Physics Opportunities in Hall C at 12 GeV
August 5, 2008

Mysteries of nucleon structure at large x

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Outline

- Open questions at large x

- Valence quarks in parity-violating DIS

  $\longrightarrow$ finite-Q^2 corrections $\longrightarrow$ **Xiaochao Zheng's talk**

- Target mass corrections

- Resonances & quark-hadron duality

  $\longrightarrow$ truncated moments

- Extraction of neutron structure from nuclear data

  $\longrightarrow$ new method for unpolarized & *polarized* SFs

- Summary

Open questions

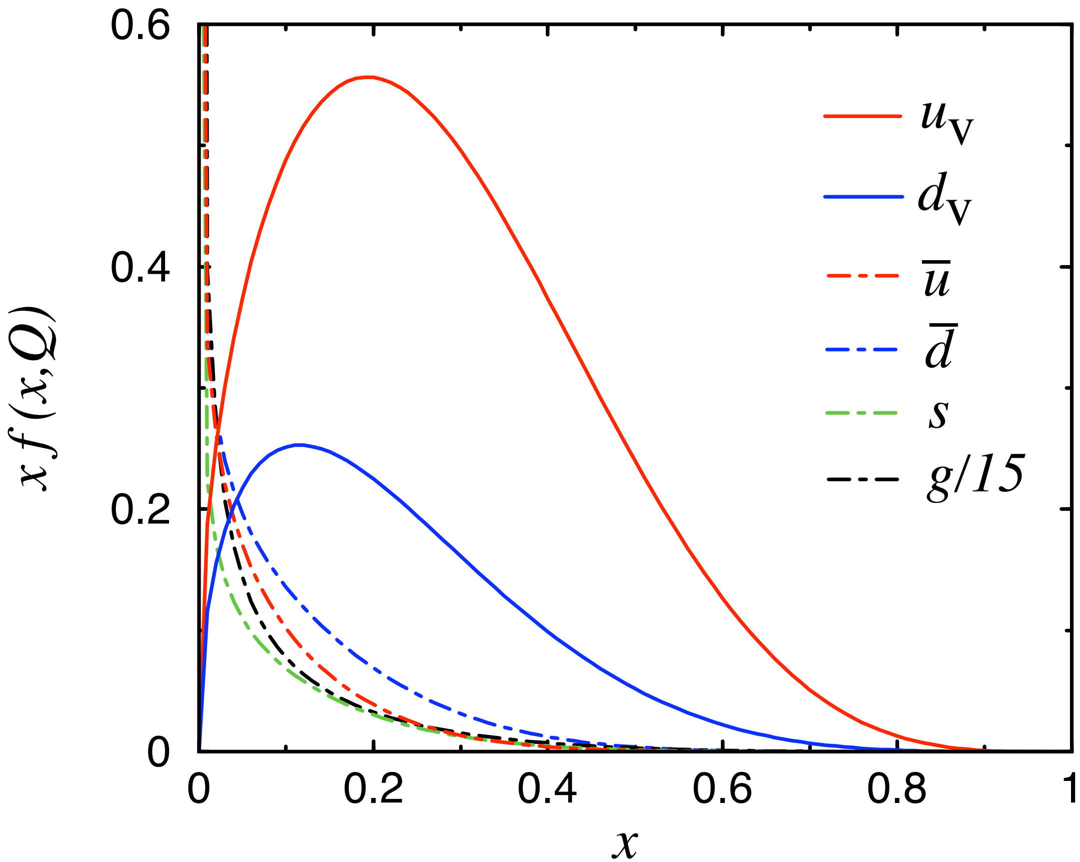
- What is the structure of valence quarks at large x?
  - $\longrightarrow$ how does d/u ratio behave as $x \rightarrow 1$
  - $\longrightarrow$ how is spin distributed amongst valence quarks
- To what extent are low Q^2 data dominated by leading twist?
  - $\longrightarrow$ can JLab data be used to constrain global PDFs (joint analysis with CTEQ under way)
- How large are higher twists?
  - $\longrightarrow$ how to quantify duality violation
- Can we reliably extract neutron structure functions from nuclei?
  - $\longrightarrow$ can we recover neutron resonance structure?

