"

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

Bloom-Gilman duality



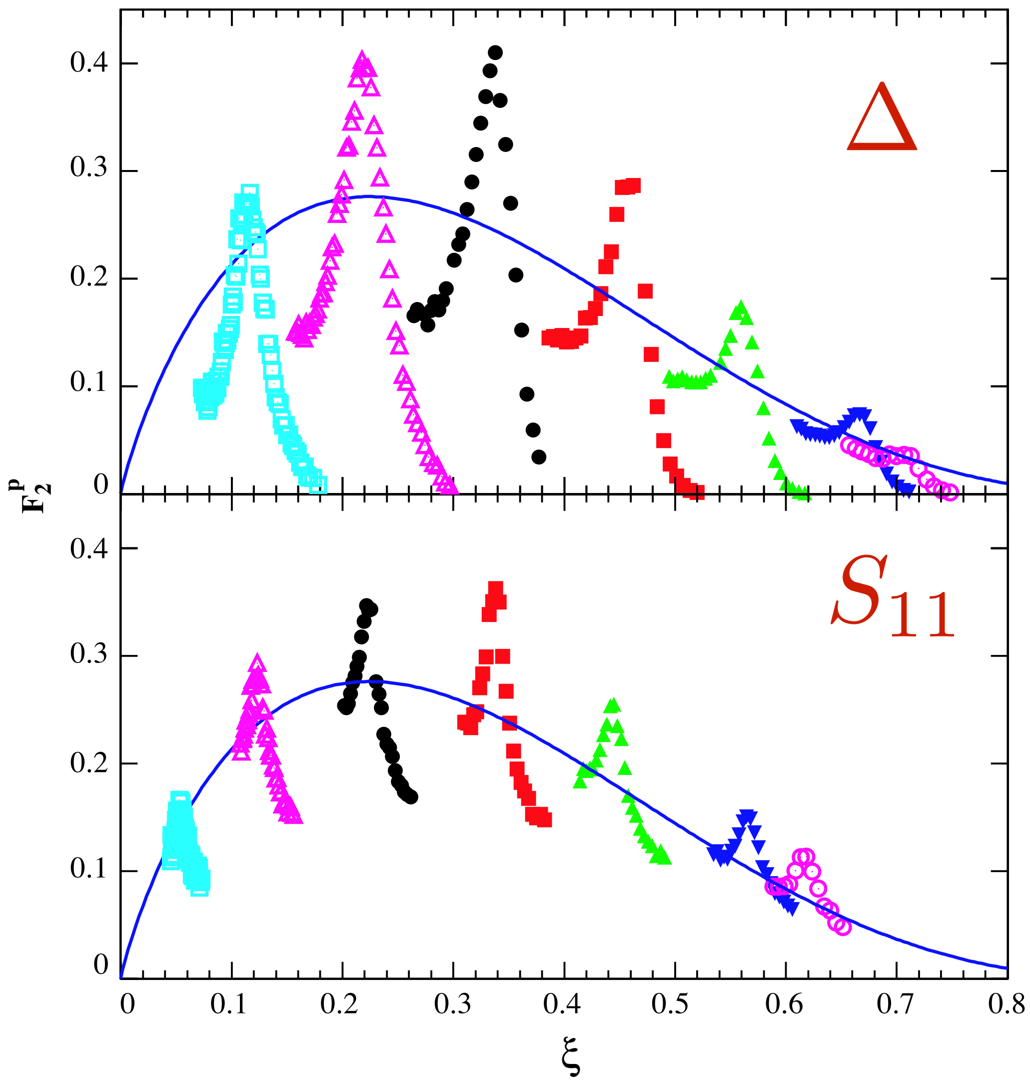
*Niculescu et al., PRL **85**, 1182 (2000)*

Average over
(strongly Q^2 dependent)
resonances
$\approx Q^2$ independent
scaling function

"Nachtmann scaling variable"

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

- Duality exists also in local regions, around individual resonances



⇒ *local* Bloom-Gilman duality

Duality in QCD

("global duality")

Duality in QCD

- Operator product expansion

→ expand *moments* of structure functions in powers of $1/Q^2$

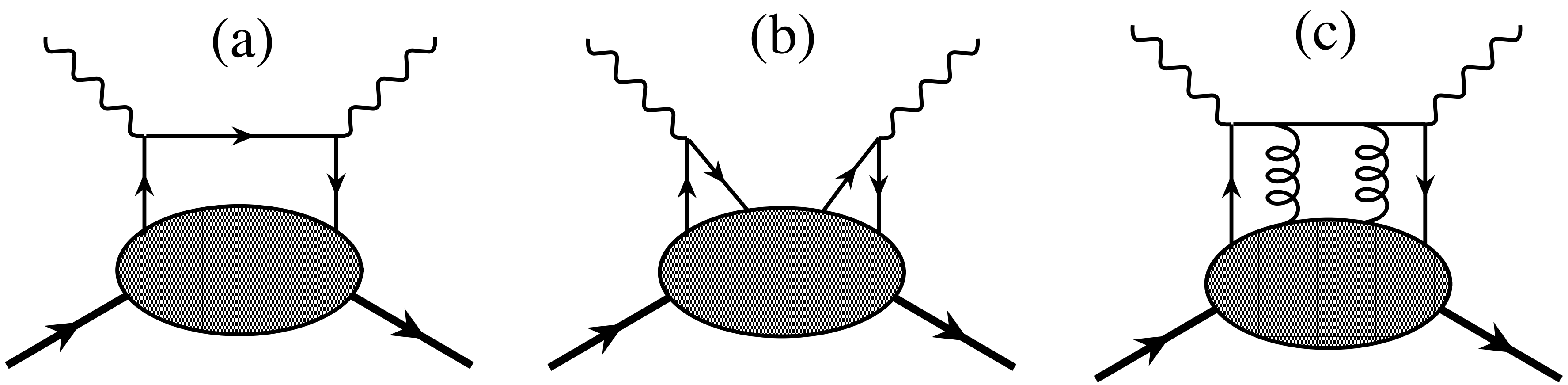
$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x, Q^2)$$

$$= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific "twist" τ

$$\tau = \text{dimension} - \text{spin}$$

Duality in QCD



$\tau = 2$

single quark scattering

$e.g. \quad \bar{\psi}\ \gamma_\mu\ \psi$

$\tau > 2$

qq and qg correlations

$e.g. \quad \bar{\psi}\ \gamma_\mu\ \psi\ \bar{\psi}\ \gamma_\nu\ \psi$

or $\quad \bar{\psi}\ \widetilde{G}_{\mu\nu}\gamma^\nu\ \psi$

Duality in QCD

- Operator product expansion

  → expand *moments* of structure functions in powers of $1/Q^2$

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

- If moment $\approx$ independent of Q^2

  → higher twist terms $A_n^{(\tau>2)}$ small

Duality in QCD

- Operator product expansion

  → expand *moments* of structure functions in powers of $1/Q^2$

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

- Duality ⟷ suppression of higher twists

de Rujula, Georgi, Politzer, Ann. Phys. ***103****, 315 (1975)*

Duality in QCD

- Much of recent new data is in *resonance* region, $W < 2$ GeV

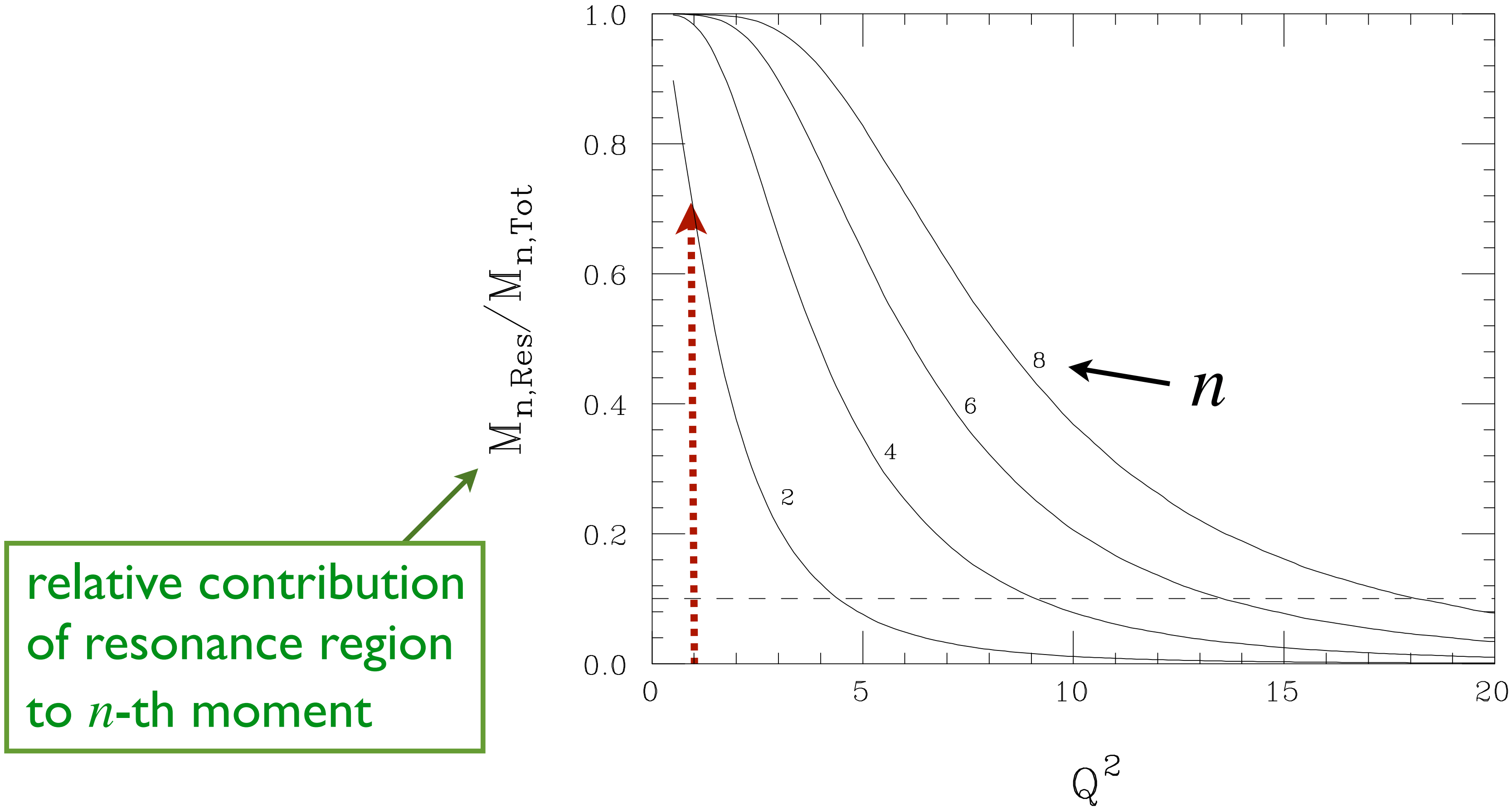
→ *common wisdom:* pQCD analysis not valid in resonance region

→ *in fact:* partonic interpretation of moments *does* include resonance region

- Resonances are an *integral part* of deep inelastic structure functions!

