BONUS Collaboration Meeting
Jefferson Lab, June 25, 2009

Nuclear Corrections to Neutron Structure Functions

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Outline

- Why is neutron structure at large x important?
  - → d/u ratio
  - → isospin dependence of duality (& higher twists)

- Nuclear corrections at finite Q^2
  - → generalized nuclear smearing formula

- New method for extracting neutron from *inclusive* data
  - → applicable in DIS and *resonance* regions
  - → future comparison with BONUS data

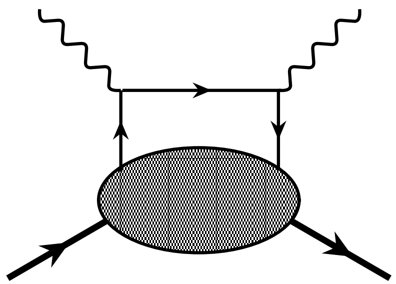
d/u ratio as $x \to 1$

- Ratio of d to u quark distributions particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavor symmetry

proton wave function

$$p^{\uparrow} = -\frac{1}{3}d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3}d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6}u^{\uparrow}(ud)_1 - \frac{1}{3}u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}}u^{\uparrow}(ud)_0$$



interacting quark

spectator diquark

diquark spin

- Ratio of d to u quark distributions particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavor symmetry

proton wave function

$$
\begin{aligned}
p^{\uparrow} \; &= -\frac{1}{3} d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3} d^{\downarrow}(uu)_1 \\
&+ \frac{\sqrt{2}}{6} u^{\uparrow}(ud)_1 \; - \; \frac{1}{3} u^{\downarrow}(ud)_1 \; + \; \frac{1}{\sqrt{2}} u^{\uparrow}(ud)_0
\end{aligned}
$$

$\longrightarrow$ $u(x) = 2\ d(x)$ for all x

$\longrightarrow$ $\dfrac{F_2^n}{F_2^p} = \dfrac{2}{3}$

scalar diquark dominance

$M_\Delta > M_N \quad \Longrightarrow \quad (qq)_1$ has larger energy than $(qq)_0$

$\Longrightarrow$ scalar diquark dominant in $x \to 1$ limit

since only u quarks couple to scalar diquarks

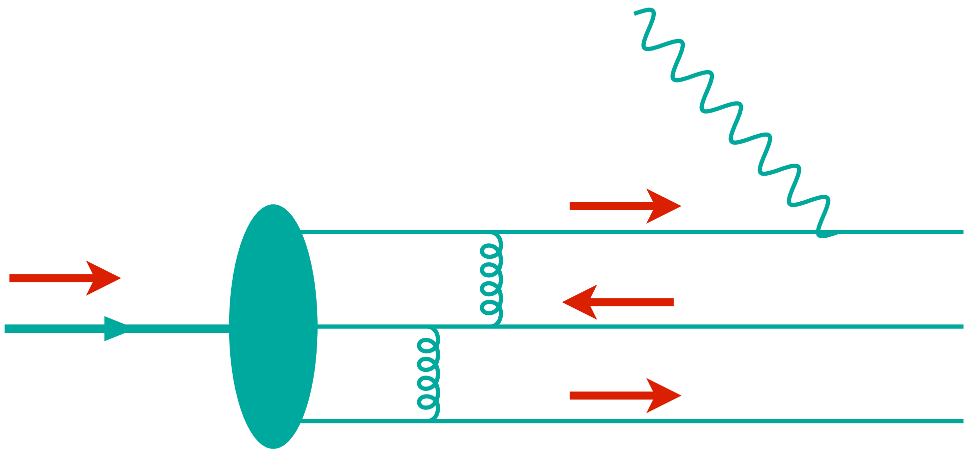
$$\longrightarrow \quad \frac{d}{u} \to 0$$

$$\longrightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$

Feynman 1972, Close 1973, Close/Thomas 1988

hard gluon exchange

at large x, helicity of struck quark = helicity of hadron



$$q^{\uparrow} \gg q^{\downarrow}$$

$\Longrightarrow$ helicity-zero diquark dominant in $x \to 1$ limit

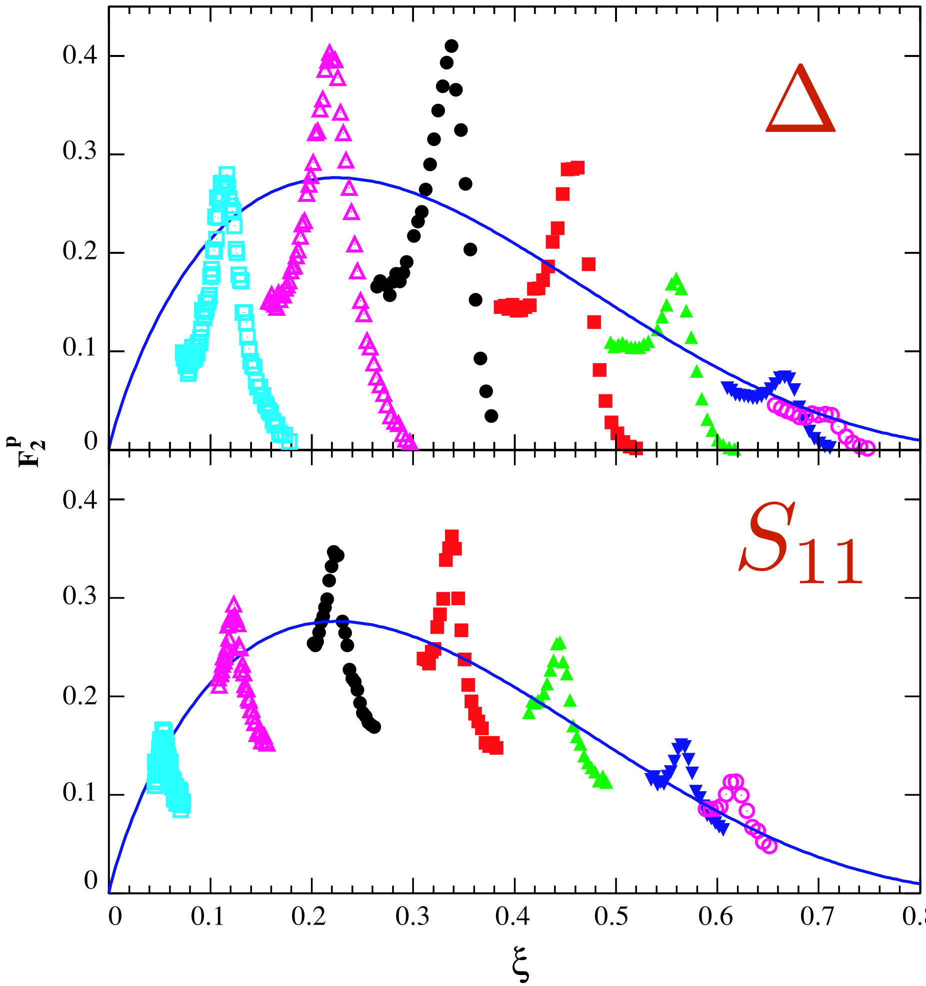
$\longrightarrow \quad \dfrac{d}{u} \to \dfrac{1}{5}$

$\longrightarrow \quad \dfrac{F_2^n}{F_2^p} \to \dfrac{3}{7}$

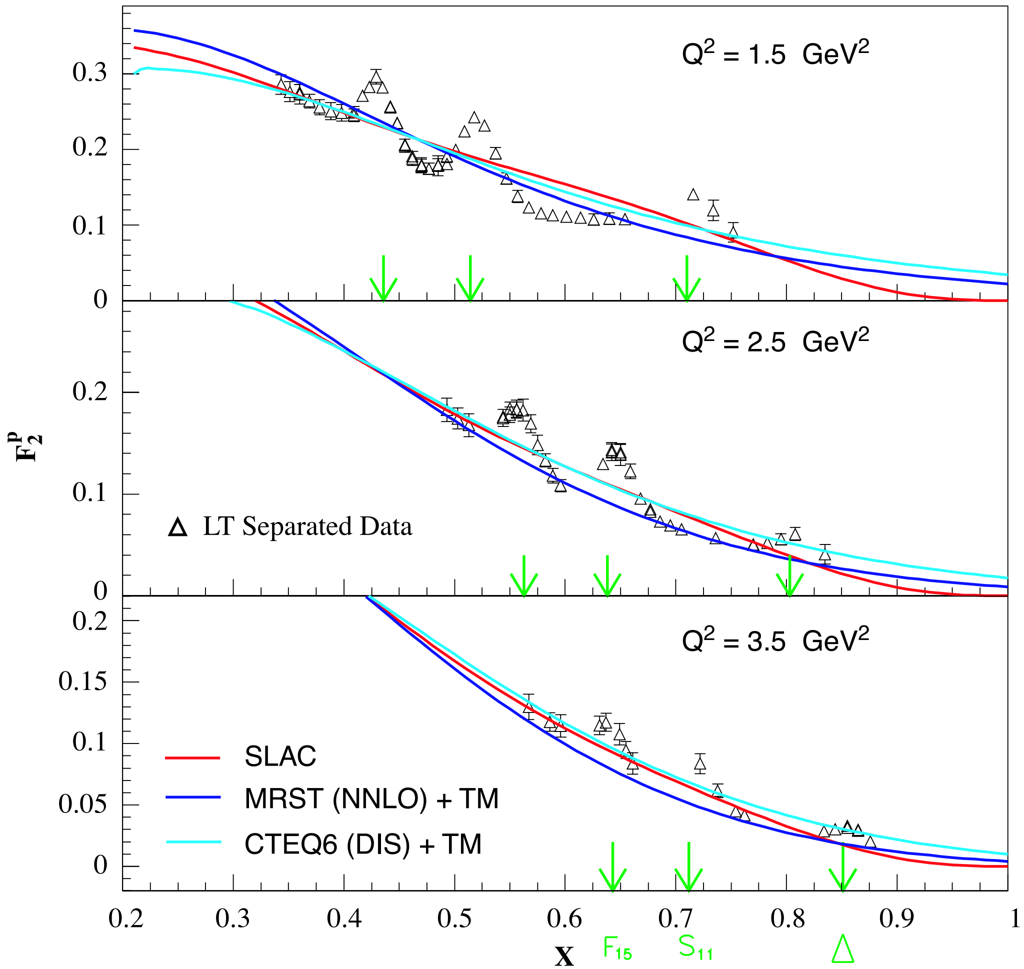
Farrar, Jackson 1975

Duality in the Neutron?

Bloom-Gilman duality well established for the *proton*

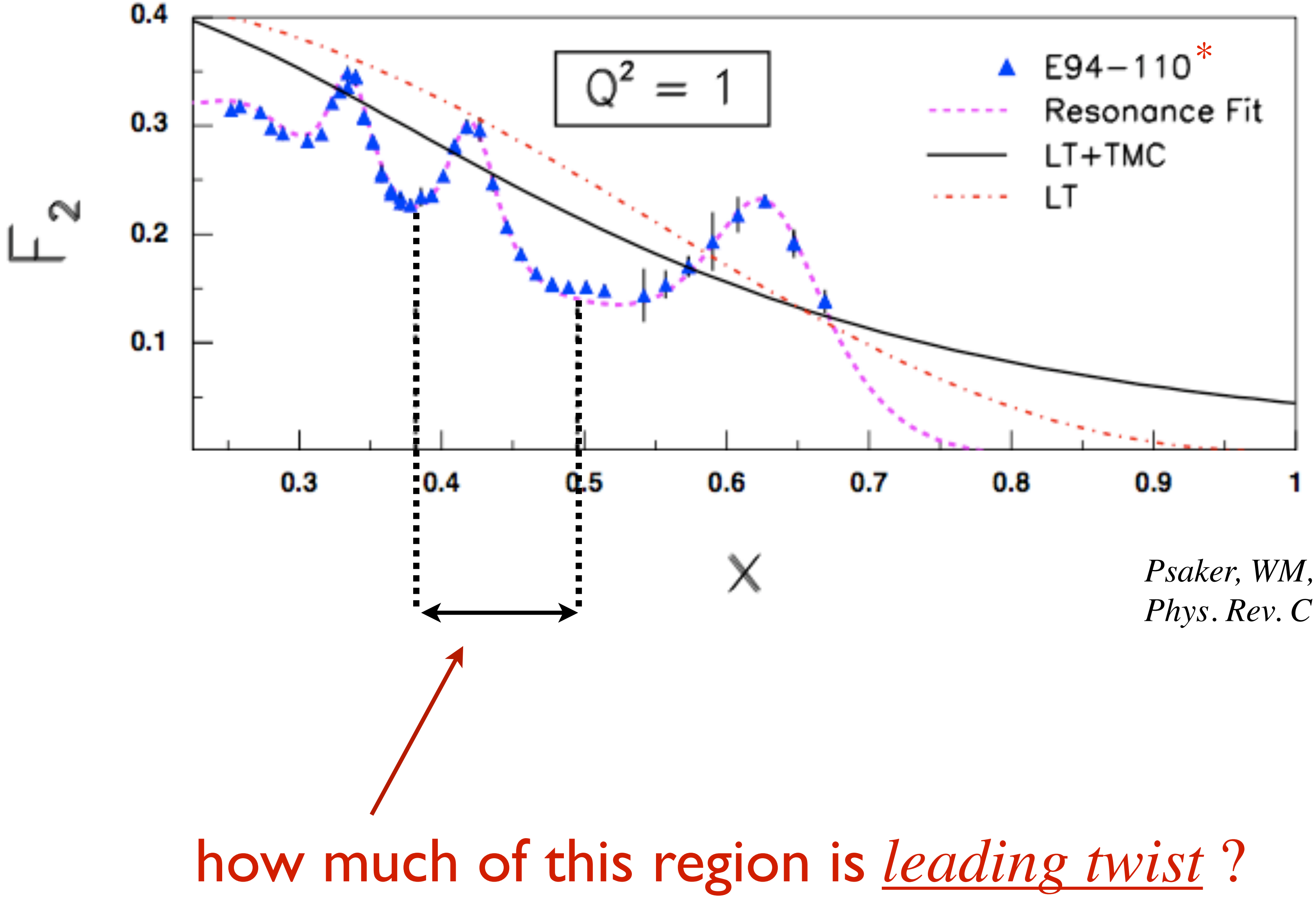


*Niculescu et al., PRL **85** (2000) 1182, 1185*



Christy et al. (2005)