Valence quarks

Valence quarks

- Most direct connection between quark distributions and models of the nucleon is through *valence* quarks

- Nucleon structure at intermediate & large x dominated by valence quarks



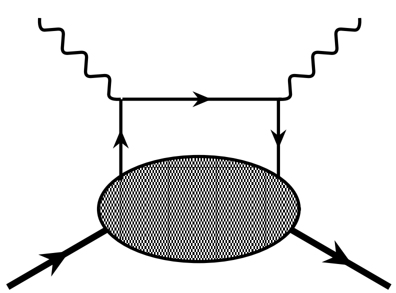
Valence quarks

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

- SU(6) spin-flavour 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

Valence quarks

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

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

Valence quarks

- 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

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

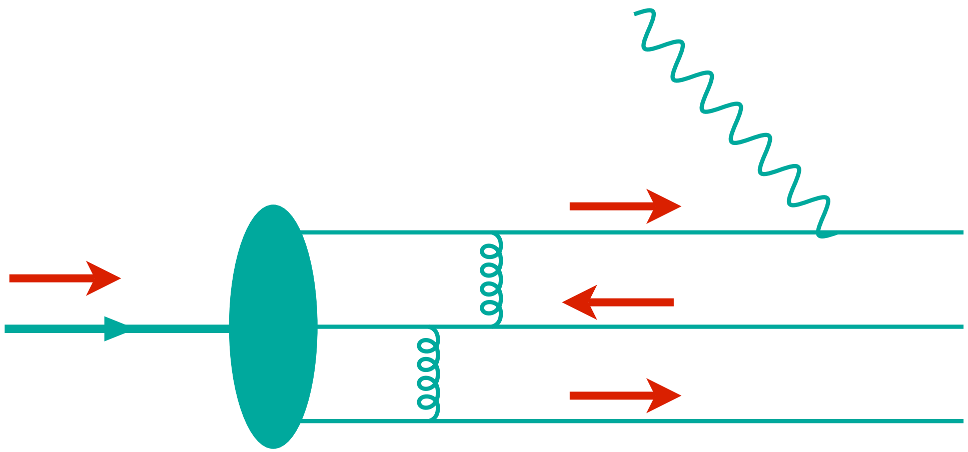
$\longrightarrow \quad \dfrac{F_2^n}{F_2^p} \to \dfrac{1}{4}$

Feynman 1972, Close 1973, Close/Thomas 1988

Valence quarks

- 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

$\longrightarrow$ $$\frac{d}{u} \to \frac{1}{5}$$

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

Farrar, Jackson 1975

Quark polarization at large x

SU(6) symmetry

$$A_1^p = \frac{5}{9}\,, \qquad A_1^n = 0$$

$$\frac{\Delta u}{u} = \frac{2}{3}\,, \quad \frac{\Delta d}{d} = -\frac{1}{3}$$

scalar diquark dominance

$$A_1^p \to 1\,, \qquad A_1^n \to 1$$

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to -\frac{1}{3}$$

pQCD (helicity conservation)

$$A_1^p \to 1\,, \qquad A_1^n \to 1$$

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to 1$$

Valence quarks

- At large x, valence u and d distributions extracted from p and n structure functions