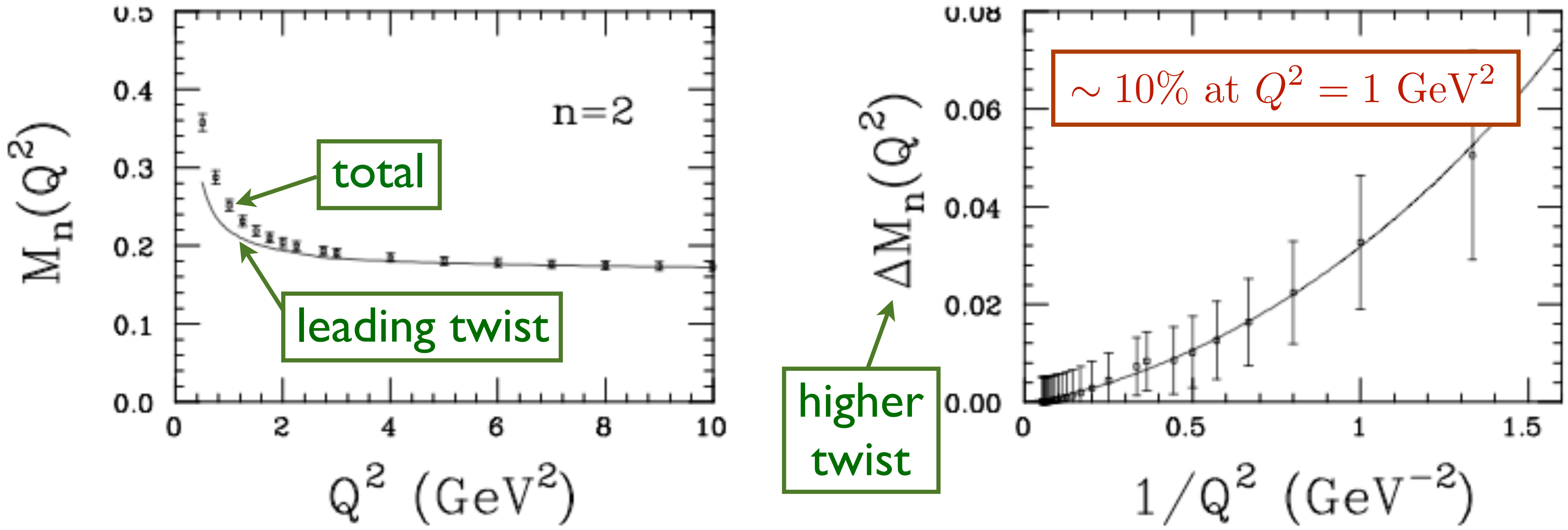
→ implicit role of quark-hadron duality

Proton moments



$\Rightarrow$ At $Q^2 = 1\ \mathrm{GeV}^2$, $\sim$ 70% of lowest moment of F_2^p comes from $W < 2\ \mathrm{GeV}$

Proton moments



➡ <u>BUT</u> resonances and DIS continuum conspire to produce only $\sim$ <u>10%</u> *higher twist* contribution!

Ji, Unrau, PRD ***52****, 72 (1995)*

→ total higher twist *small* at $Q^2 \sim 1-2\ \mathrm{GeV}^2$

- on average, nonperturbative interactions between quarks and gluons not dominant at these scales

- suggests *strong cancellations* between resonances, resulting in dominance of *leading twist*

- OPE does not tell us *why* higher twists are small

  → need more detailed information (*e.g.* about individual resonances) to understand behavior dynamically

Local Duality &
Truncated Moments

Truncated moments

- complete moments can be studied via twist expansion

  $\longrightarrow$ Bloom-Gilman duality has a precise meaning

  (*i.e.*, duality violation = higher twists)

- rigorous connection between local duality & QCD difficult

  $\longrightarrow$ need prescription for how to average over resonances

- *truncated* moments allow study of restricted regions in x (or W) within pQCD in well-defined, systematic way

$$\overline{M}_n(\Delta x, Q^2) = \int_{\Delta x} dx\ x^{n-2}\ F_2(x, Q^2)$$

Truncated moments

- truncated moments obey DGLAP-like evolution equations, similar to PDFs

$$\frac{d\overline{M}_n(\Delta x, Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\left(P'_{(n)} \otimes \overline{M}_n\right)(\Delta x, Q^2)$$

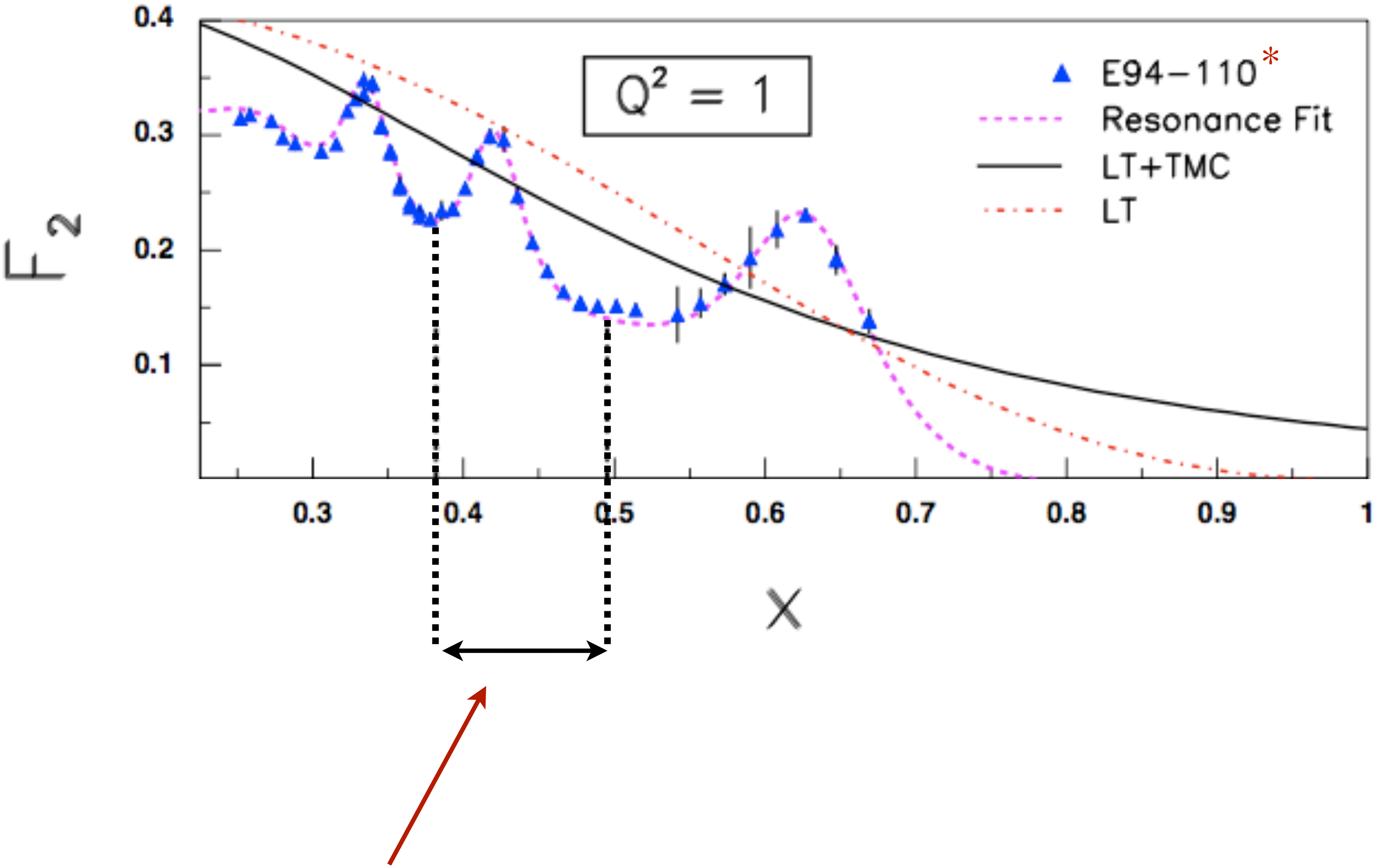
where modified splitting function is

$$P'_{(n)}(z, \alpha_s) = z^n \; P_{NS,S}(z, \alpha_s)$$

→ can follow evolution of <u>specific resonance (region)</u> with Q^2 in pQCD framework!

→ suitable when complete moments not available

F_2^p resonance spectrum

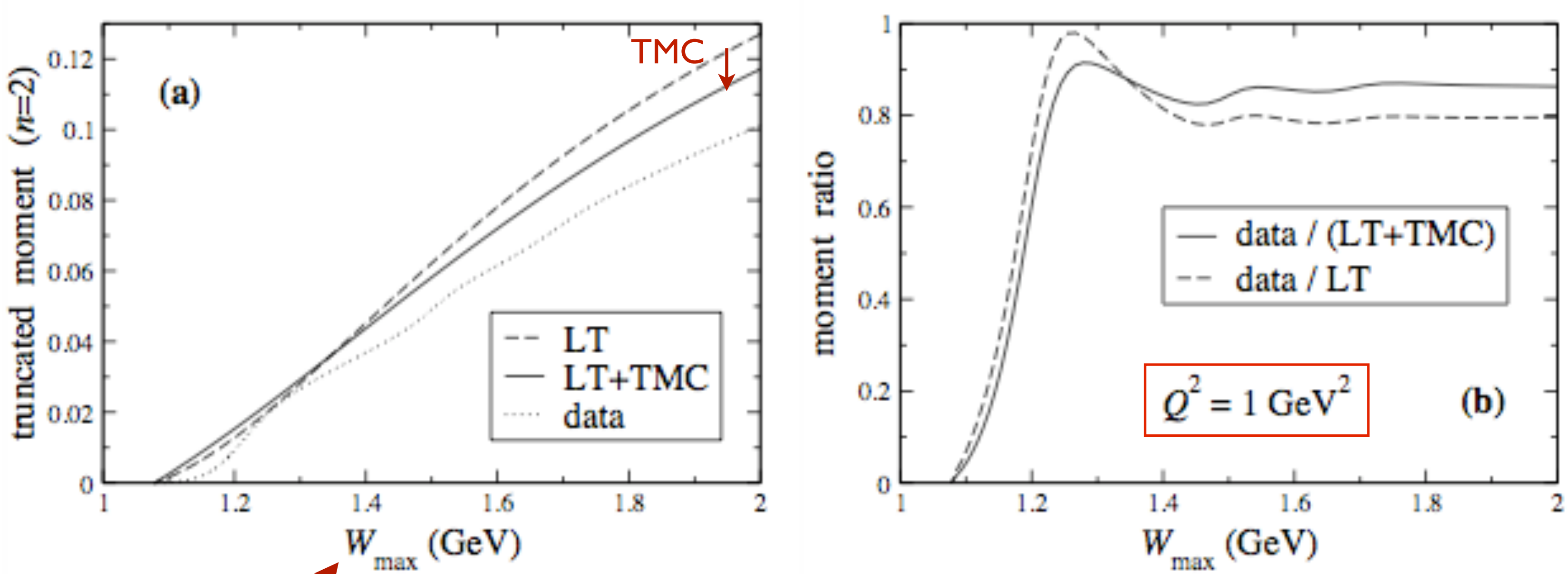


* JLab Hall C

how much of this region is *leading twist* ?