F_2^p resonance spectrum



* JLab Hall C

Psaker, WM, Christy, Keppel, Phys. Rev. C ***78*** *(2008) 025206*

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

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

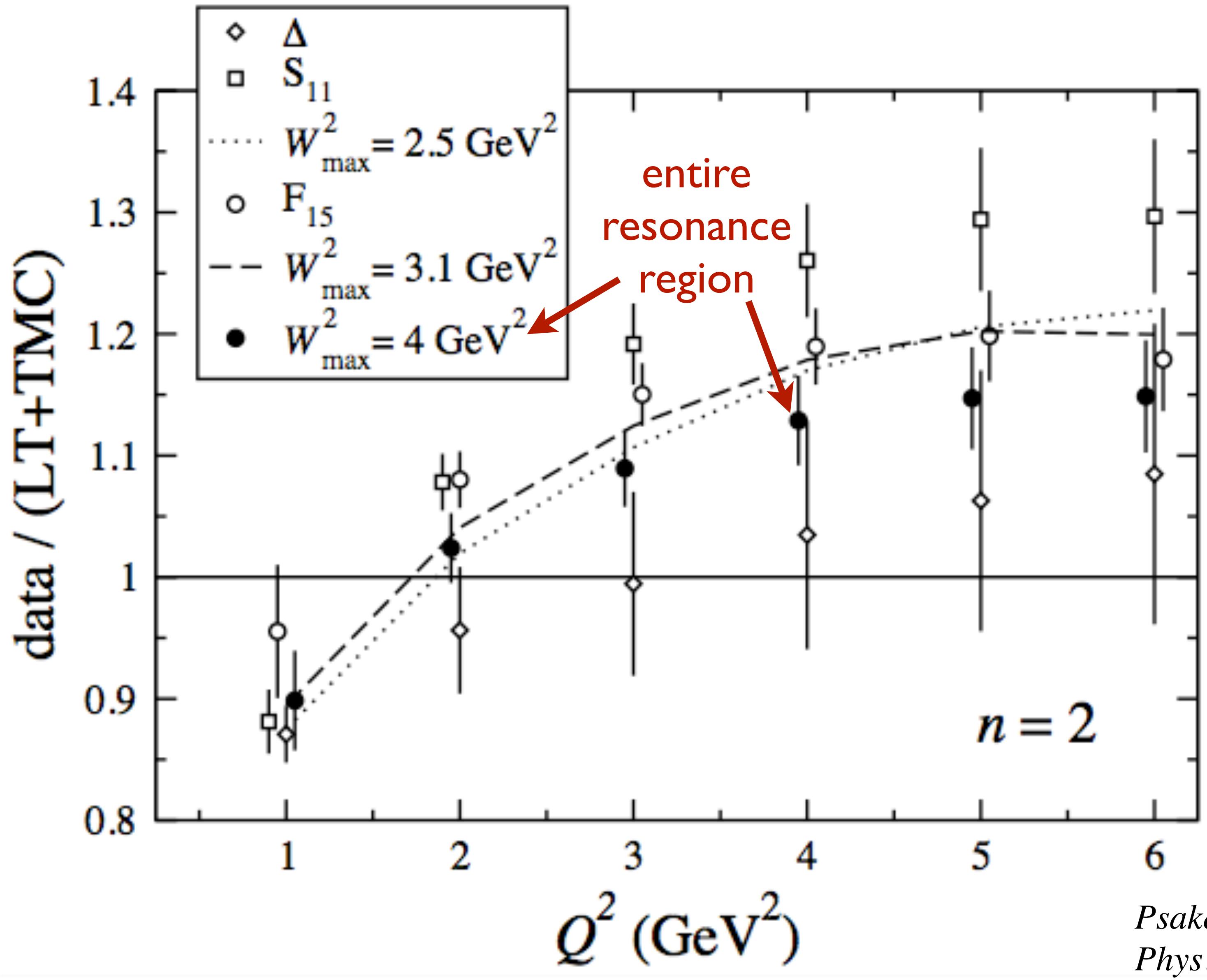
- obey DGLAP-like evolution equations, similar to PDFs

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

where modified splitting function is

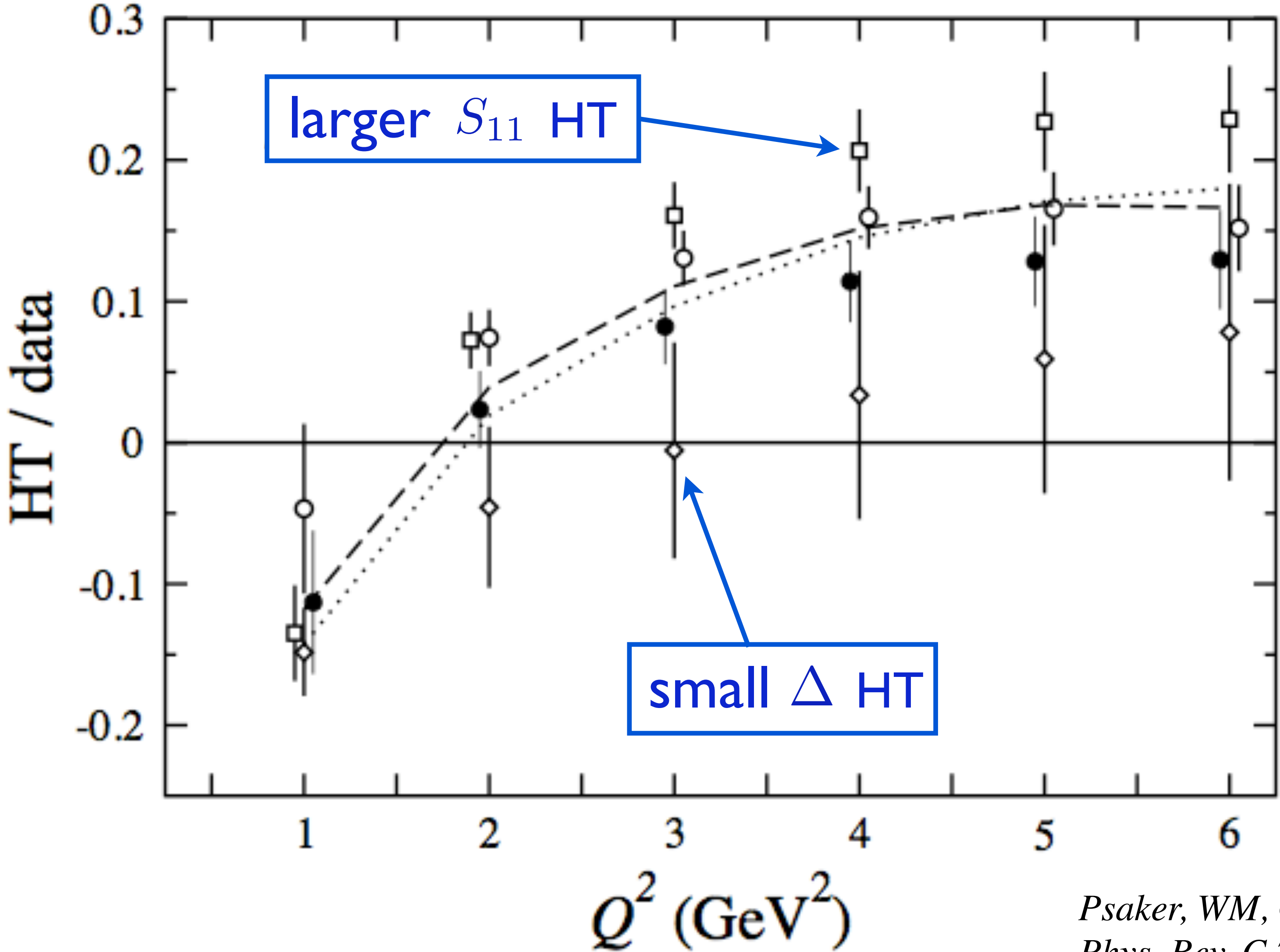
$$P'_{(n)}(z, \alpha_s) = z^n \; P_{NS,S}(z, \alpha_s)$$

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



*Psaker, WM, Christy, Keppel, Phys. Rev. C **78** (2008) 025206*

- analysis in terms of "truncated moments"



Psaker, WM, Christy, Keppel, Phys. Rev. C ***78*** *(2008) 025206*

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

- Minimum condition for duality

$\longrightarrow$ at least one complete set of *even* and *odd* parity resonances must be summed over

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

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

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

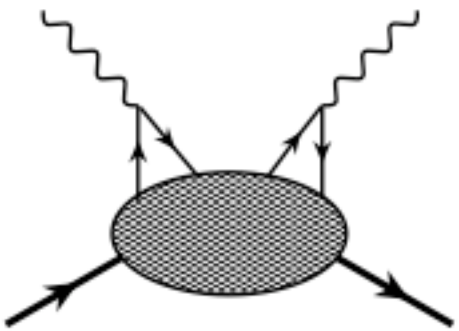
- Proton sum saturated by lower-lying resonances

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

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

Is duality in the proton a coincidence?

→ consider symmetric nucleon wave function



cat's ears diagram (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 ($\left(\sum_i e_i\right)^2$) — incoherent ($\sum_i e_i^2$)

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

⇒ need to test duality in the neutron!