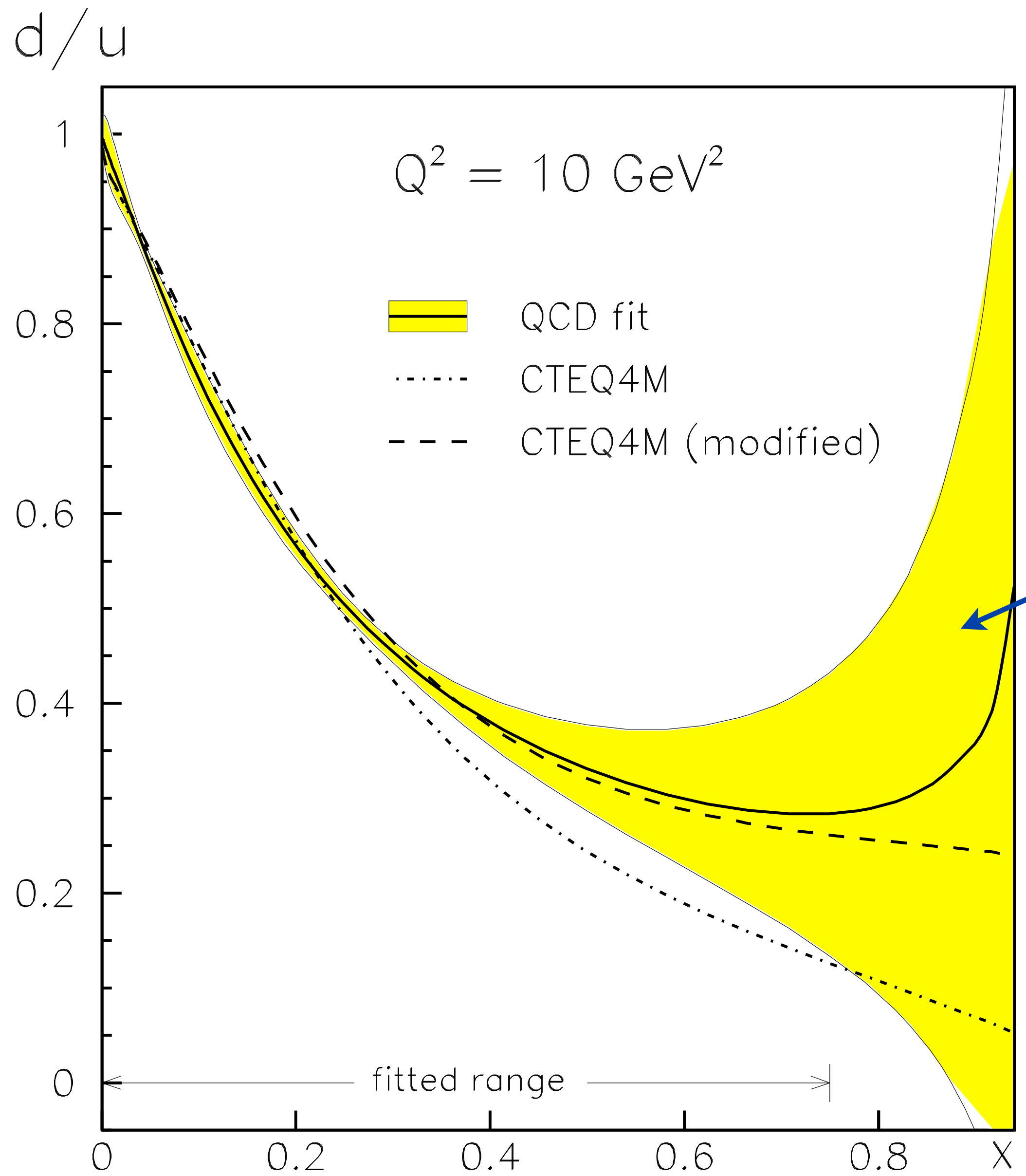
$$F_2^p \approx \frac{4}{9} u_v + \frac{1}{9} d_v$$