Data analysis

- assume data at large enough Q^2 are *entirely* leading twist
- evolve fit to data at large Q^2 down to lower Q^2
- apply target mass corrections and compare with low-Q^2 data



$$W^2 = M^2 + \frac{Q^2}{x}(1-x)$$

Psaker, WM et al.
PRC ***78****, 025206 (2008)*

Data analysis

- consider individual resonance regions:

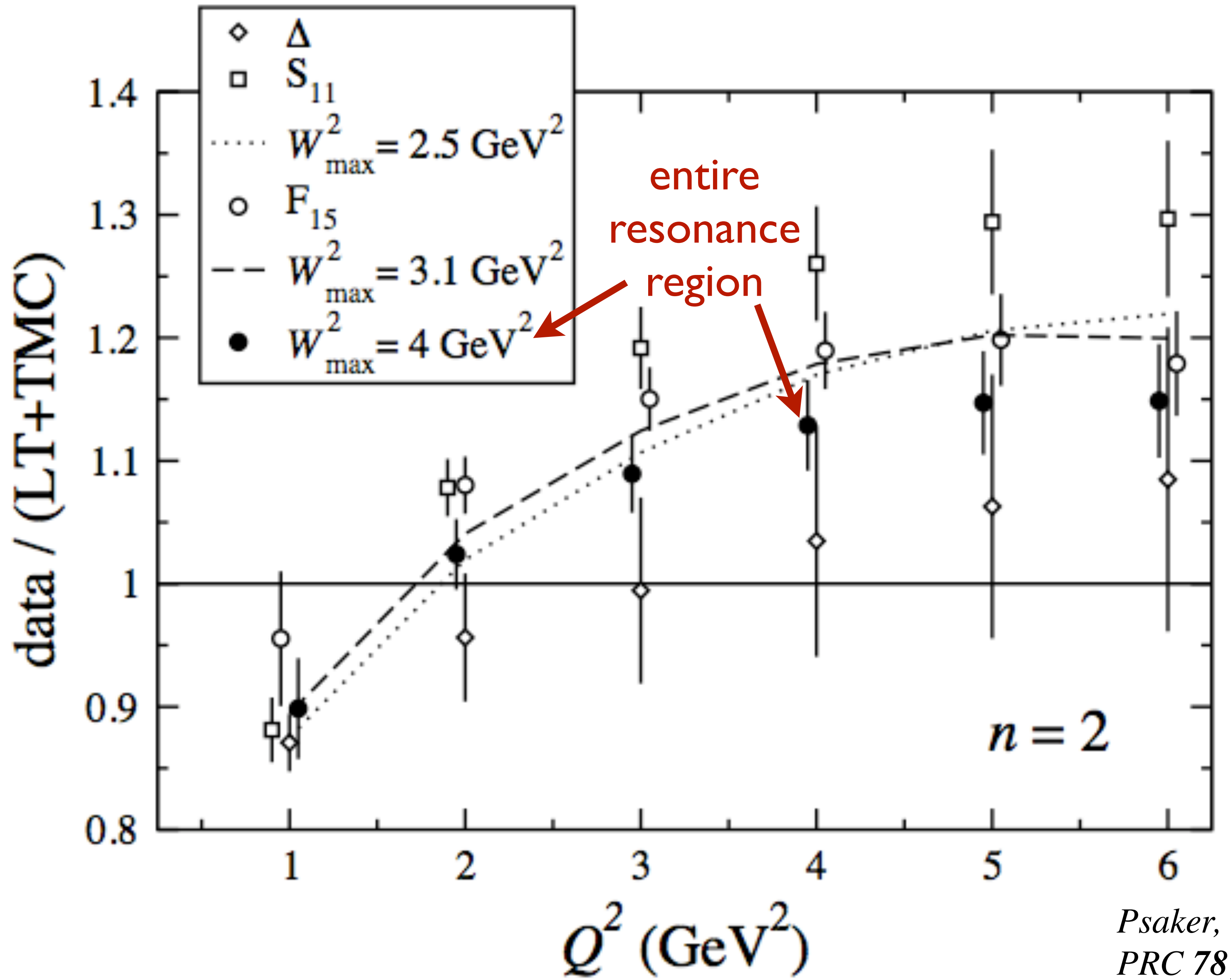
$\rightarrow$ $W^2_{\rm thr} < W^2 < 1.9\ {\rm GeV}^2$ "$\Delta(1232)$"

$\rightarrow$ $1.9 < W^2 < 2.5\ {\rm GeV}^2$ "$S_{11}(1535)$"

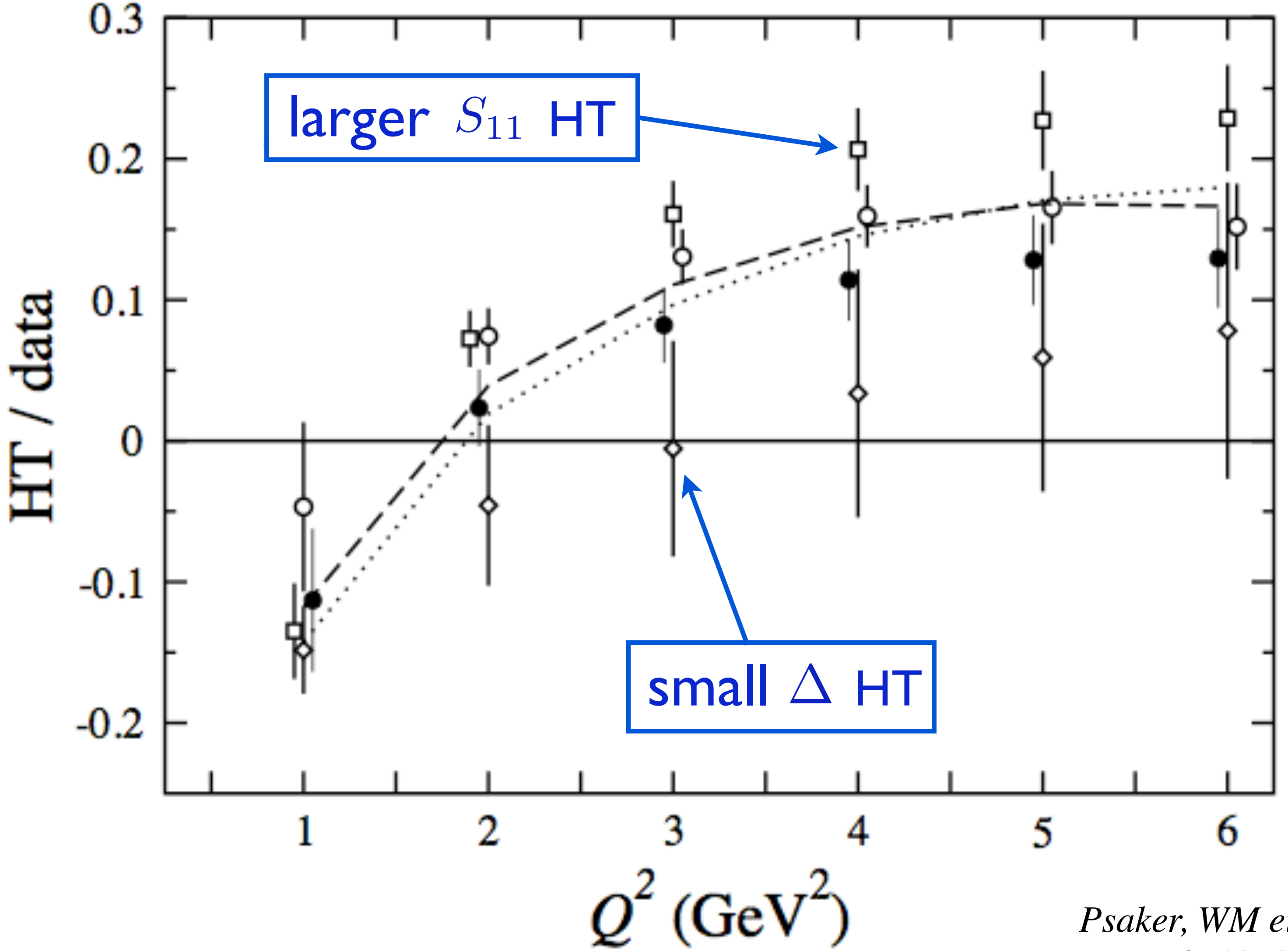
$\rightarrow$ $2.5 < W^2 < 3.1\ {\rm GeV}^2$ "$F_{15}(1680)$"

as well as total resonance region:

$\rightarrow$ $W^2 < 4\ {\rm GeV}^2$



Psaker, WM et al.
*PRC **78**, 025206 (2008)*



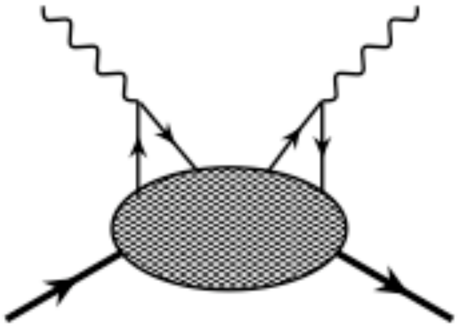
Psaker, WM et al.
*PRC **78**, 025206 (2008)*

→ higher twists $< 10\text{–}15\%$ for $Q^2 > 1$ GeV^2

Duality in the Neutron

- Is duality in the proton a coincidence?

→ consider model with symmetric nucleon wave function



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

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

↑ *coherent* ↑ *incoherent*

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

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

Brodsky, hep-ph/0006310

⇒ need to test duality in the neutron!

How can the *square of a sum* become the *sum of squares*?

→ in *hadronic* language, duality is realized by summing over at least one complete set of *even* and *odd* parity resonances

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

→ in NR Quark Model, even and odd parity states generalize to **56** (L=0) and **70** (L=1) multiplets of spin-flavor SU(6)

- assume magnetic coupling of photon to quarks (better approximation at high Q^2)
- in this limit Callan-Gross relation valid $F_2 = 2xF_1$
- structure function given by squared sum of transition FFs

$$F_1(\nu,\vec{q}^{\,2}) \sim \sum_R |F_{N\to R}(\vec{q}^{\,2})|^2 \delta(E_R - E_N - \nu)$$

How can the *square of a sum* become the *sum of squares*?