- No **FREE** neutron targets

  (neutron half-life ~ 12 mins)

  → use deuteron as "effective" neutron target

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

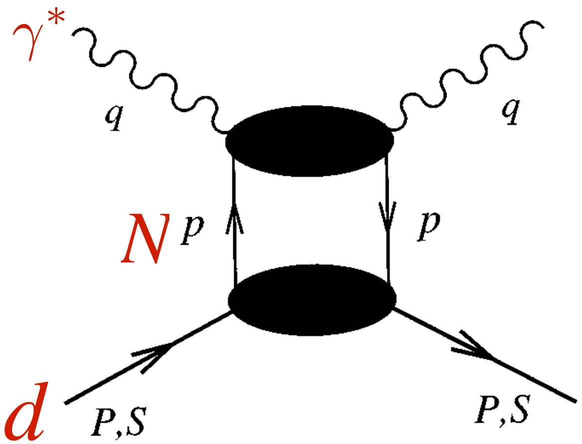
  → nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

  → need to correct for "nuclear EMC effect"

Nuclear Effects in the Deuteron

- nuclear "impulse approximation"

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



$N = p + n$

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

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

nucleon momentum distribution in d ("smearing function")

off-shell correction ($\sim 1\%$)

→ 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*** *(2008) 015210*

N momentum distributions in d

- weak binding approximation (WBA):
  expand amplitudes to order $\vec{p}^2/M^2$

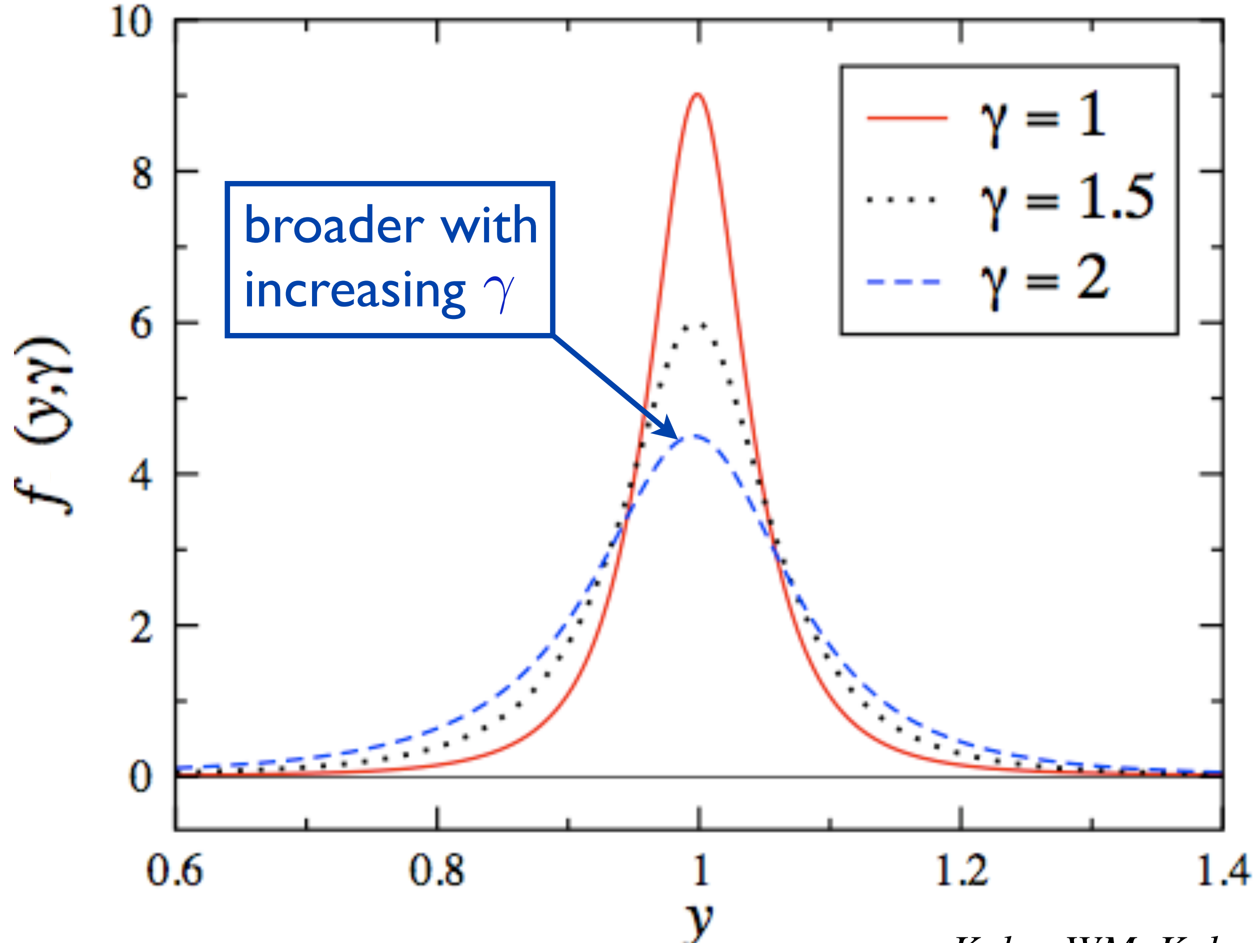
$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\, |\psi_d(p)|^2\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right) \times \frac{1}{\gamma^2}\left[1 + \frac{\gamma^2 - 1}{y^2}\left(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^2}{2M^2}(1 - 3\hat{p}_z^2)\right)\right]$$

→ deuteron wave function $\psi_d(p)$

→ deuteron separation energy $\varepsilon = \varepsilon_d - \dfrac{\vec{p}^2}{2M}$

→ approaches usual nonrelativistic momentum distribution in $\gamma \to 1$ limit

N momentum distributions in d



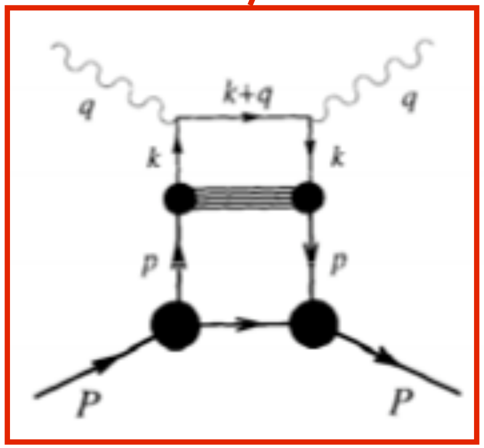
*Kahn, WM, Kulagin, PRC **79**, 035205 (2009)*

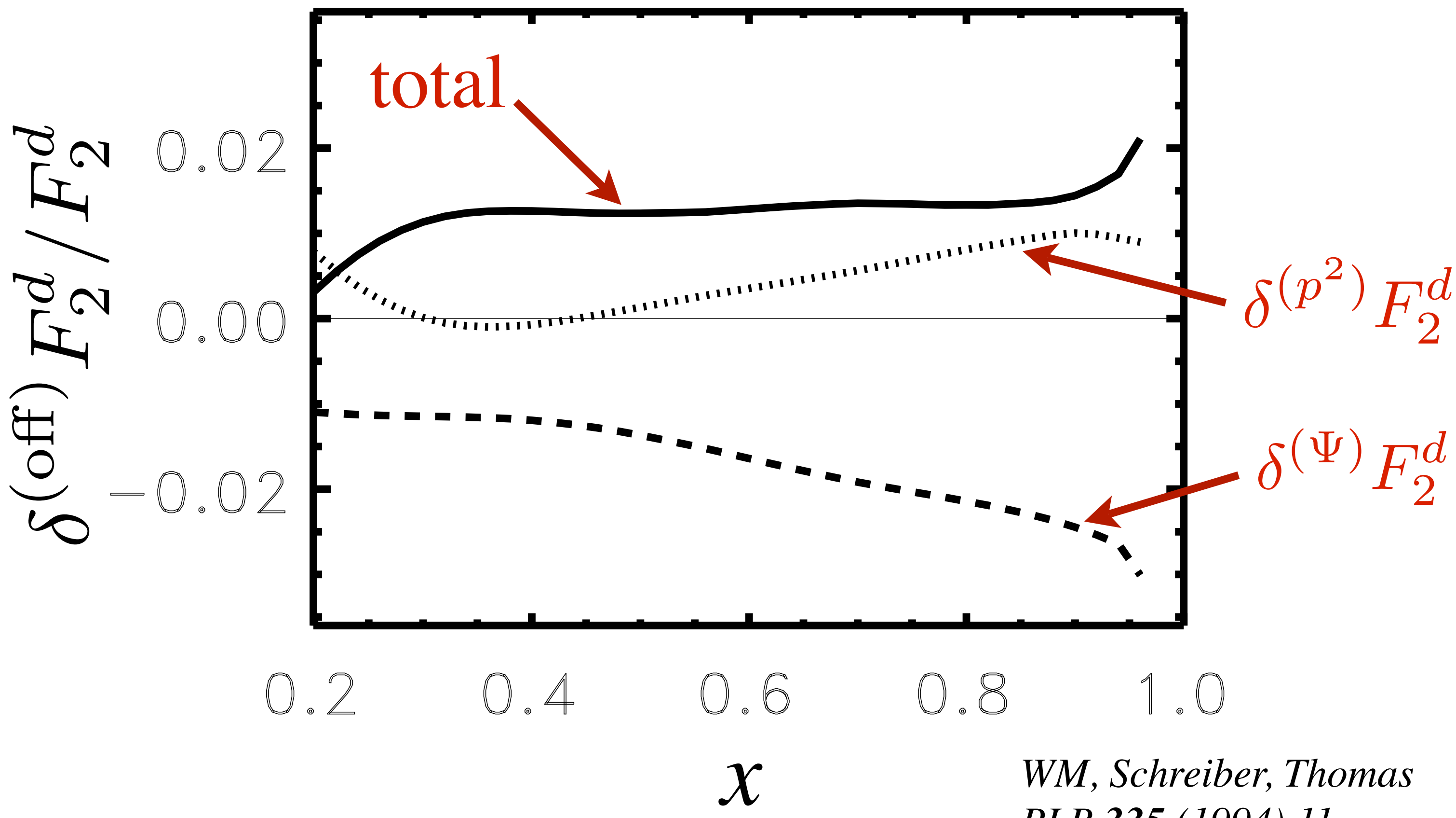
→ for most kinematics $\gamma \lesssim 2$

Off-shell correction

$\delta^{(\text{off})} F_2^d$ → $\delta^{(\Psi)} F_2^d$ negative energy components of ψ_d

→ $\delta^{(p^2)} F_2^d$ off-shell N structure function

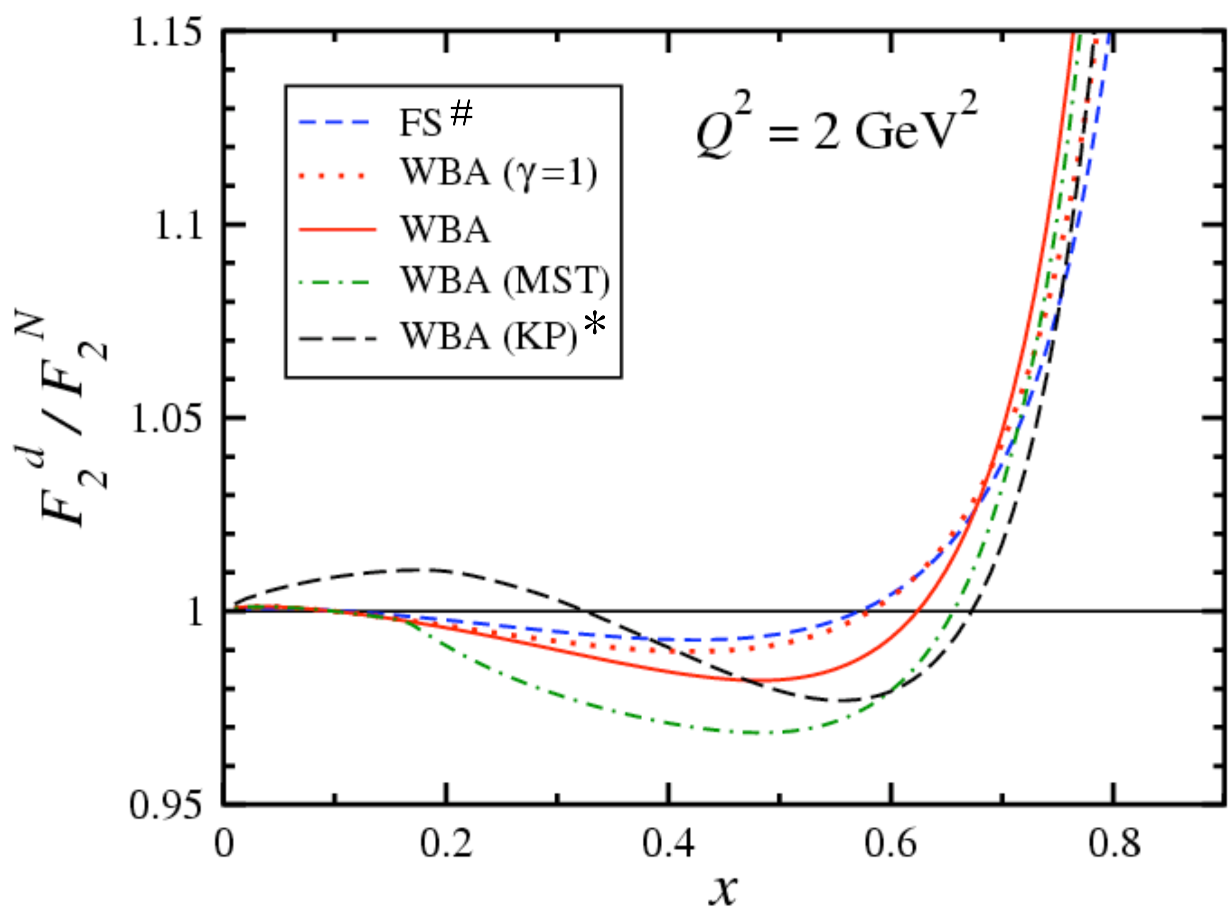




WM, Schreiber, Thomas
PLB ***335*** *(1994) 11*

→ $\leq 1 - 2\ \%$ effect

EMC effect in deuteron



Frankfurt, Strikman light-cone model (no binding)