$$F_2^n \approx \frac{4}{9} d_v + \frac{1}{9} u_v$$

- u quark distribution well determined from p

- d quark distribution requires n structure function

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



large uncertainty at large x in d/u ratio

Botje, Eur. Phys. J. C 14 (2000) 285

Nuclear effects

- no free neutron targets

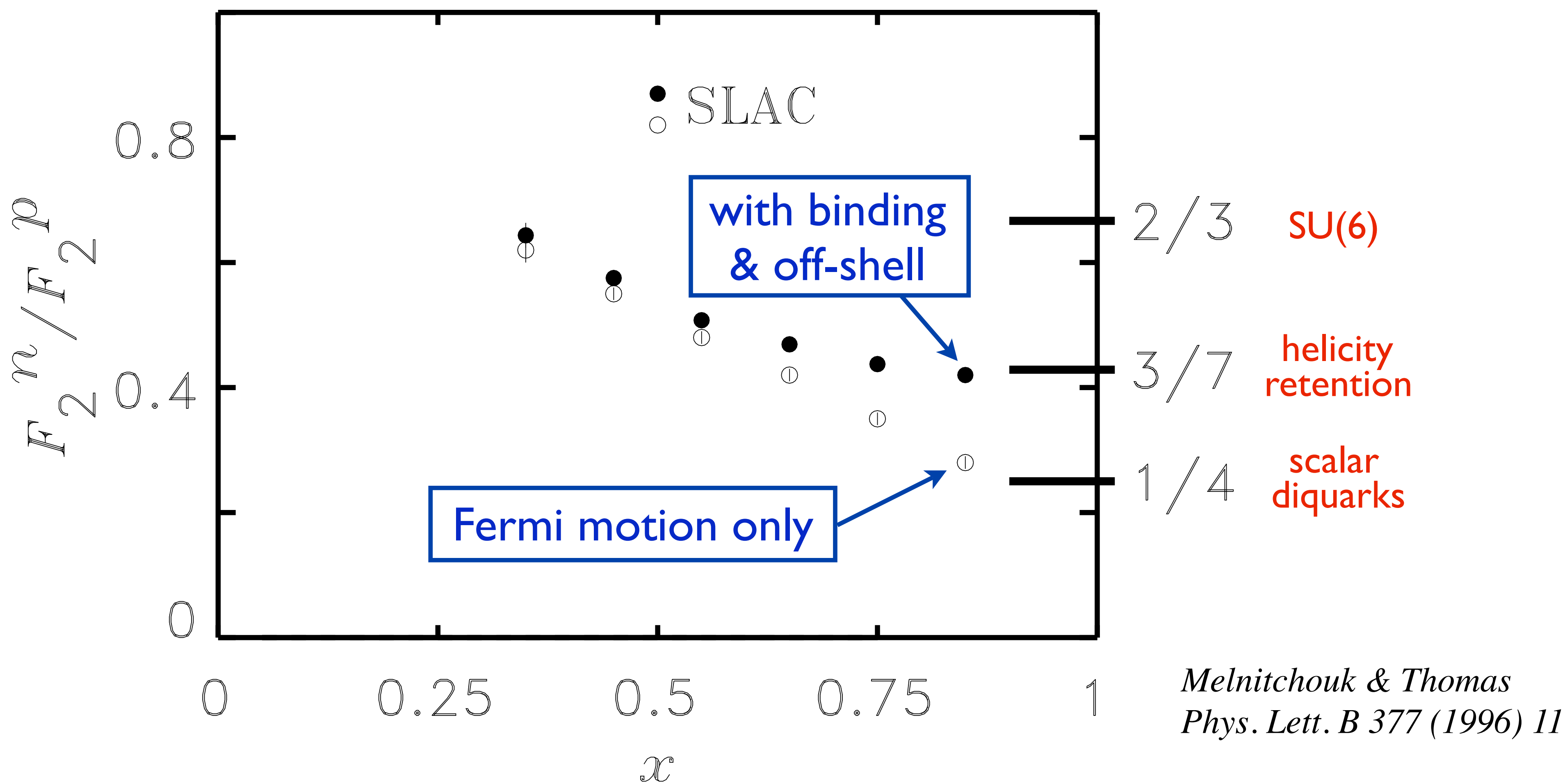
  (neutron half-life ~ 12 mins)

  ⟹ use deuteron as "effective" neutron target

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

  ⟹ nuclear effects (nuclear binding, Fermi motion, shadowing) *<u>obscure neutron structure</u>* information

  ⟹ "nuclear EMC effect"



→ without EMC effect in d

F_2^n underestimated at large x!