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→ in NR Quark Model, even and odd parity states generalize to **56** (L=0) and **70** (L=1) multiplets of spin-flavor SU(6)

representation	$^2\mathbf{8}[\mathbf{56}^+]$	$^4\mathbf{10}[\mathbf{56}^+]$	$^2\mathbf{8}[\mathbf{70}^-]$	$^4\mathbf{8}[\mathbf{70}^-]$	$^2\mathbf{10}[\mathbf{70}^-]$	Total
F_1^p	$9\rho^2$	$8\lambda^2$	$9\rho^2$	0	λ^2	$18\rho^2+9\lambda^2$
F_1^n	$(3\rho+\lambda)^2/4$	$8\lambda^2$	$(3\rho-\lambda)^2/4$	$4\lambda^2$	λ^2	$(9\rho^2+27\lambda^2)/2$

$\lambda\ (\rho) =$ (anti) symmetric component of ground state wfn.

Close, WM, PRC ***68****, 035210 (2003)*

- SU(6) limit $\Longrightarrow$ $\lambda = \rho$

  $\longrightarrow$ relative strengths of $N \rightarrow N^*$ transitions:

$SU(6):$	$[\mathbf{56}, \mathbf{0}^+]^\mathbf{2}\mathbf{8}$	$[\mathbf{56}, \mathbf{0}^+]^\mathbf{4}\mathbf{10}$	$[\mathbf{70}, \mathbf{1}^-]^\mathbf{2}\mathbf{8}$	$[\mathbf{70}, \mathbf{1}^-]^\mathbf{4}\mathbf{8}$	$[\mathbf{70}, \mathbf{1}^-]^\mathbf{2}\mathbf{10}$	$total$
F_1^p	9	8	9	0	1	27
F_1^n	4	8	1	4	1	18

- summing over all resonances in $\mathbf{56}^+$ and $\mathbf{70}^-$ multiplets

  $\longrightarrow$ $\dfrac{F_1^n}{F_1^p} = \dfrac{2}{3}$ as in quark-parton model (for $u=2d$) !

- proton sum saturated by lower-lying resonances

  $\longrightarrow$ expect duality to appear *earlier* for p than n

Close, WM, PRC ***68***, *035210 (2003)*

Neutron structure functions

- Problem: no free neutron targets!

  (neutron half-life ~ 12 mins)

  → use deuteron as "effective neutron target"

  → extract F_2^n from F_2^d and F_2^p data

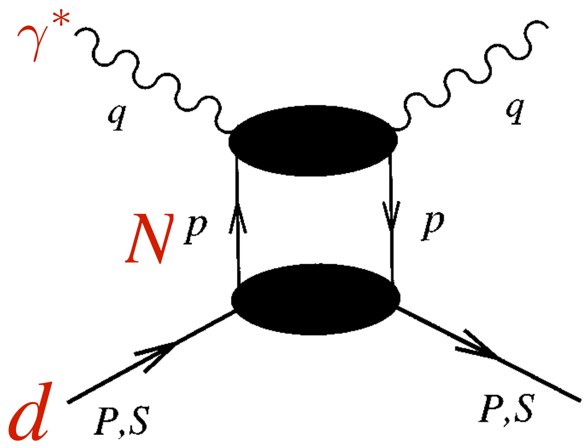
- But: deuteron is a nucleus, and $F_2^d \neq F_2^p + F_2^n$

  → nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

  → need to correct for "nuclear EMC effect"

- nuclear "impulse approximation"

→ incoherent scattering from individual nucleons in d
(good approx. at $x >> 0$)



N=p+n

$$F_2^d(x,Q^2) = \int_x dy\ f(y,\gamma)\ F_2^N(x/y,Q^2)$$

$$+\ \delta^{(\text{off})} F_2^d$$

nucleon momentum distribution in d ("smearing function")

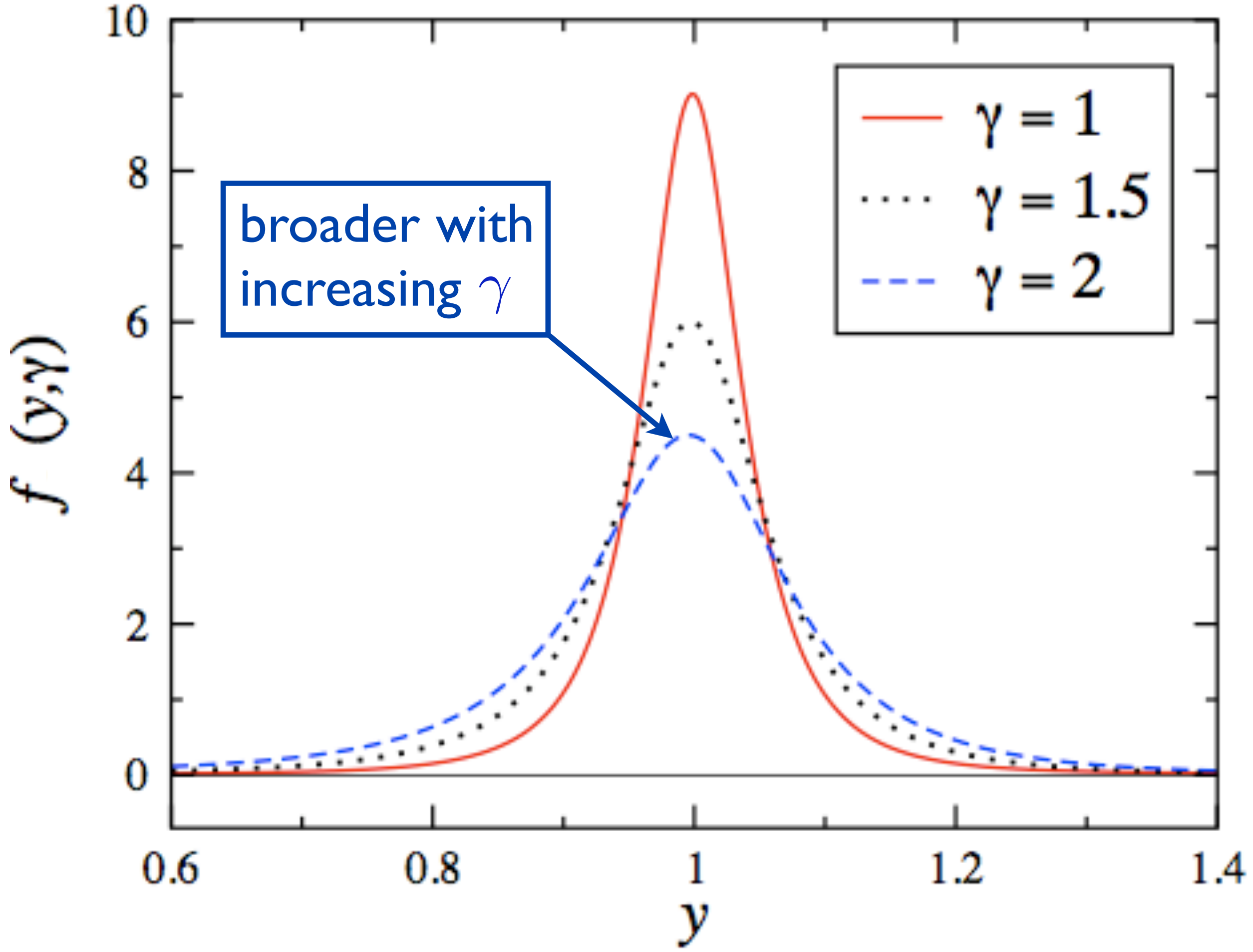
off-shell correction (~1%)

→ at finite Q^2, smearing function depends also on parameter

$$\gamma = |\mathbf{q}|/q_0 = \sqrt{1+4M^2x^2/Q^2}$$

Kulagin, WM, PRC **77***, 015210 (2008)*

N momentum distributions in d



→ for most kinematics $\gamma \lesssim 2$

Unsmearing – additive method

- calculated F_2^d depends on input F_2^n

  $\longrightarrow$ extracted n depends on input n ... cyclic argument

- solution: (additive) iteration procedure

  0. subtract $\delta^{(\mathrm{off})} F_2^d$ from d data: $F_2^d \to F_2^d - \delta^{(\mathrm{off})} F_2^d$

  1. define difference between smeared and free SFs

$$F_2^d - \widetilde{F}_2^p = \widetilde{F}_2^n \equiv f \otimes F_2^n \equiv F_2^n + \Delta$$

  2. first guess for $F_2^{n(0)}$ $\longrightarrow$ $\Delta^{(0)} = \widetilde{F}_2^{n(0)} - F_2^n$