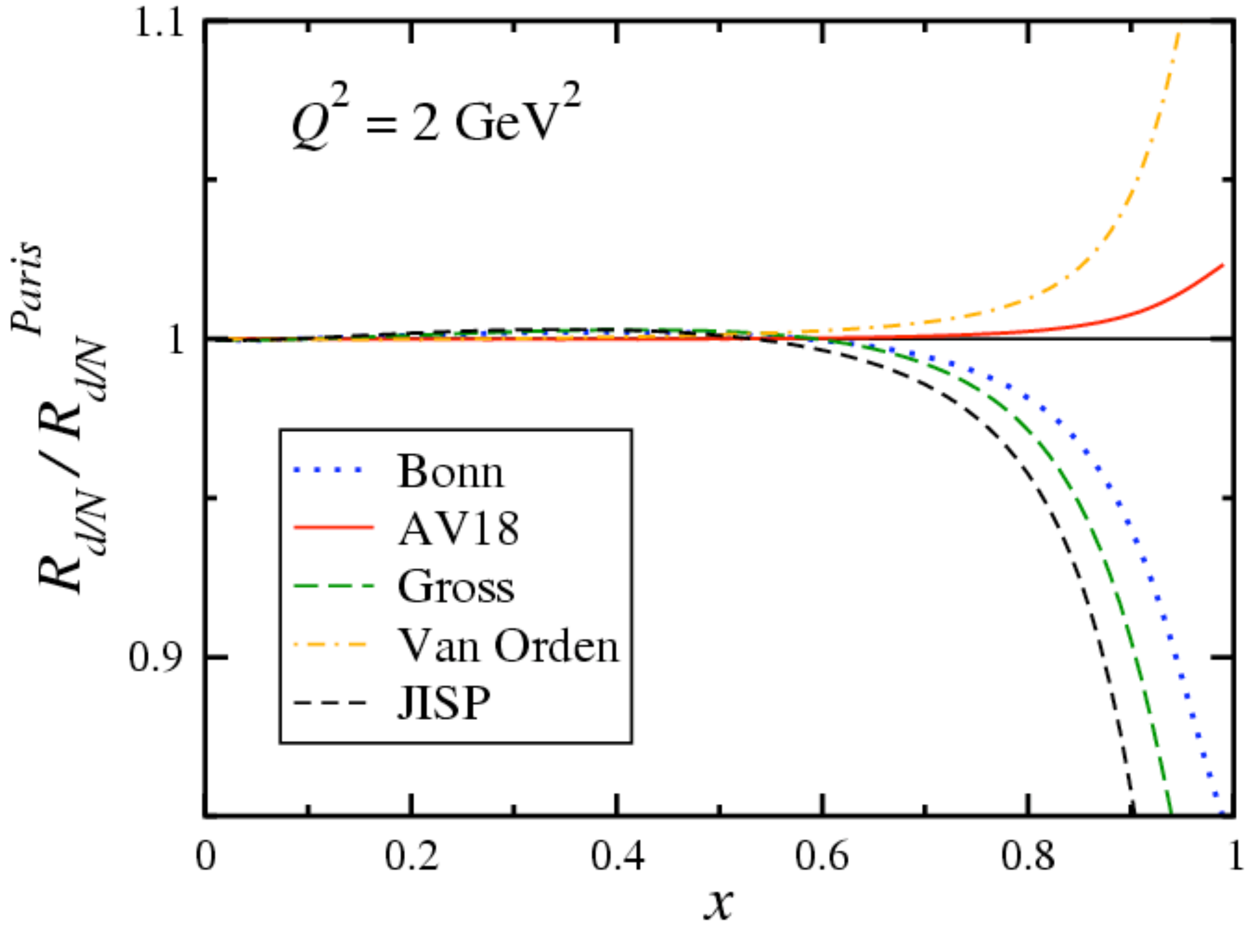
* *Kulagin, Petti NPA **765** (2006)126*

→ larger EMC effect (smaller d/N ratio) at $x \sim 0.5–0.6$ with binding + off-shell corrections

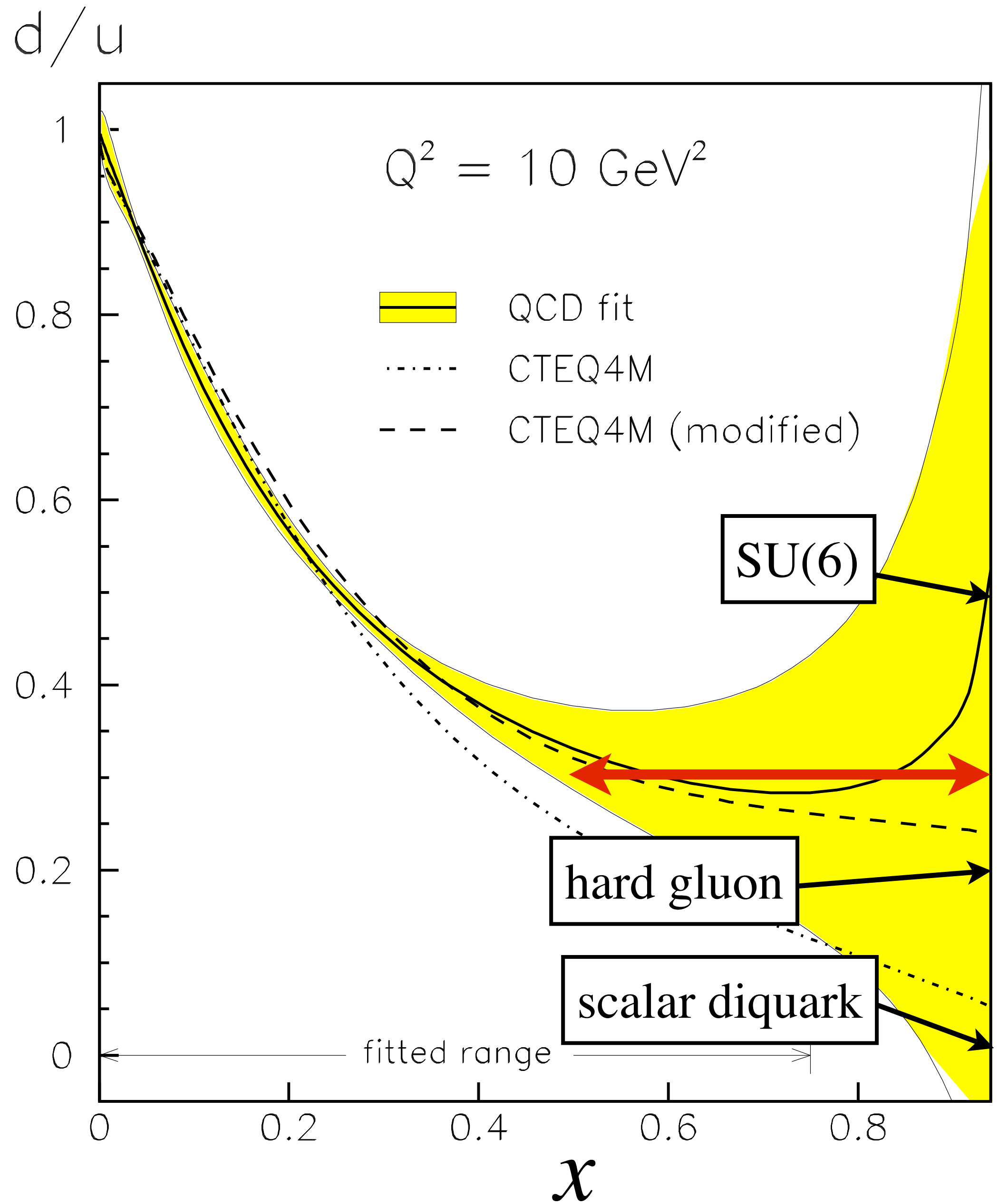
→ can significantly affect neutron extraction

EMC effect in deuteron

deuteron wave function dependence



→ mild dependence for $x < 0.8–0.85$



large uncertainty from nuclear effects in deuteron

(range of nuclear models*)

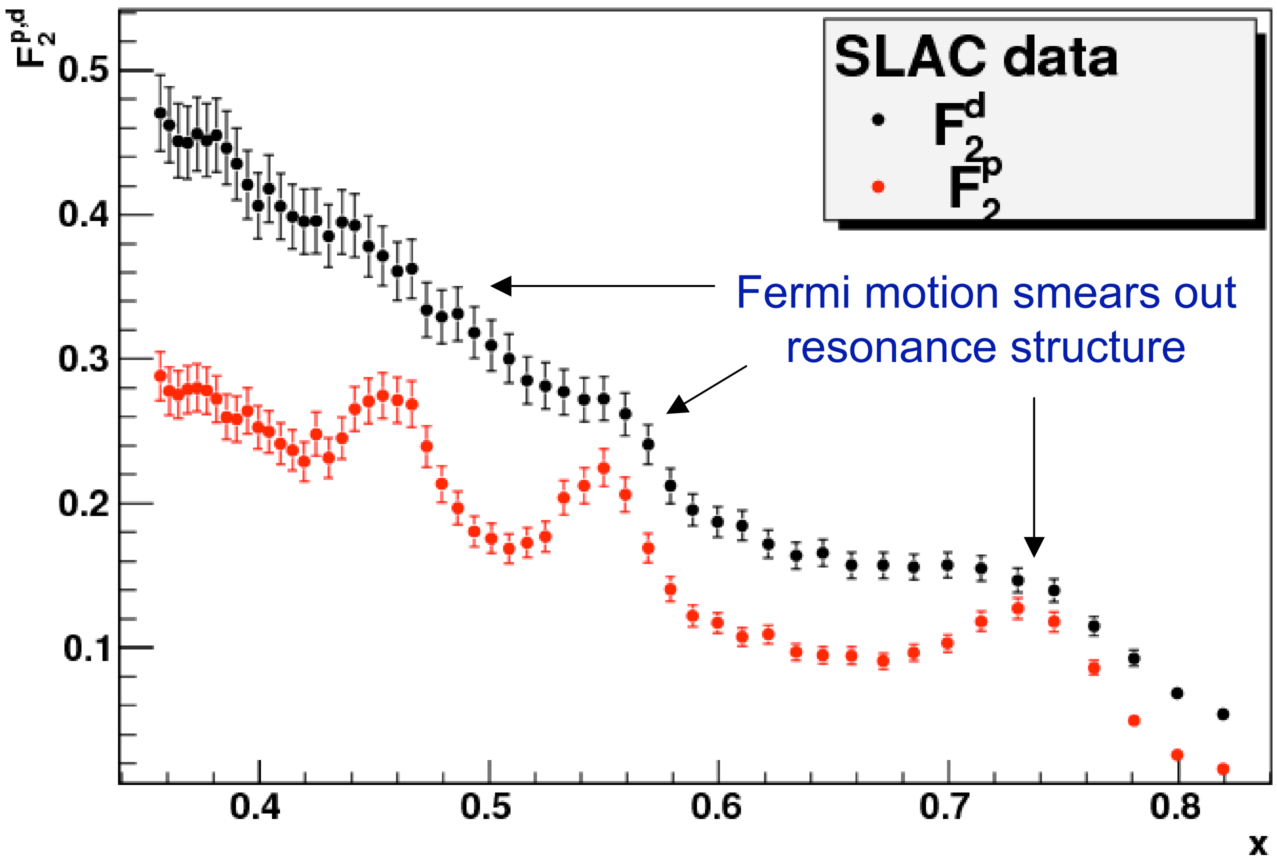
beyond $x \sim 0.5$

→ symmetry breaking mechanism remains unknown!

* most PDFs assume *no* nuclear corrections

Extraction of Neutron Structure Function

Fermi smearing in the deuteron



→ can one reconstruct ("unsmear") neutron resonance structure from deuteron data?