“Cleaner” methods of determining d/u

- $e\ d \to e\ p_{\rm spec}\ X$ — “BONUS”
- $e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X$ — mirror-symmetric nuclei
- $e\ p \to e\ \pi^{\pm}\ X$ — semi-inclusive DIS as flavor tag
- $e^{\mp}\ p \to \nu(\bar{\nu}) X$
  $\nu(\bar{\nu})\ p \to l^{\mp}\ X$
  $p\ p(\bar{p}) \to W^{\pm} X$
  $\vec{e}_L(\vec{e}_R)\ p \to e\ X$
  — weak current as flavor probe

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  — weak current as flavor probe

Parity-violating DIS

(with Tim Hobbs)

Parity-violating e scattering

- Left-right polarization asymmetry in $\vec{e}\, p \to e\, X$

$$A^{\rm PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

$\longrightarrow$ measure interference between e.m. and weak currents

- In terms of structure functions

$$A^{\rm PV} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left(g_A^e\, Y_1\, \frac{F_1^{\gamma Z}}{F_1^\gamma} + \frac{g_V^e}{2}\, Y_3\, \frac{F_3^{\gamma Z}}{F_1^\gamma}\right)$$

$$Y_1 = \frac{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma Z})) - 2xyM/E}{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma})) - 2xyM/E}\left(\frac{1+R^{\gamma Z}}{1+R^\gamma}\right)$$

$$Y_3 = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2(1-r^2/(1+R^{\gamma})) - 2xyM/E}\left(\frac{r^2}{1+R^\gamma}\right)$$

where $y = \nu/E$ and $r^2 = 1 + 4M^2x^2/Q^2$

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Parity-violating e scattering

- Longitudinal-transverse interference cross section ratio

$$R^{\gamma Z} = \frac{\sigma_L^{\gamma Z}}{\sigma_T^{\gamma Z}} \quad \longrightarrow \quad \text{unknown phenomenology}$$

- At large Q^2: $\quad Y_1 \to 1, \quad Y_3 \to \dfrac{1-(1-y)^2}{1+(1-y)^2}$

$$\longrightarrow \quad A^{\mathrm{PV}} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)(Y_1\ a_1 \ + \ Y_3\ a_3)$$