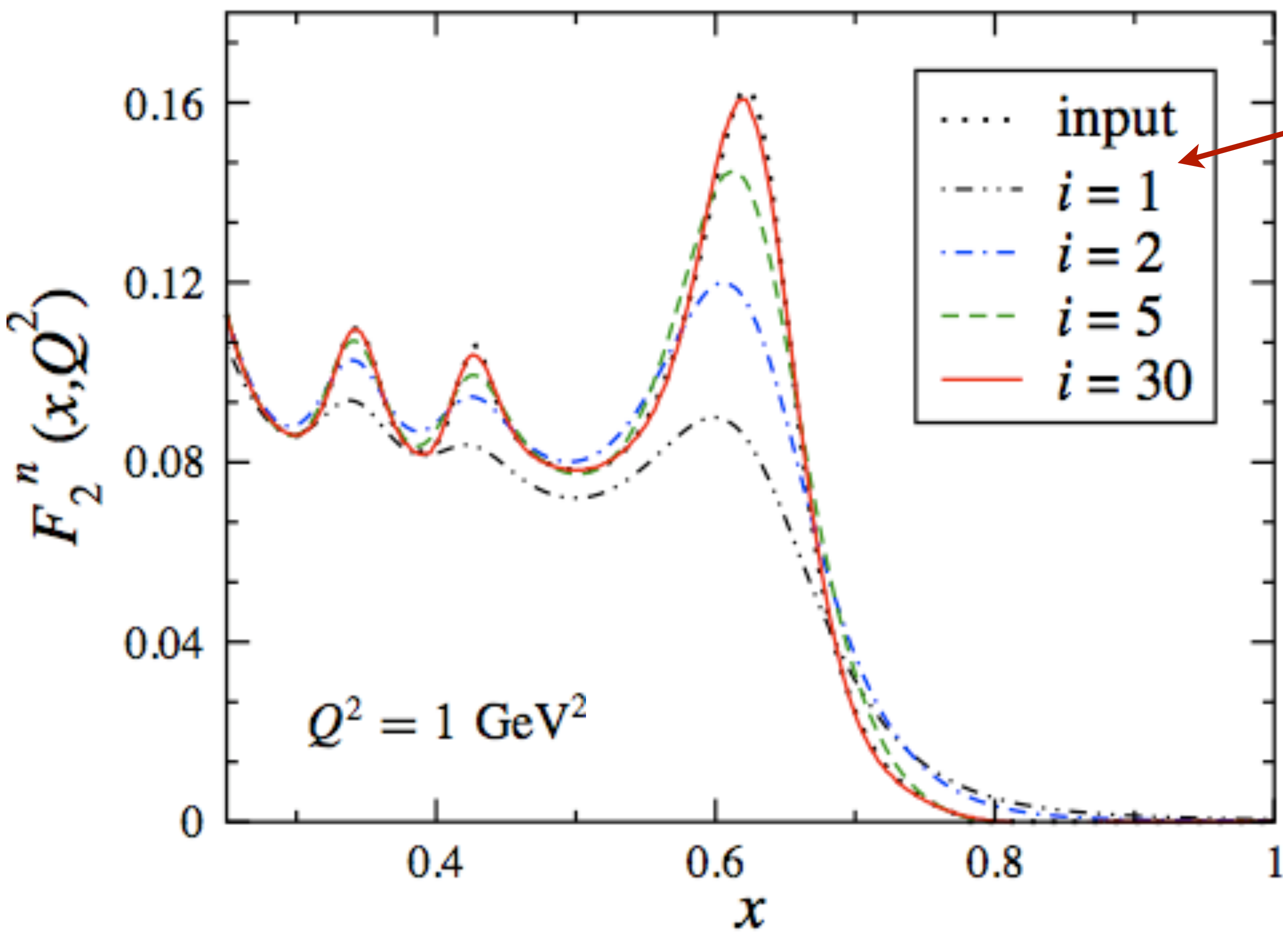
  3. after one iteration, gives

$$F_2^{n(1)} = F_2^{n(0)} + (\widetilde{F}_2^n - \widetilde{F}_2^{n(0)})$$

  4. repeat until convergence

Unsmearing – test of convergence

- F_2^d constructed from known F_2^p and F_2^n inputs
  (using MAID resonance parameterization)



initial guess
$F_2^{n(0)} = 0$

Kahn, WM, Kulagin
*PRC **79**, 035205 (2008)*

⟶ can reconstruct almost arbitrary shape

Unsmearing – test of convergence

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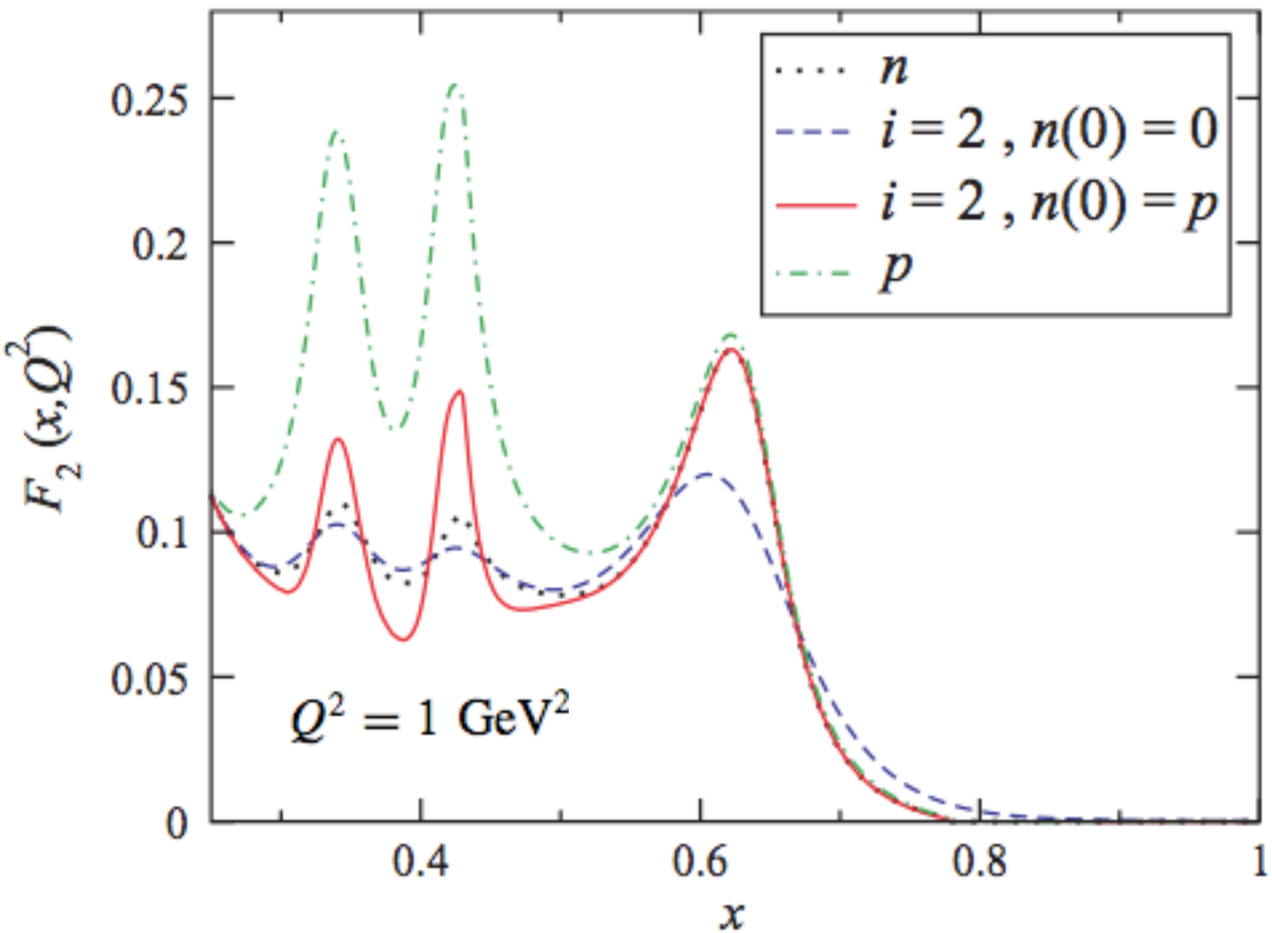
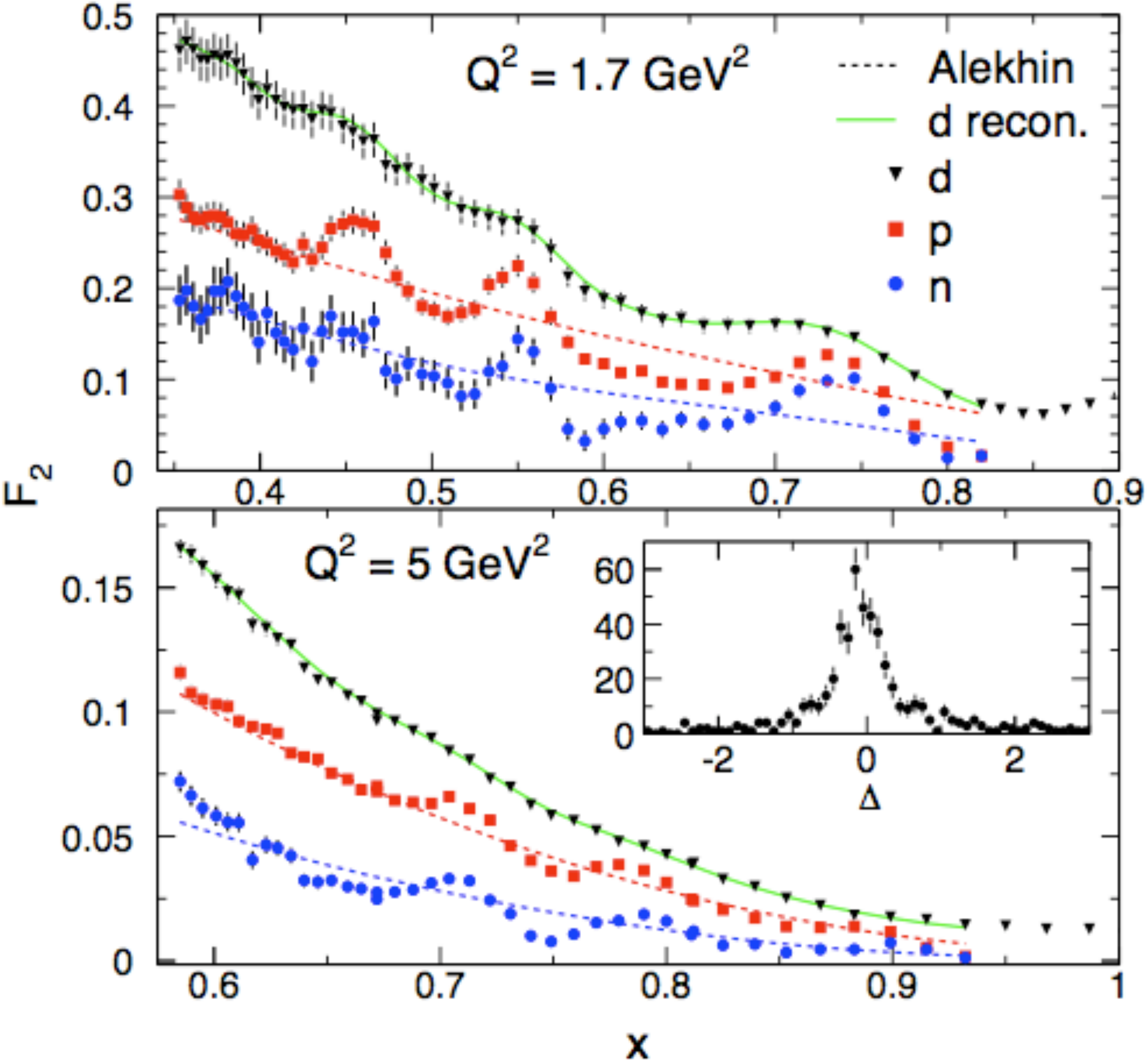