→ usual "multiplicative" unsmearing method does not work for "bumpy" data or which change sign (spin-dep. SFs)

Unsmearing – additive method

- calculated F_2^d depends on input F_2^n

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

Solution: iteration procedure

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

1. define difference Δ between smeared and free SFs

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

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

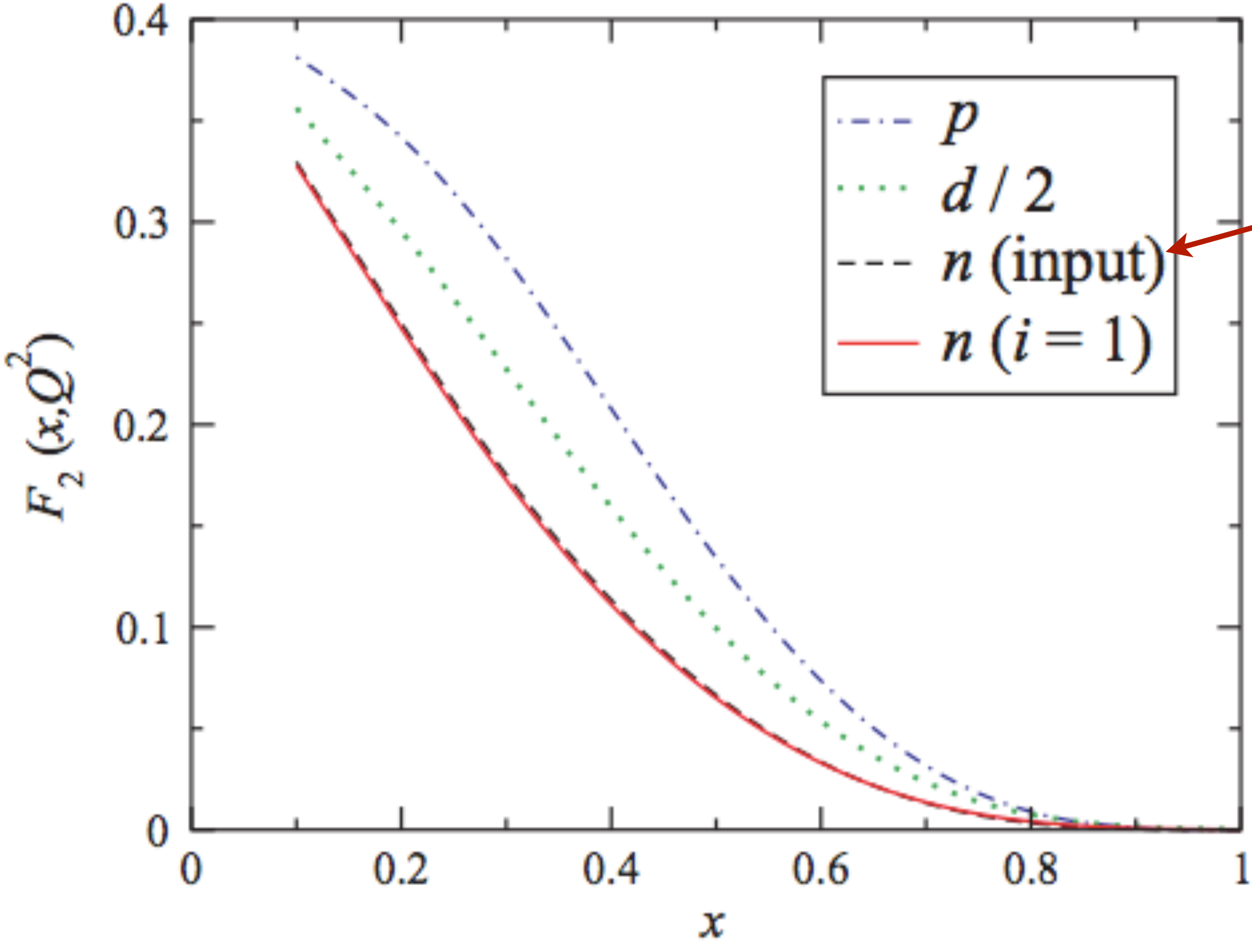
3. after one iteration, gives

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

4. repeat until convergence obtained

Unsmearing – test of convergence

- F_2^d constructed from known F_2^p and F_2^n inputs
  (using leading twist MRST parameterization)



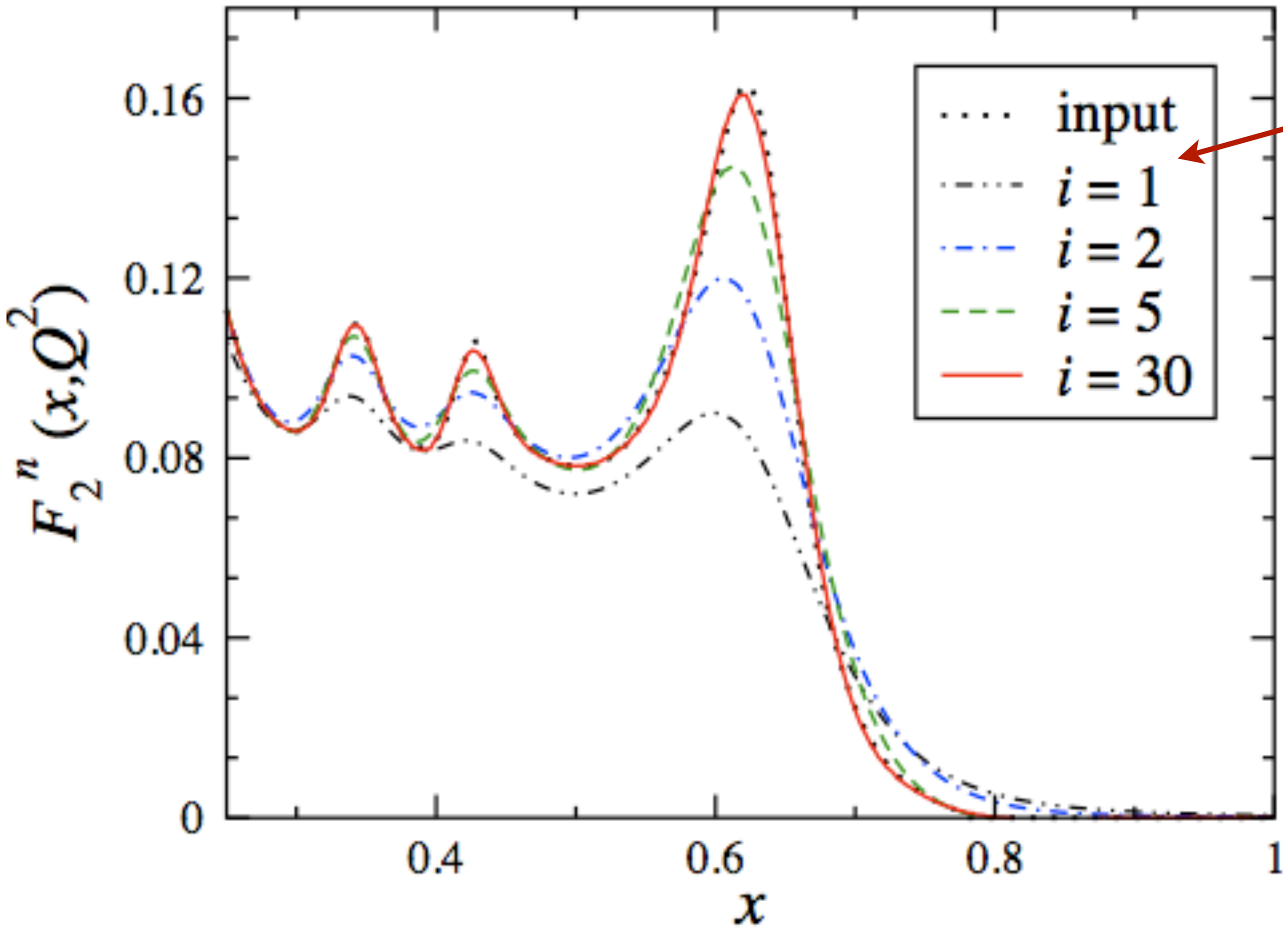
initial guess
$F_2^{n(0)} = 0$

Kahn, WM,
PRC ***79*** *(2009) 035205*

⟶ rapid convergence in DIS region

Unsmearing – test of convergence

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



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

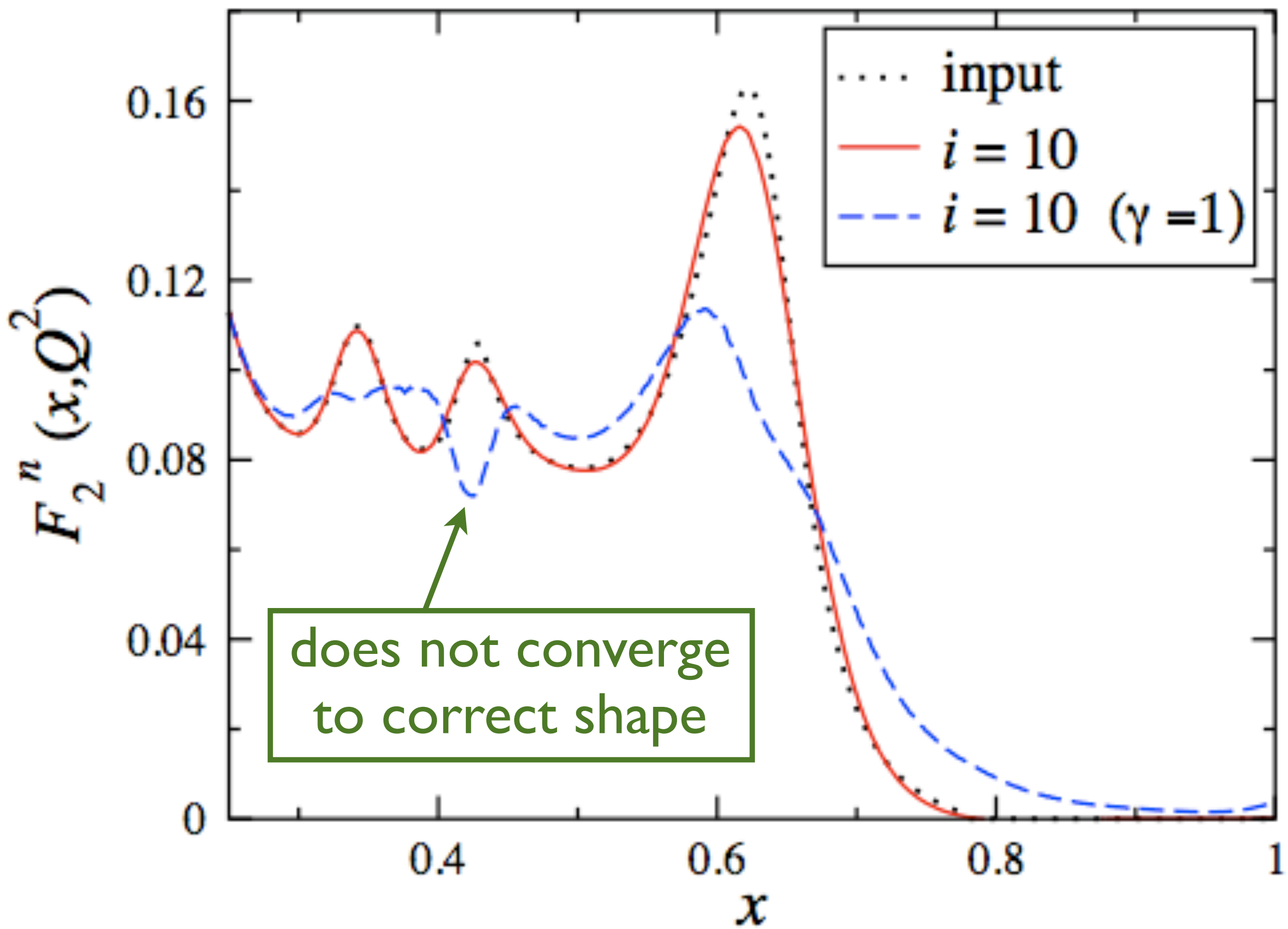
* even faster convergence if choose $F_2^{n(0)} = F_2^p$