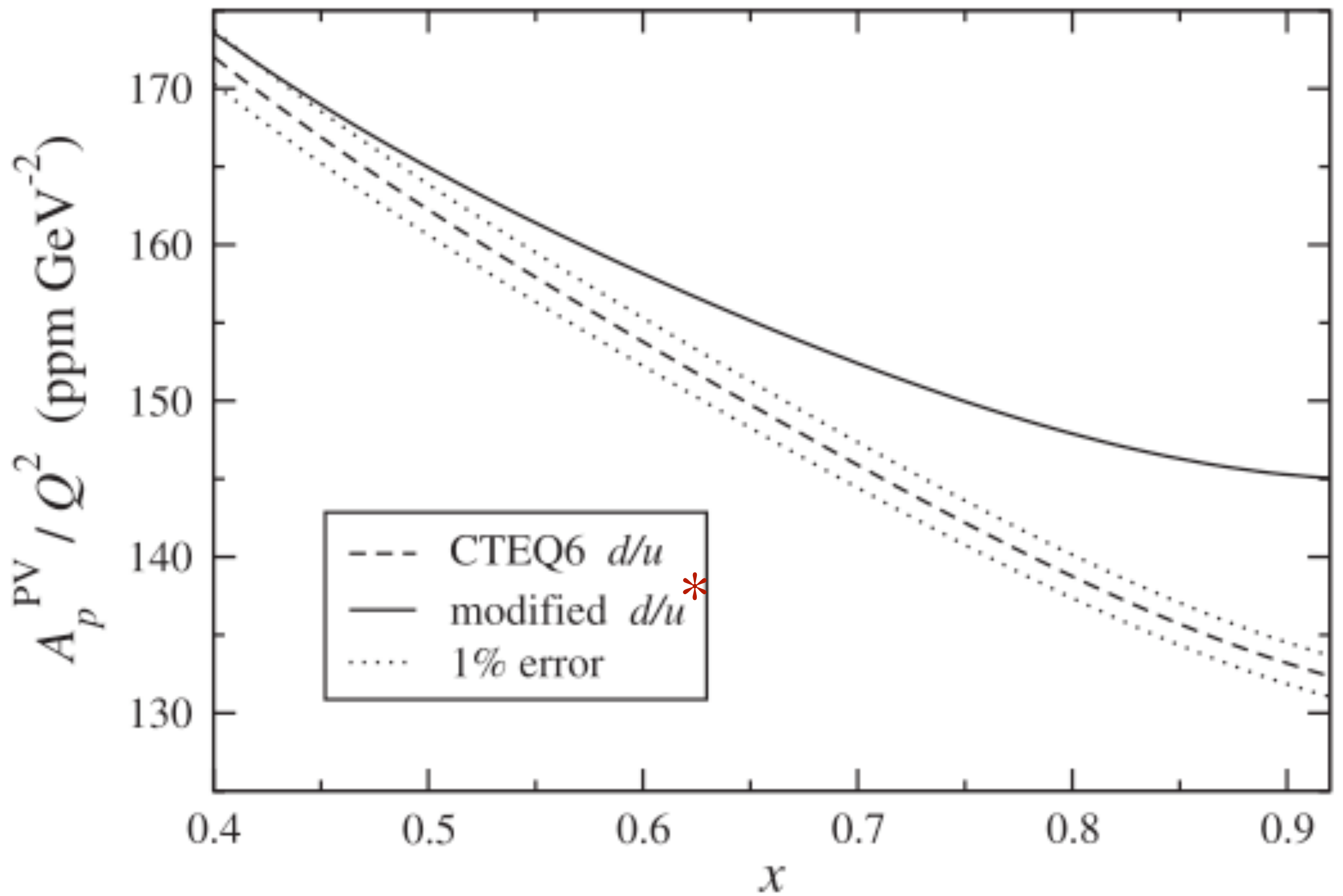
where $\quad a_1 = \dfrac{2\sum_q C_{1q}\ (q+\bar{q})}{\sum_q e_q^2\ (q+\bar{q})} \qquad a_3 = \dfrac{2\sum_q C_{2q}\ (q-\bar{q})}{\sum_q e_q^2\ (q-\bar{q})}$