Kahn, WM, Kulagin
*PRC **79**, 035205 (2008)*

→ fast convergence with $n(0)=p$ initial condition

Extracted neutron data

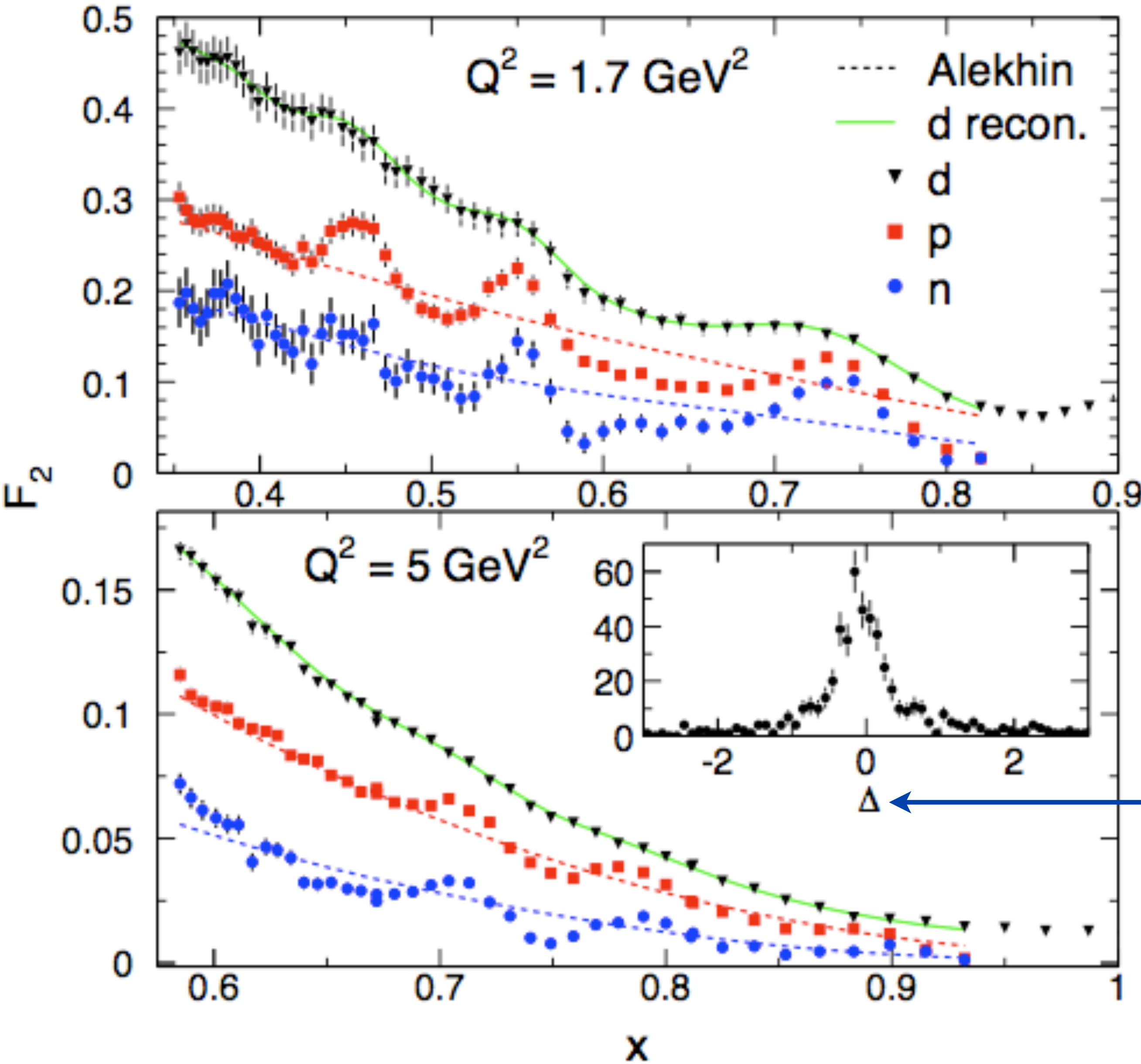


→ JLab & SLAC data

→ 2 iterations with $n(0)=p$

Malace, Kahn, WM, Keppel
arXiv:0910.4920 [hep-ph]

Extracted neutron data



→ JLab & SLAC data

→ 2 iterations with $n(0)=p$

- good agreement with reconstructed d
- weak dependence on input neutron

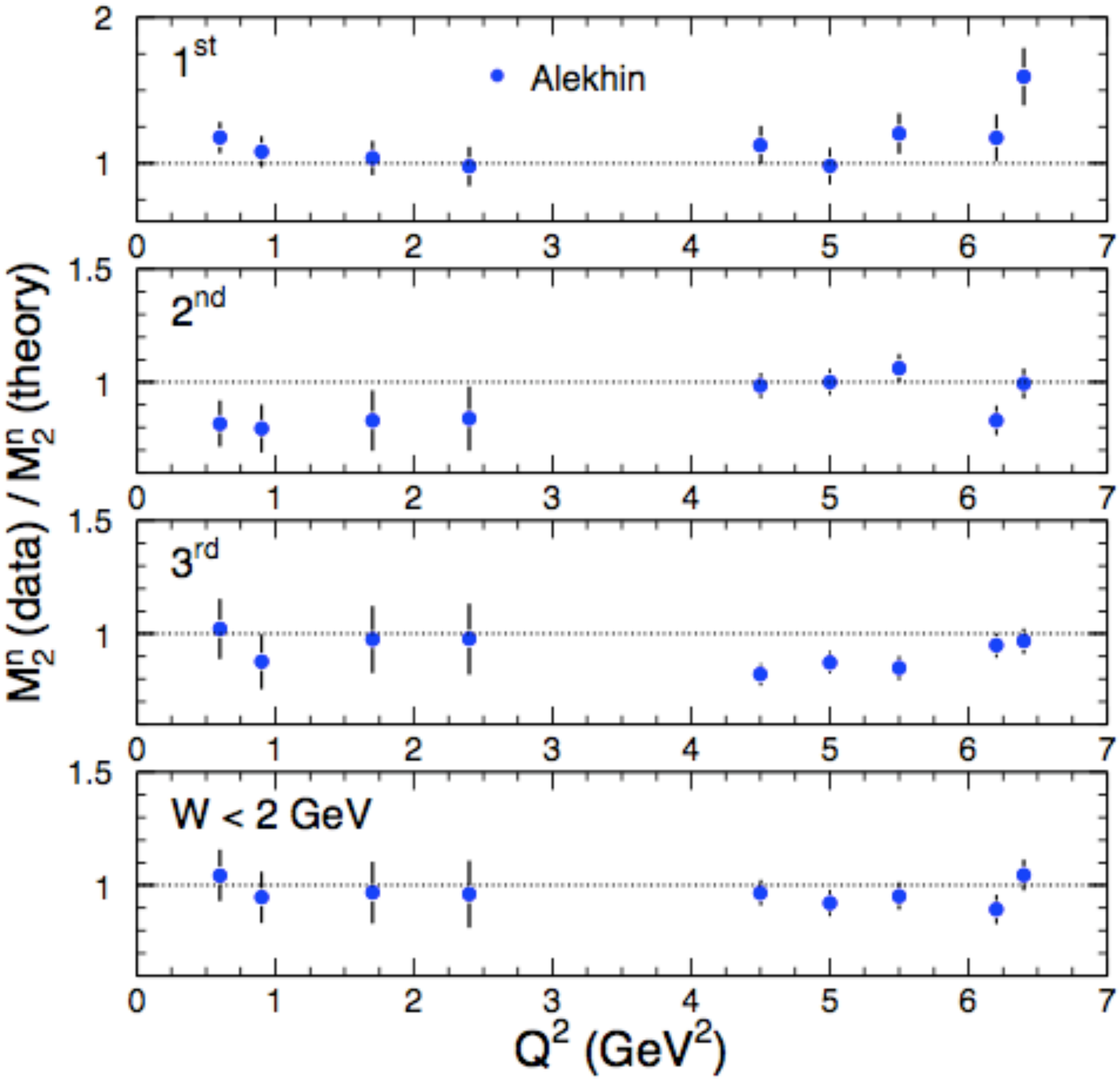
$$\left[F_2^n(n(0)=p) - F_2^n(n(0)=p/2)\right]/\sigma(F_2)$$

- clear neutron resonance structure observed

Malace, Kahn, WM, Keppel
arXiv:0910.4920 [hep-ph]

- striking similarity with QCD fit to DIS data!

Truncated moment ratio



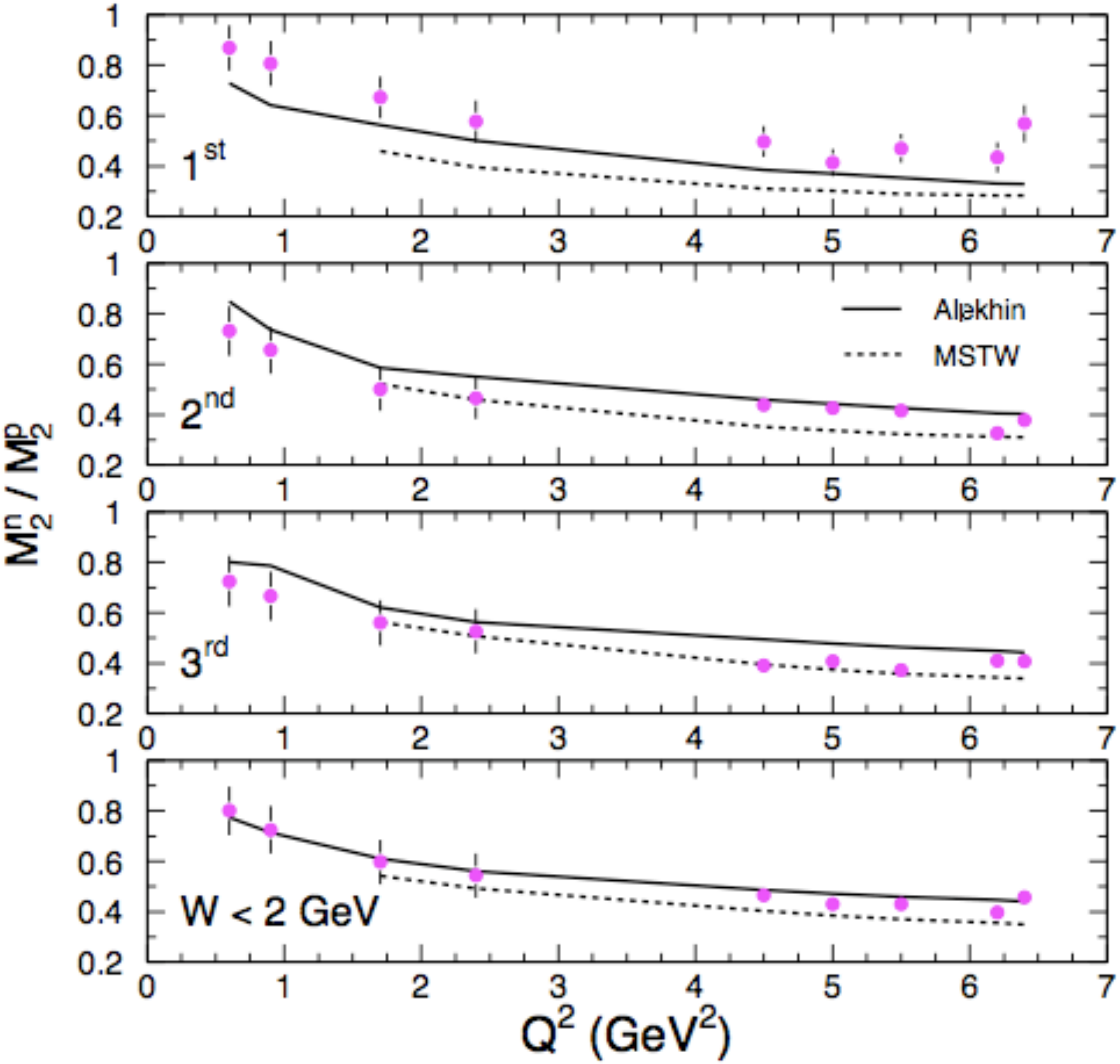
Malace, Kahn, WM, Keppel
arXiv:0910.4920 [hep-ph]