*Kahn, WM, PRC **79** (2009) 035205*

⟶ can reconstruct almost arbitrary shape

Unsmearing – Q^2 dependence

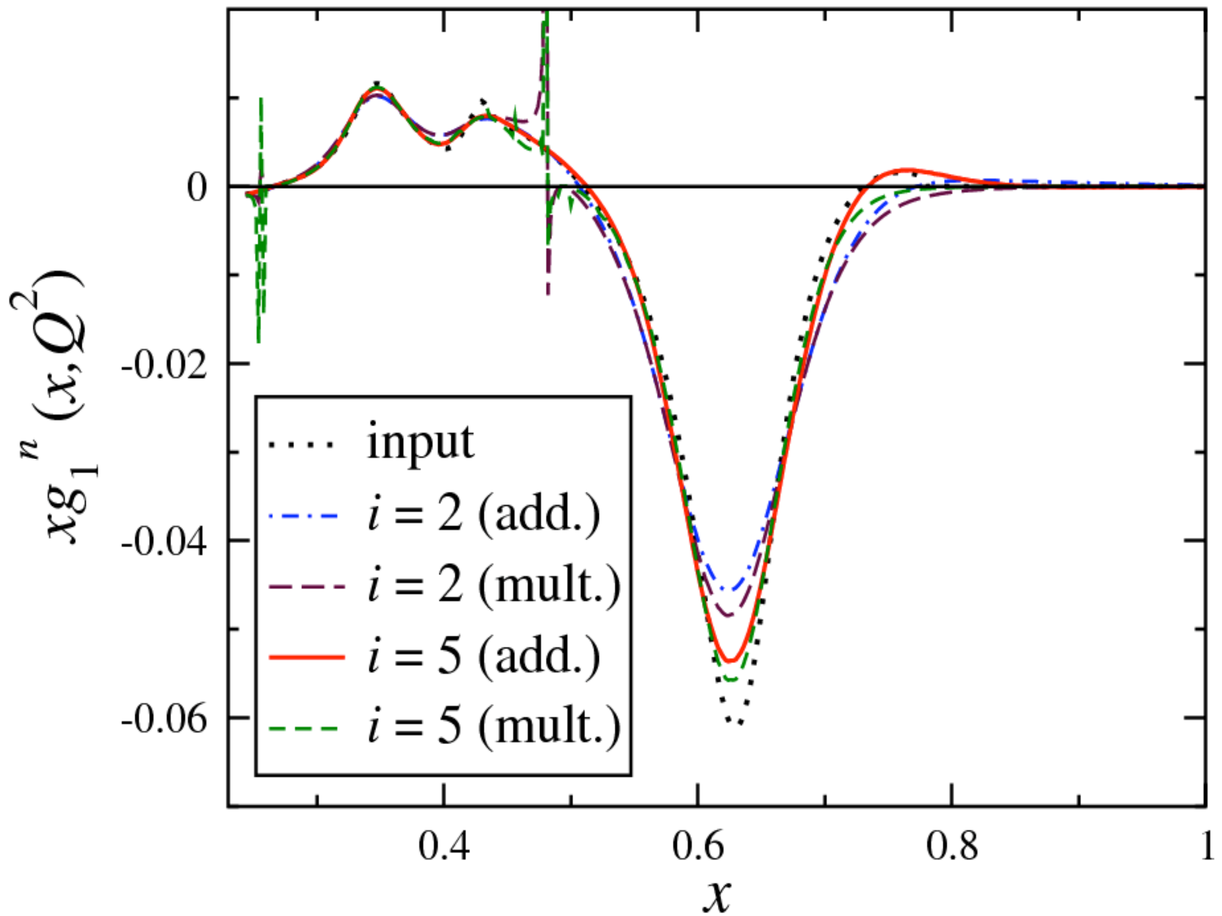
- important to use correct γ dependence in extraction



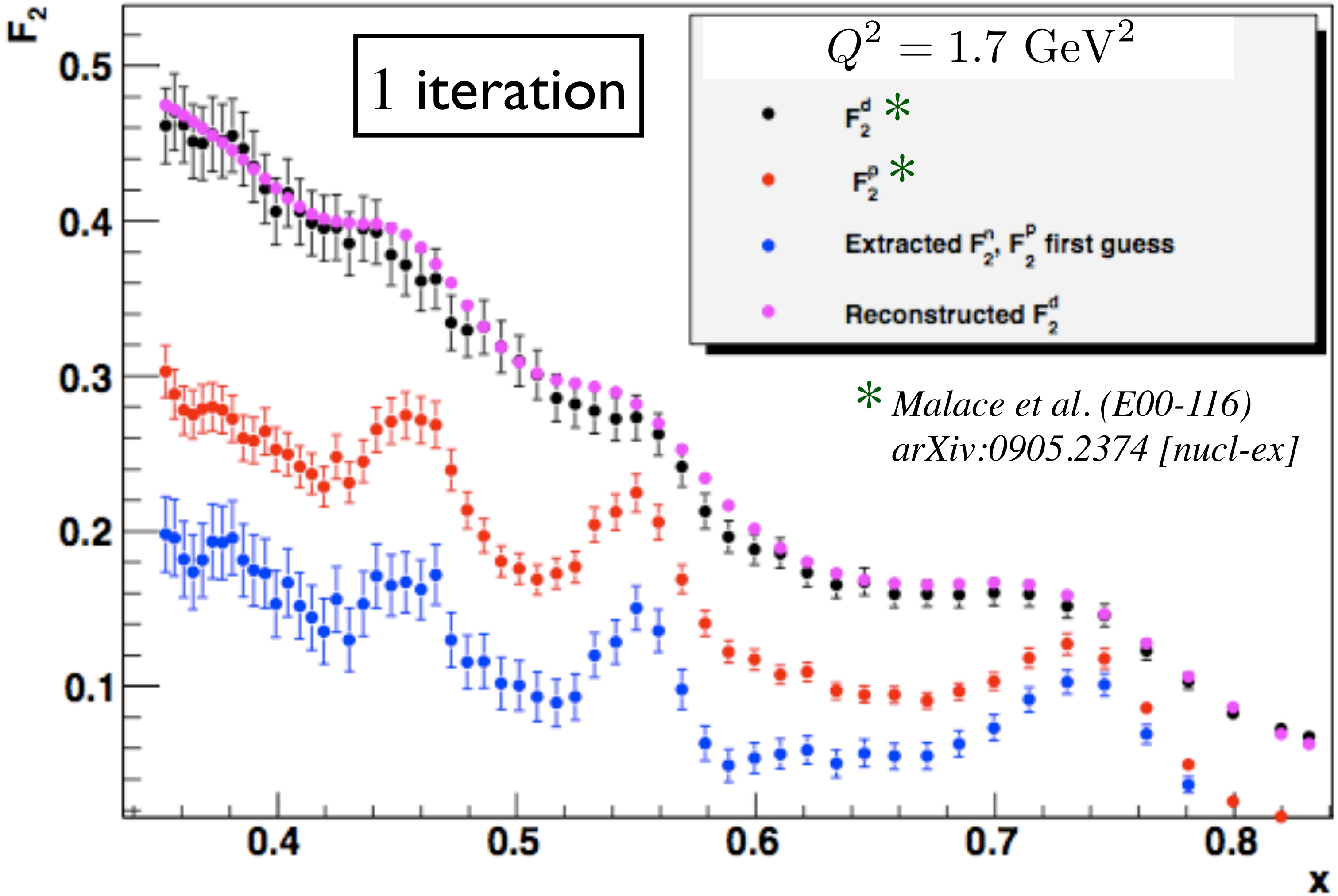
Kahn, WM,
*PRC **79** (2009) 035205*

→ important also in DIS region
(do not have resonance "benchmarks")

Unsmearing spin-dependent structure functions



Data extraction

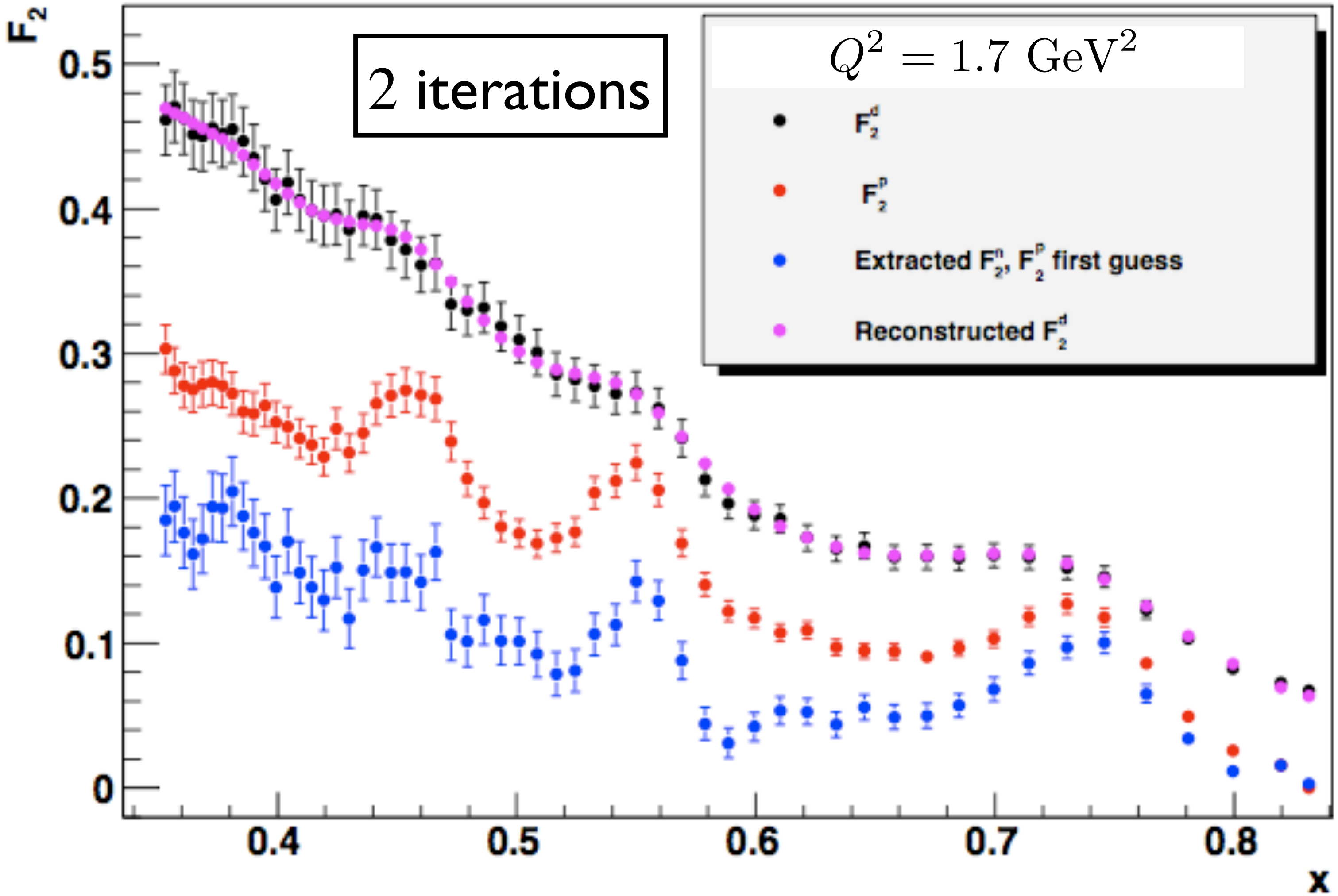


neutron errors ⟶ vary d data points by Gaussians

(proton data smeared, so errors very small)