$$C_{1q} = g_A^e\ g_V^q \qquad\qquad C_{2q} = g_V^e\ g_A^q$$

Parity-violating e scattering

- Proton asymmetry sensitive to d/u ratio

$$a_1^p = \frac{12C_{1u} - 6C_{1d}\ d/u}{4 + d/u}$$

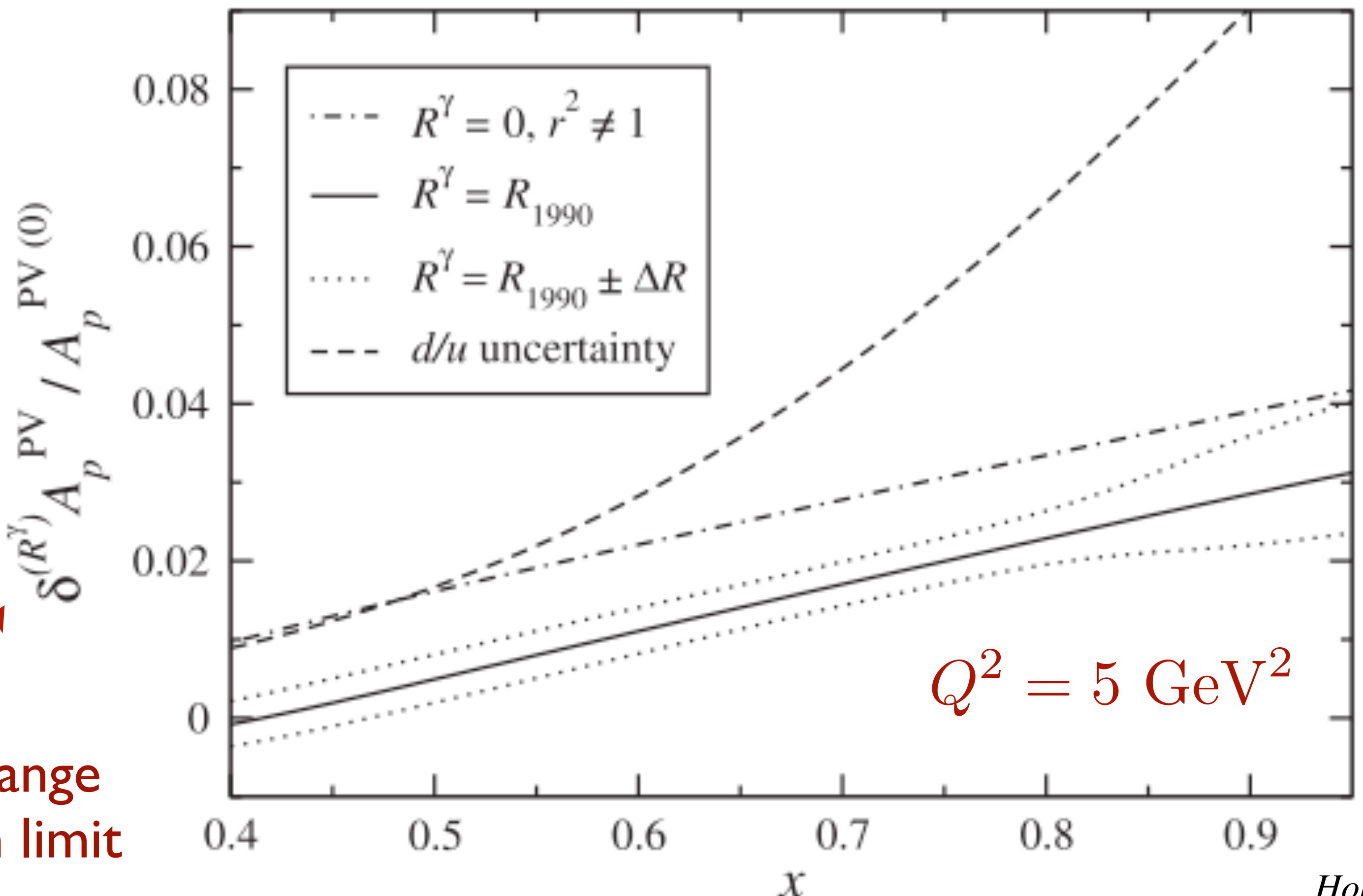


* $d/u \to 0.2$ as $x \to 1$

Hobbs, Melnitchouk
Phys. Rev. D 77, 114023 (2008)