→ "theory" is QCD fit to $W > 2$ GeV data

Alekhin et al., 0908.2762 [hep-ph]

- *globally*, deviations from unity generally $< 10\%$
- *locally*, deviations in individual resonance regions < 15–20%
- largest deviations in Δ resonance region
  (fits least constrained at high x)

Isospin dependence



→ MSTW fit to $W > 4$ GeV data

Martin et al., 0905.3531 [hep-ph]

- good agreement overall
- maximal duality violation in Δ region
  - → I=1 res. transition: $p=n$
  - → DIS: $p \gg n$
  - → QCD fit underestimates resonance data

Malace, Kahn, WM, Keppel
arXiv:0910.4920 [hep-ph]

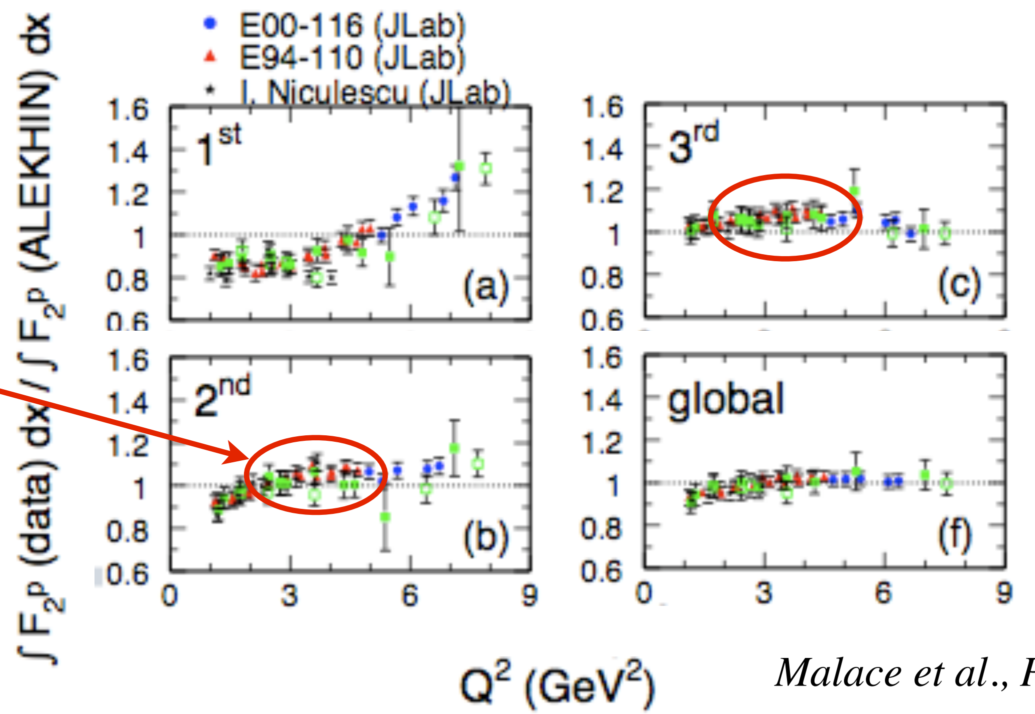
Quark model comparison

- Quark model predicts systematic deviations of resonance data from local duality

$SU(6):$	$[\mathbf{56},0^+]^2\mathbf{8}$	$[\mathbf{56},0^+]^4\mathbf{10}$	$[\mathbf{70},1^-]^2\mathbf{8}$	$[\mathbf{70},1^-]^4\mathbf{8}$	$[\mathbf{70},1^-]^2\mathbf{10}$	*total*
F_1^p	9	8	9	0	1	27
F_1^n	4	8	1	4	1	18

- Proton data expected to *overestimate* DIS function in 2nd and 3rd resonance regions (odd parity states)

data exceeds DIS function



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

Quark model comparison

- Quark model predicts systematic deviations of resonance data from local duality

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F_1^p	9	8	9	0	1	27
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- Proton data expected to *overestimate* DIS function in 2nd and 3rd resonance regions (odd parity states)

- Neutron data predicted to lie *below* DIS function in 2nd region

⟹ Patterns borne out by data!

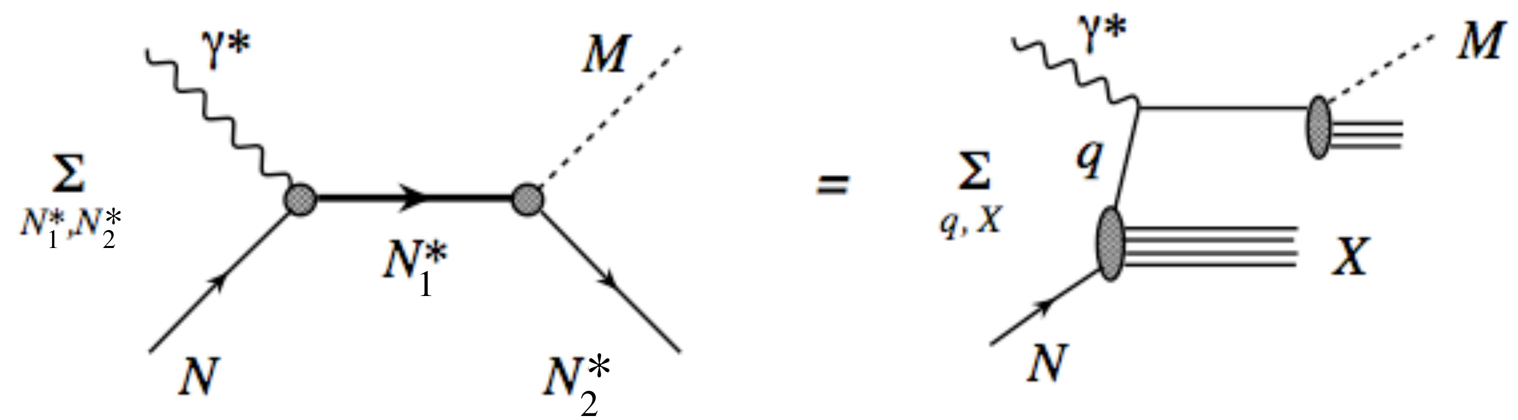
⟹ Suggests duality is *not accidental*, but a general feature of resonance−scaling transition

Duality in Semi-Inclusive Meson Production

- Duality expected to work better for inclusive observables (*e.g.* structure functions)

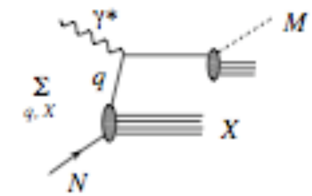
  → what about for *semi-inclusive* scattering?

- <u>Hypothesis</u>: equivalent descriptions afforded by scattering from partons or via N^* excitations



→ test whether hypothesis is consistent with *models* and *data*

Partonic description

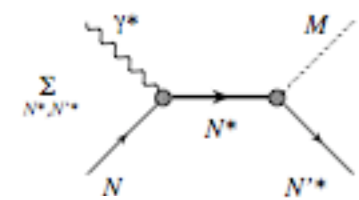


$$\mathcal{N}_N^\pi(x,z) \;=\; e_u^2\, u^N(x)\, D_u^\pi(z) \;+\; e_d^2\, d^N(x)\, D_d^\pi(z)$$

$q \rightarrow \pi$ fragmentation function

$z = E_\pi/\nu$ fractional energy carried by pion

Hadronic description

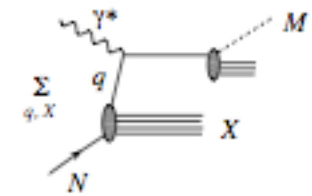


$$\mathcal{N}_N^\pi(x,z) = \sum_{N_2^*} \left| \sum_{N_1^*} F_{\gamma N \to N_1^*}(Q^2, M_1^*)\, \mathcal{D}_{N_1^* \to N_2^* \pi}(M_1^*, M_2^*) \right|^2$$

transition form factor

decay function

Partonic description

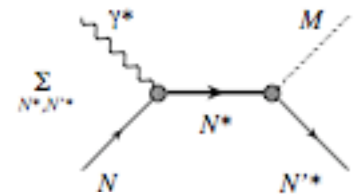


$$\mathcal{N}_N^{\pi}(x,z) \;=\; e_u^2\, u^N(x)\, D_u^{\pi}(z) \;+\; e_d^2\, d^N(x)\, D_d^{\pi}(z)$$

→ ratios given by quark charges

$$\frac{\mathcal{N}_n^{\pi^+}}{\mathcal{N}_p^{\pi^-}} \;=\; \frac{\mathcal{N}_p^{\pi^+}}{\mathcal{N}_n^{\pi^-}} \;=\; \frac{e_u^2}{e_d^2} \;=\; 4$$

Hadronic description

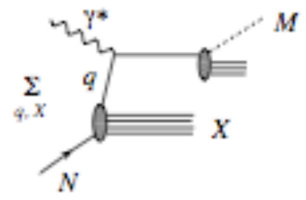


$$\mathcal{N}_N^{\pi}(x,z) \;=\; \sum_{N_2^*} \left| \sum_{N_1^*} F_{\gamma N \to N_1^*}(Q^2, M_1^*)\; \mathcal{D}_{N_1^* \to N_2^* \pi}(M_1^*, M_2^*) \right|^2$$

transition form factor

decay function

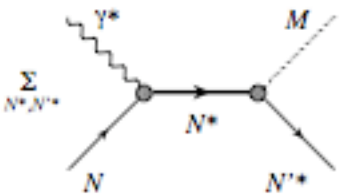
Partonic description



$$\mathcal{N}_N^{\pi}(x,z) \;=\; e_u^2\, u^N(x)\, D_u^{\pi}(z) \;+\; e_d^2\, d^N(x)\, D_d^{\pi}(z)$$

→ ratios given by quark charges

$$\frac{\mathcal{N}_n^{\pi^+}}{\mathcal{N}_p^{\pi^-}} = \frac{\mathcal{N}_p^{\pi^+}}{\mathcal{N}_n^{\pi^-}} = \frac{e_u^2}{e_d^2} = 4$$



Hadronic description

→ magnetic interaction operator for $\gamma N \to N_1^*$

$$\sum_i e_i\, \sigma_i^+$$

→ pion emission operator for $N_1^* \to N_2^*\, \pi^{\pm}$

$$\sum_i \tau_i^{\mp}\, \sigma_{zi}$$

- Relative probabilities $\mathcal{N}_N^\pi$ in SU(6) symmetric quark model (summed over N_1^*)