⟶ run 50 sample extractions, calculate RMS error

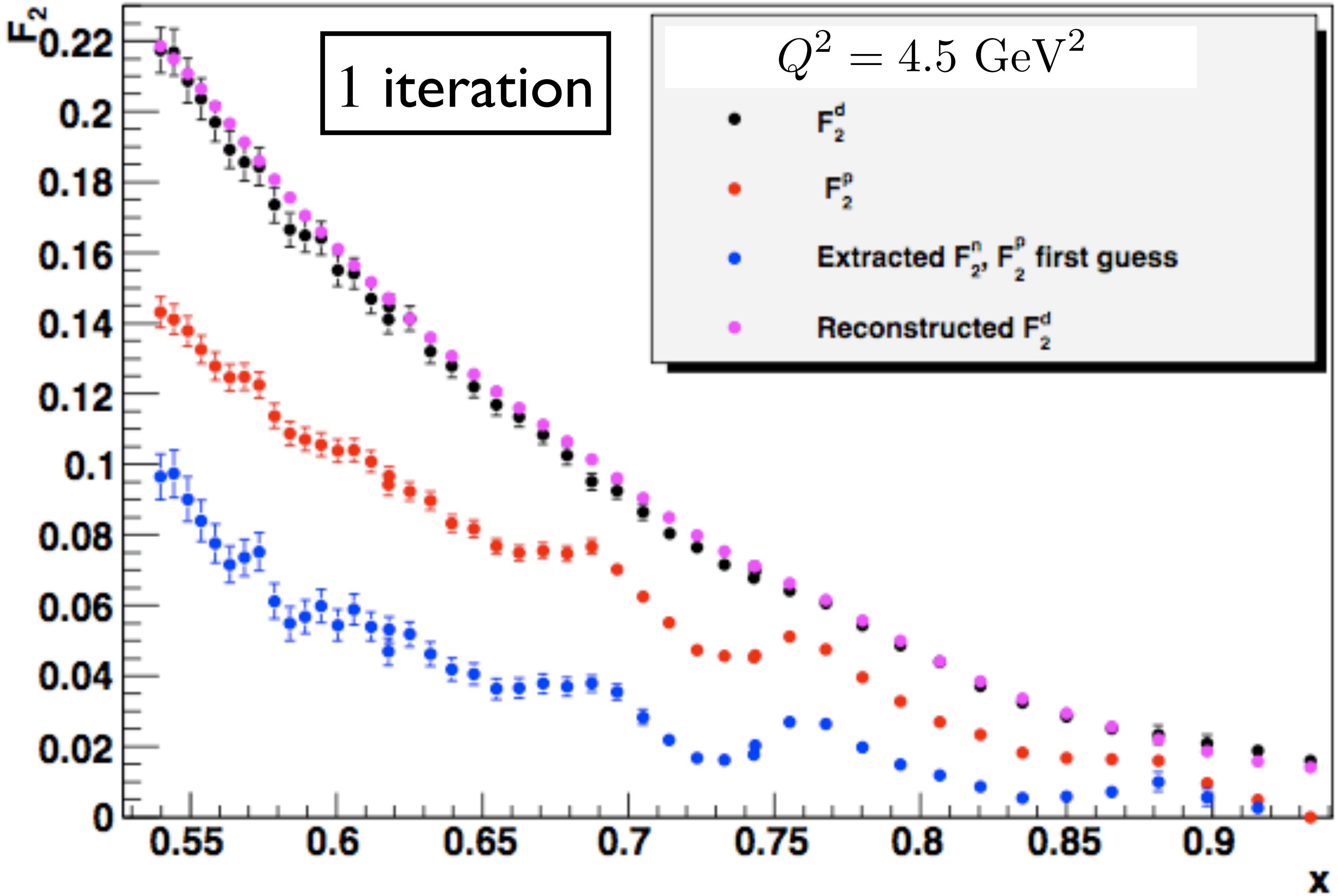
Data extraction



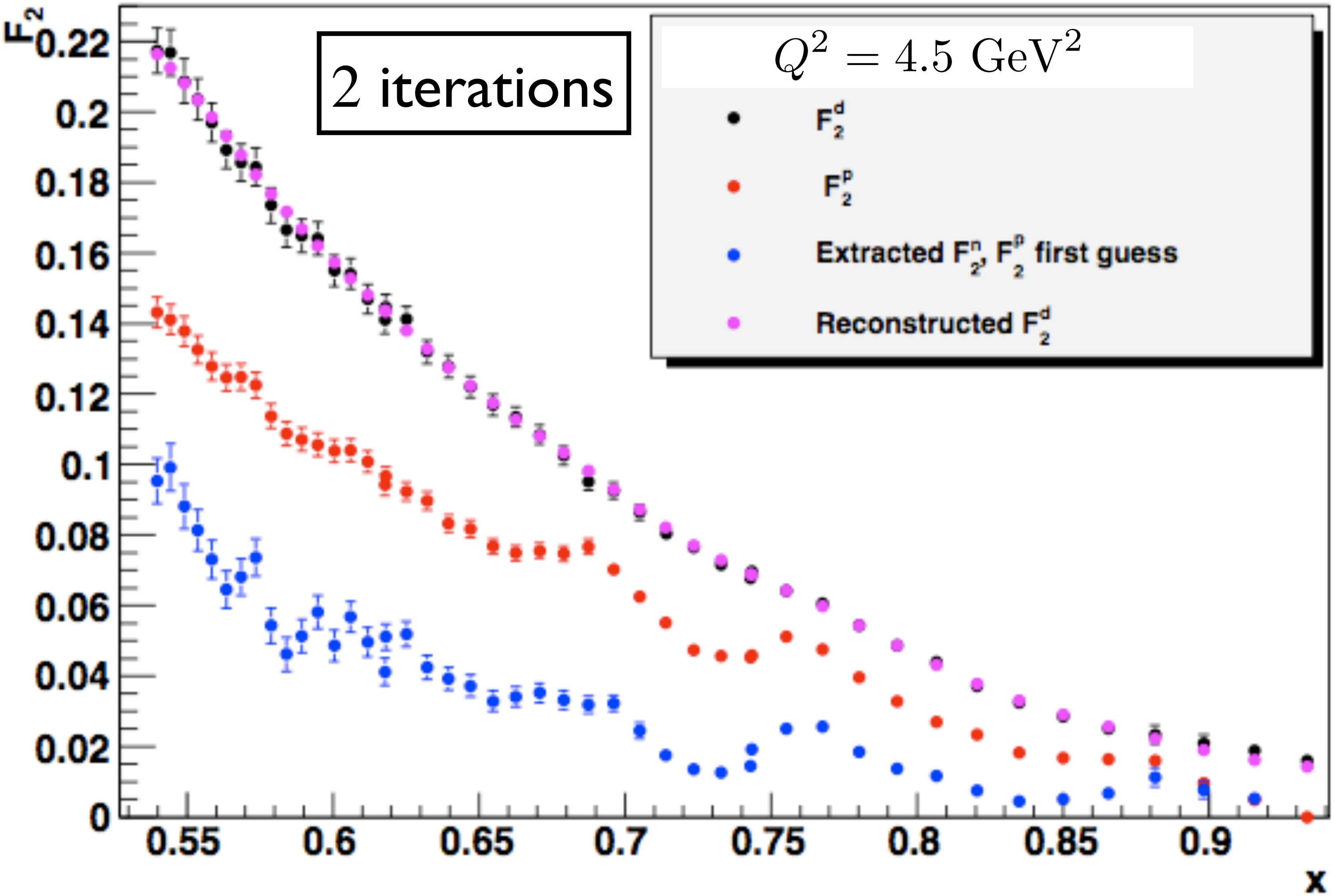
$\longrightarrow$ relatively stable results after only 2 iterations!

$\longrightarrow$ excellent agreement of reconstructed d with data

Data extraction

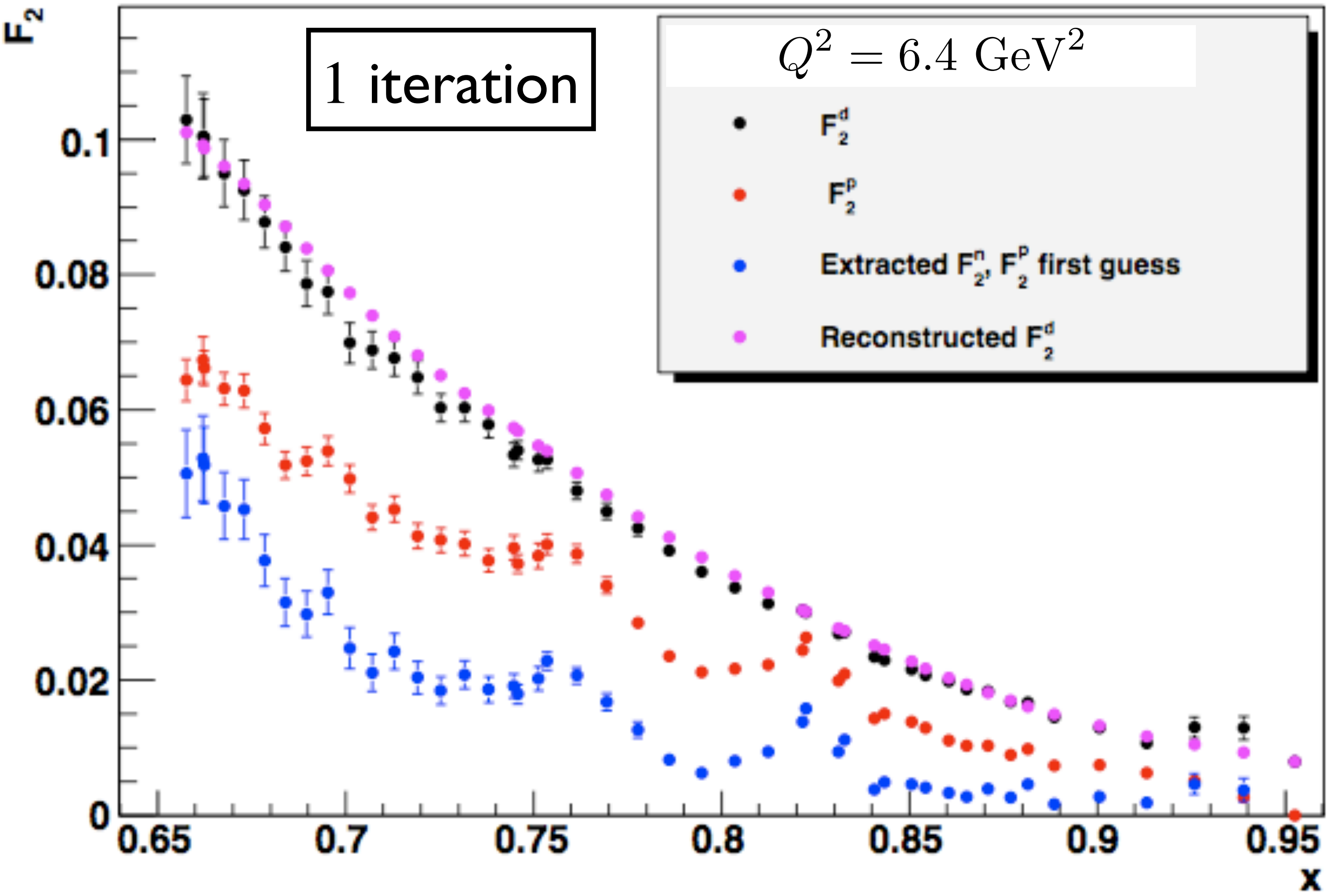


Data extraction

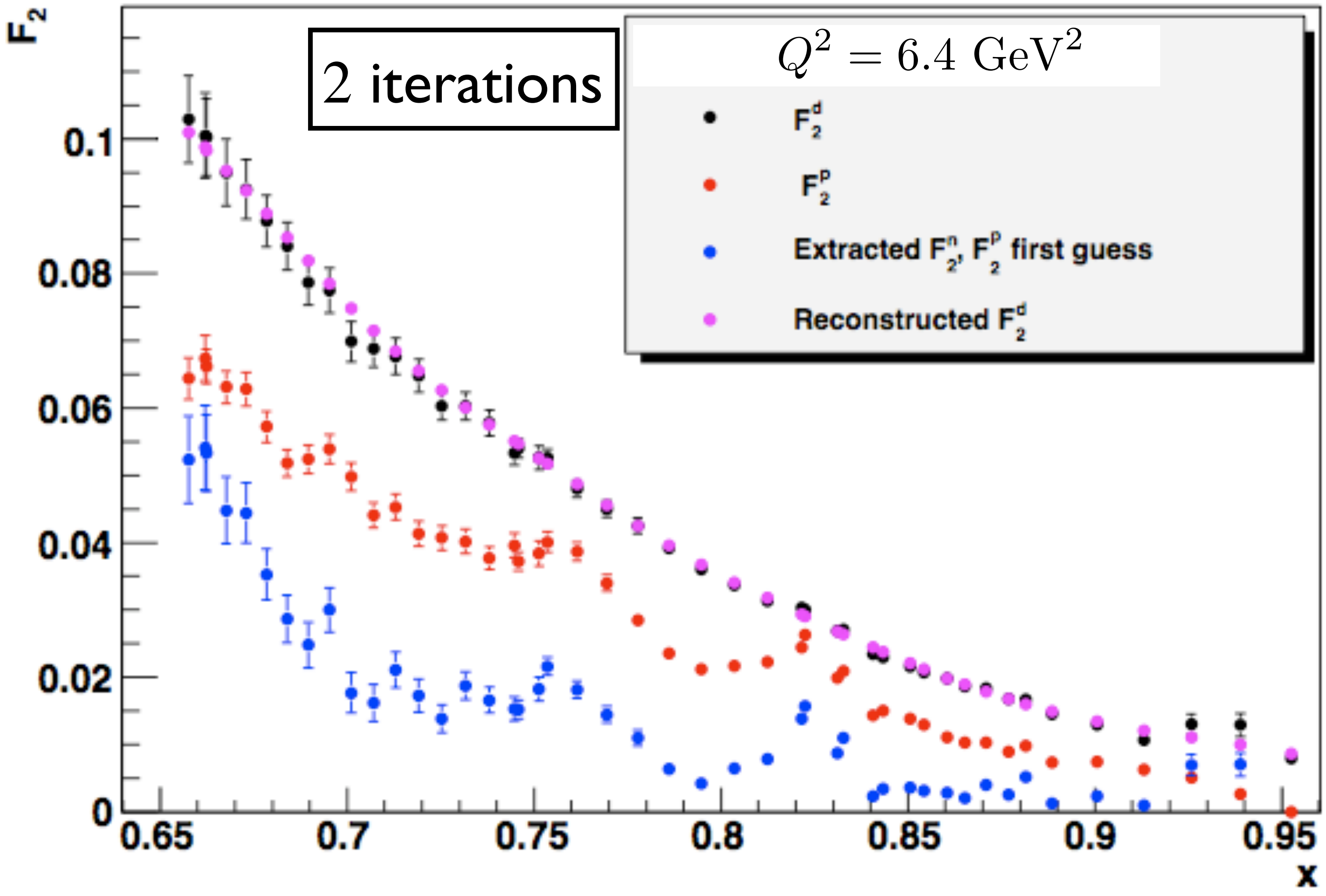


→ clear neutron resonance structure visible

Data extraction

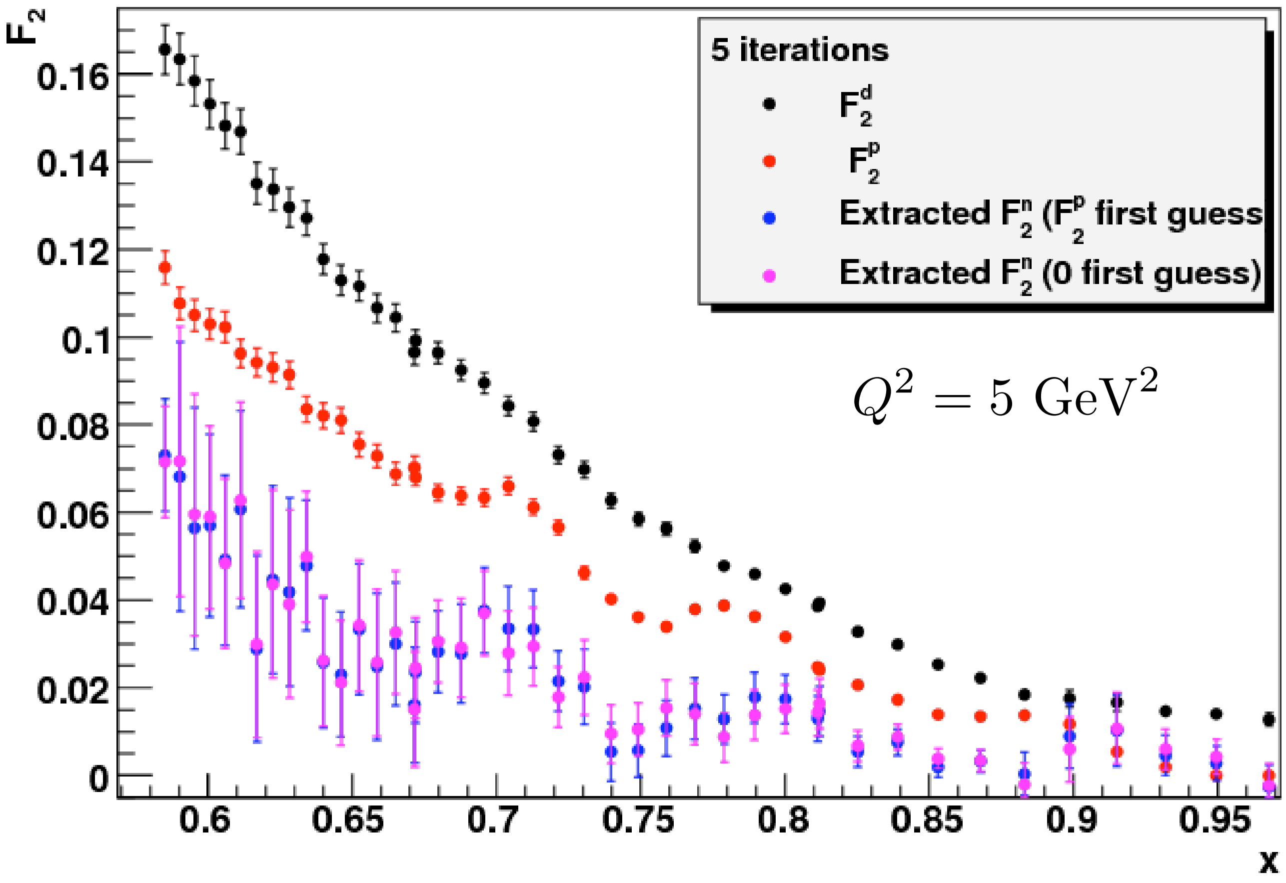


Data extraction



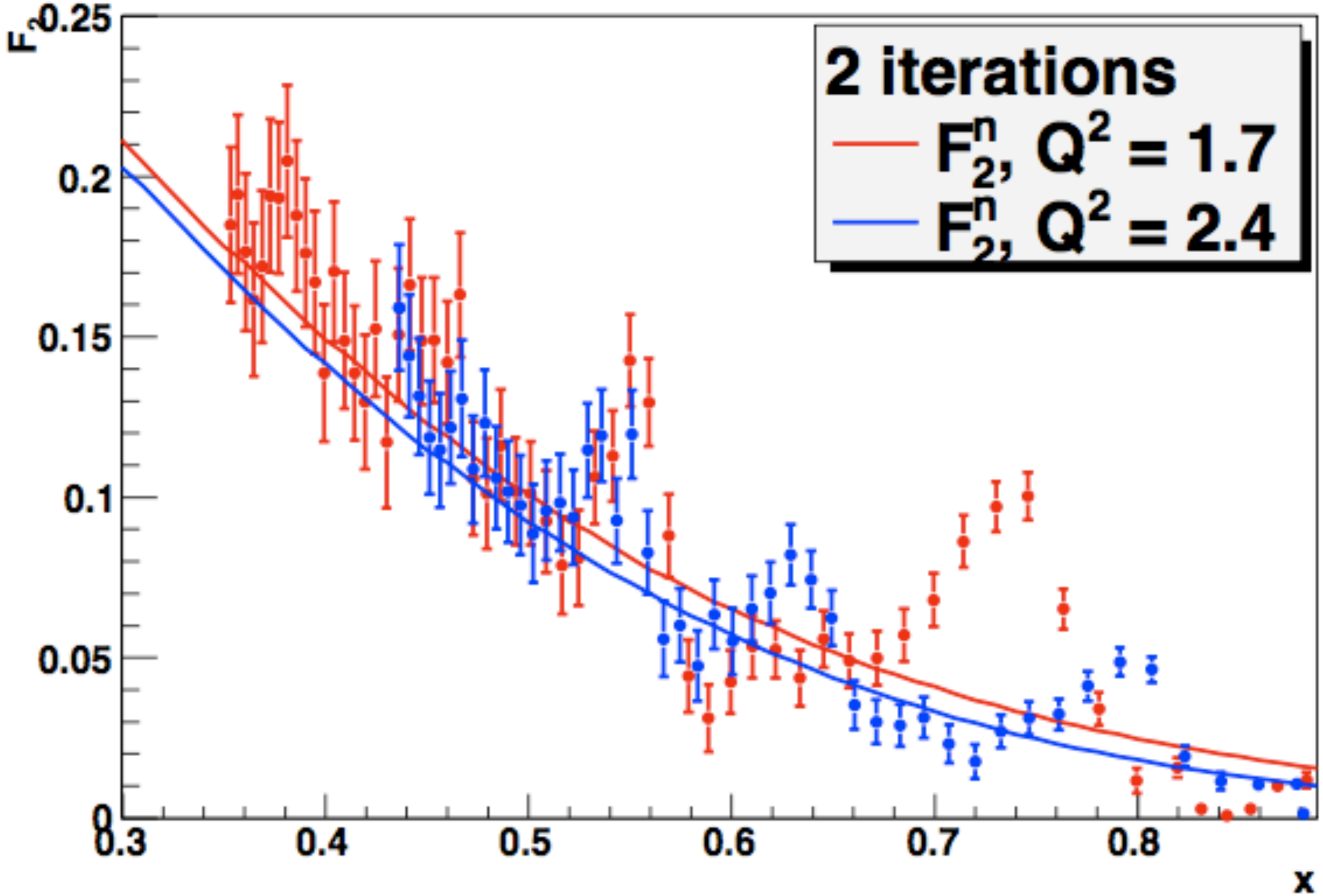
Data extraction

- dependence on initial guess for n



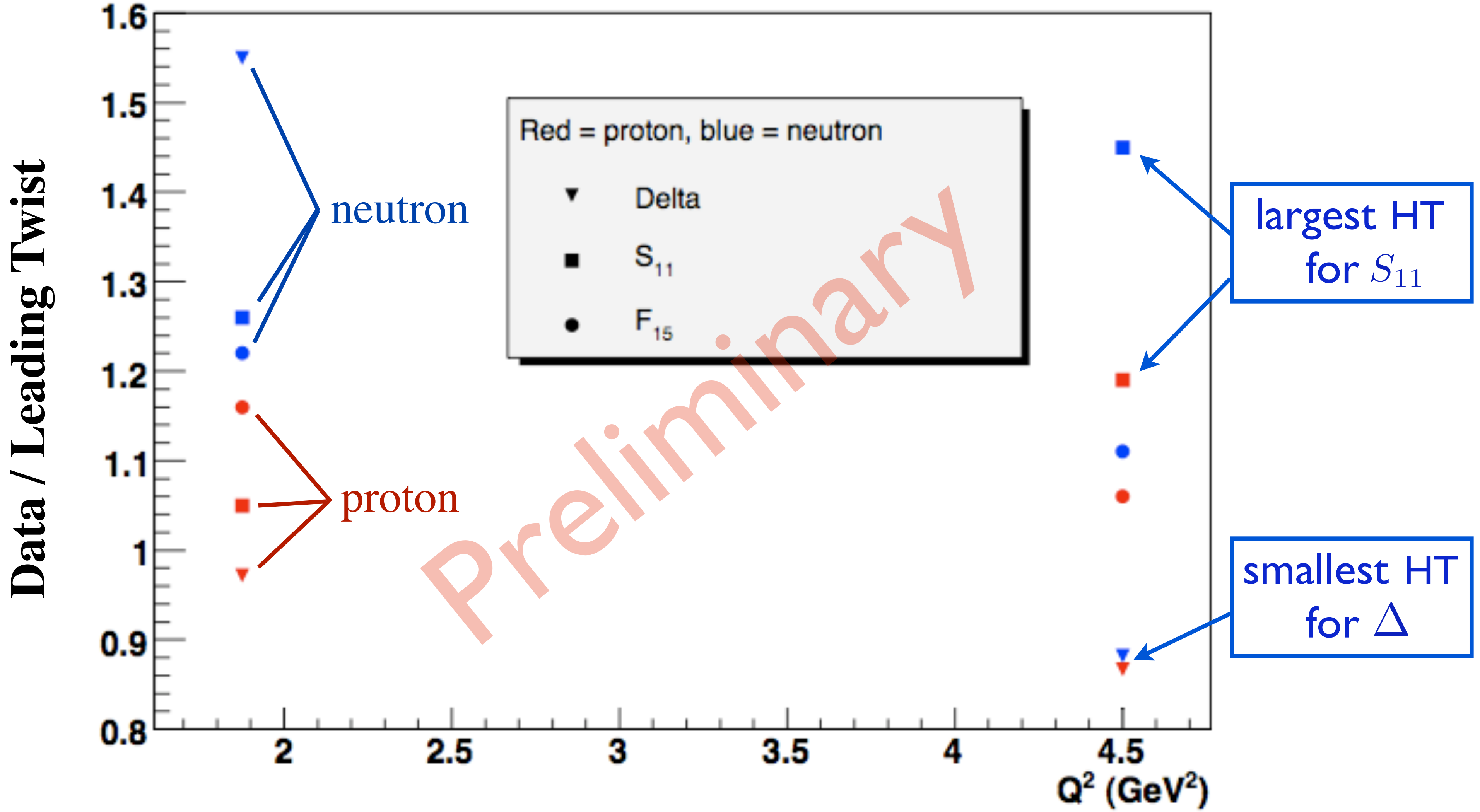
→ results converge eventually, but errors increase for more iterations

Duality test



→ comparison with leading twist (MRST) parameterization + target mass corrections

Duality test



→ neutron HT indeed larger than proton!

→ consistent with quark model expectations

Limitations of method

- Need data up to $x = 1$

  $\longrightarrow$ usually not a problem – unless cut d quasi-elastic tail

- Difficult to use on sparse data sets

  $\longrightarrow$ discontinuities in d data sharply magnified in n

- Some dependence on starting point for iteration

  $\longrightarrow$ convergence faster with judicious first guess for n

- Method limited to convolution representation

  $\longrightarrow$ corrections beyond convolution to be evaluated

Summary

- Nuclear corrections in deuteron computed at finite Q^2 through generalized convolution

- New unsmearing method for extracting neutron SFs

  → first(?) extraction in resonance and DIS regions

- Test of duality in the neutron

  → violations *larger* in neutron than in proton (as expected from quark models)

  → need to estimate systematic errors from nuclear corrections

- Comparison with BONUS data will test methodology

The End