	N_2^*					
	$^2\mathbf{8}, \mathbf{56}^+$	$^4\mathbf{10}, \mathbf{56}^+$	$^2\mathbf{8}, \mathbf{70}^-$	$^4\mathbf{8}, \mathbf{70}^-$	$^2\mathbf{10}, \mathbf{70}^-$	sum
$\gamma p \to \pi^+ N_2^*$	100 (100)	32 (–16)	64 (64)	16 (–8)	4 (4)	216 (144)
$\gamma p \to \pi^- N_2^*$	0 (0)	24 (–12)	0 (0)	0 (0)	3 (3)	27 (–9)
$\gamma n \to \pi^+ N_2^*$	0 (0)	96 (–48)	0 (0)	0 (0)	12 (12)	108 (–36)
$\gamma n \to \pi^- N_2^*$	25 (25)	8 (–4)	16 (16)	4 (–2)	1 (1)	54 (36)

spin-averaged

spin-dependent

- π^-/π^+ ratios for p and n targets (summing over N_2^*)

$$\frac{\mathcal{N}_p^{\pi^-}}{\mathcal{N}_p^{\pi^+}} = \frac{1}{8}, \qquad \frac{\mathcal{N}_n^{\pi^-}}{\mathcal{N}_n^{\pi^+}} = \frac{1}{2}$$

$$\frac{\mathcal{N}_n^{\pi^+}}{\mathcal{N}_p^{\pi^+}} = \frac{\mathcal{N}_p^{\pi^-}}{\mathcal{N}_n^{\pi^-}} = \frac{1}{2}, \qquad \frac{\mathcal{N}_n^{\pi^+}}{\mathcal{N}_p^{\pi^-}} = \frac{\mathcal{N}_p^{\pi^+}}{\mathcal{N}_n^{\pi^-}} = 4$$

- Consistent with parton model in SU(6) limit, $d/u = 1/2$

- For *spin-dependent* ratios (e & N longitudinally polarized)

$$\frac{\Delta\mathcal{N}_p^{\pi^-}}{\Delta\mathcal{N}_p^{\pi^+}} = -\frac{1}{16}\,, \qquad \frac{\Delta\mathcal{N}_n^{\pi^-}}{\Delta\mathcal{N}_n^{\pi^+}} = -1$$

$$\frac{\Delta\mathcal{N}_p^{\pi^+}}{\mathcal{N}_p^{\pi^+}} = \frac{2}{3}\,, \qquad \frac{\Delta\mathcal{N}_p^{\pi^-}}{\mathcal{N}_p^{\pi^-}} = -\frac{1}{3}$$

$$\frac{\Delta\mathcal{N}_n^{\pi^+}}{\mathcal{N}_n^{\pi^+}} = -\frac{1}{3}\,, \qquad \frac{\Delta\mathcal{N}_n^{\pi^-}}{\mathcal{N}_n^{\pi^-}} = \frac{2}{3}$$

- Consistent with parton model ratios

$$\Delta u/u = 2/3\,,\ \ \Delta d/d = -1/3\,,\ \ \Delta d/\Delta u = -1/4$$

- Inclusive results recovered by summing over π^+ & π^-

$$\frac{\mathcal{N}_n^{\pi^++\pi^-}}{\mathcal{N}_p^{\pi^++\pi^-}} = \frac{F_1^n}{F_1^p} = \boxed{\frac{2}{3}}$$

$$\frac{\Delta\mathcal{N}_p^{\pi^++\pi^-}}{\mathcal{N}_p^{\pi^++\pi^-}} = \frac{g_1^p}{F_1^p} = \boxed{\frac{5}{9}}, \qquad \frac{\Delta\mathcal{N}_n^{\pi^++\pi^-}}{\mathcal{N}_n^{\pi^++\pi^-}} = \frac{g_1^n}{F_1^n} = \boxed{0}$$

- SU(6) symmetry may be valid at $x \sim 1/3$, but is (badly) broken at large x

- Color-magnetic interaction

→ suppression of transitions to states with S=3/2

$$\frac{\mathcal{N}_p^{\pi^-}}{\mathcal{N}_p^{\pi^+}} = \frac{1}{56}\,, \qquad \frac{\mathcal{N}_n^{\pi^-}}{\mathcal{N}_n^{\pi^+}} = \frac{7}{2}$$

→ consistent with d/u=1/14 at parton level

- Scalar diquark dominance

→ suppression of symmetric (λ) component of wfn.

$$\frac{\mathcal{N}_p^{\pi^-}}{\mathcal{N}_p^{\pi^+}} = 0\,, \qquad \frac{\mathcal{N}_n^{\pi^+}}{\mathcal{N}_n^{\pi^-}} = 0\,, \qquad \frac{\mathcal{N}_n^{\pi^-}}{\mathcal{N}_p^{\pi^+}} = \frac{1}{4}$$

→ consistent with d/u=0 at parton level

- SU(6) symmetry may be valid at $x \sim 1/3$, but is (badly) broken at large x

- Helicity conservation

→ suppression of helicity-$3/2$ amplitude

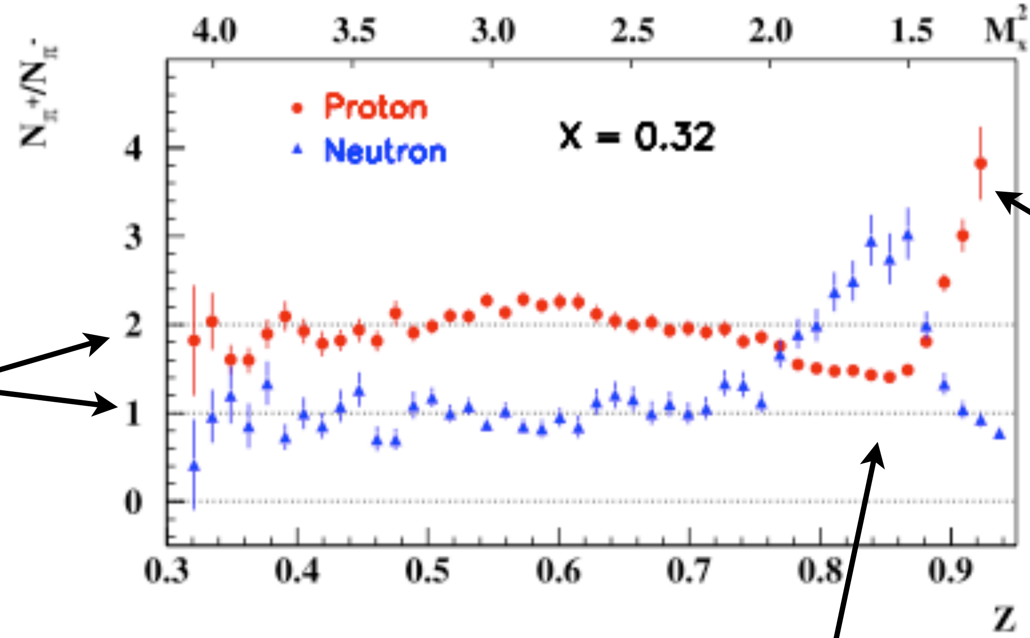
$$\frac{\mathcal{N}_p^{\pi^-}}{\mathcal{N}_p^{\pi^+}} = \frac{1}{20}, \qquad \frac{\mathcal{N}_n^{\pi^-}}{\mathcal{N}_n^{\pi^+}} = \frac{5}{4}, \quad \frac{\mathcal{N}_n^{\pi^+}}{\mathcal{N}_p^{\pi^+}} = \frac{\mathcal{N}_p^{\pi^-}}{\mathcal{N}_n^{\pi^-}} = \frac{1}{5}$$

→ consistent with $d/u = 1/5$ at parton level

⇒ All three scenarios consistent with duality!

Comparison with data (JLab Hall C)

expect p ratio $\gg n$ ratio



N elastic

p ratio $\gg n$ ratio

Δ region

n ratio $\gg p$ ratio

	N_2^*					
	^{2}**8, 56**$^+$	^{4}**10, 56**$^+$	^{2}**8, 70**$^-$	^{4}**8, 70**$^-$	^{2}**10, 70**$^-$	sum
$\gamma p \to \pi^+ N_2^*$	100 (100)	32 (−16)	64 (64)	16 (−8)	4 (4)	216 (144)
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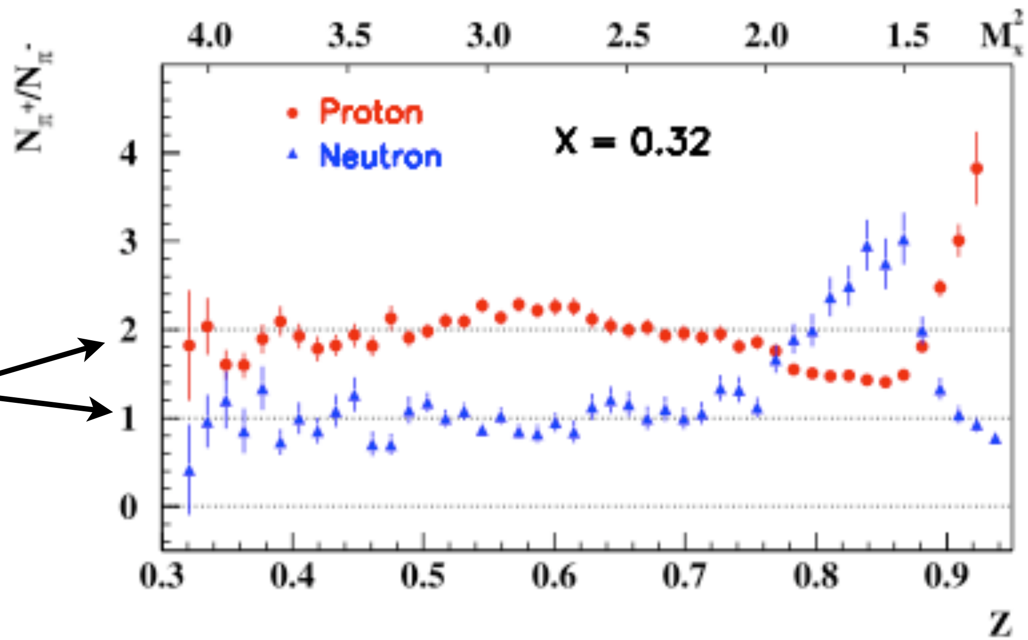
$\gamma n \to \pi^- N_2^*$	25 (25)	8 (−4)	16 (16)	4 (−2)	1 (1)	54 (36)

Comparison with data (JLab Hall C)

smaller than SU(6) predictions
(secondary fragmentation)



More quantitative comparison requires secondary fragmentation

$$\frac{\mathcal{N}_d^{\pi^+}}{\mathcal{N}_d^{\pi^-}} = \frac{4+R}{4R+1}$$

$$R \equiv \overline{D}/D$$

$$D_d^{\pi^+} = D_u^{\pi^-}$$
"unfavored"

$$D_u^{\pi^+} = D_d^{\pi^-}$$
"favored"
$z \to 1$

Summary

- Remarkable confirmation of quark-hadron duality in *proton* structure functions

  → duality violating higher twists ~ 10% in few-GeV range

- Truncated moments

  → firm foundation for study of *local* duality in QCD

- Extraction of *neutron* structure function

  → confirmation of local duality at 15-20% level

  → evidence that duality is *not* due to accidental cancellations

- Duality predicted in semi-inclusive pion production

  → quantitative comparison with data requires modeling secondary fragmentation

The End