Parity-violating e scattering

- Sensitivity to R^γ



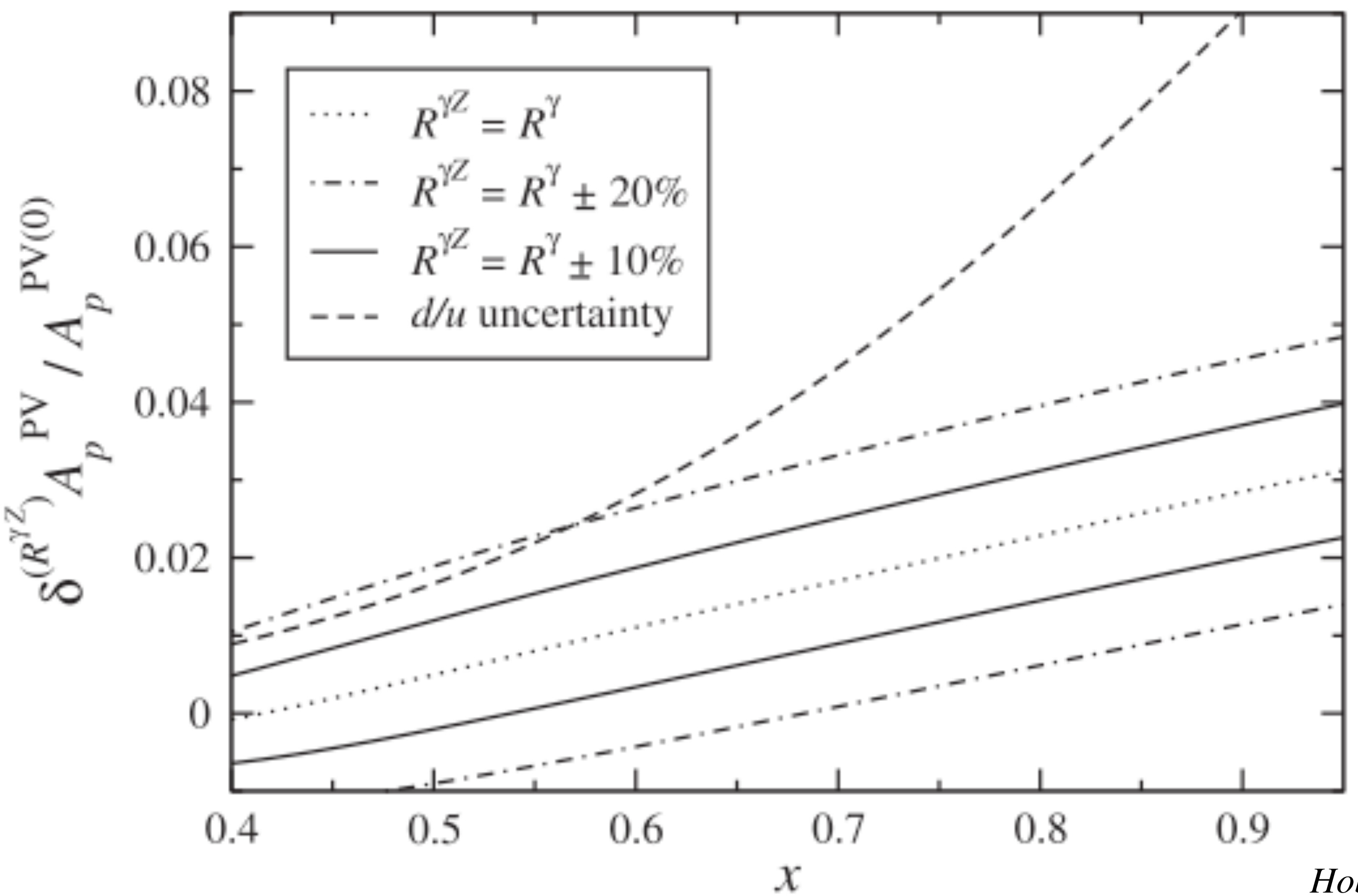
relative change to Bjorken limit asymmetry

Hobbs & Melnitchouk
Phys. Rev. D 77, 114023 (2008)

→ uncertainty due to R^γ smaller than d/u differences at large x

Parity-violating e scattering

- Sensitivity to $R^{\gamma Z}$



Hobbs & Melnitchouk
Phys. Rev. D 77, 114023 (2008)

→ correction from $R^{\gamma Z}$ needs further investigation

Target mass corrections

- Additional corrections from kinematical Q^2/ν^2 effects

  $\longrightarrow$ "target mass corrections" (TMC)

- Important at large x and low Q^2

  $\longrightarrow$ but *not unique* – depend on formalism
  ($e.g.$ OPE, collinear factorization)

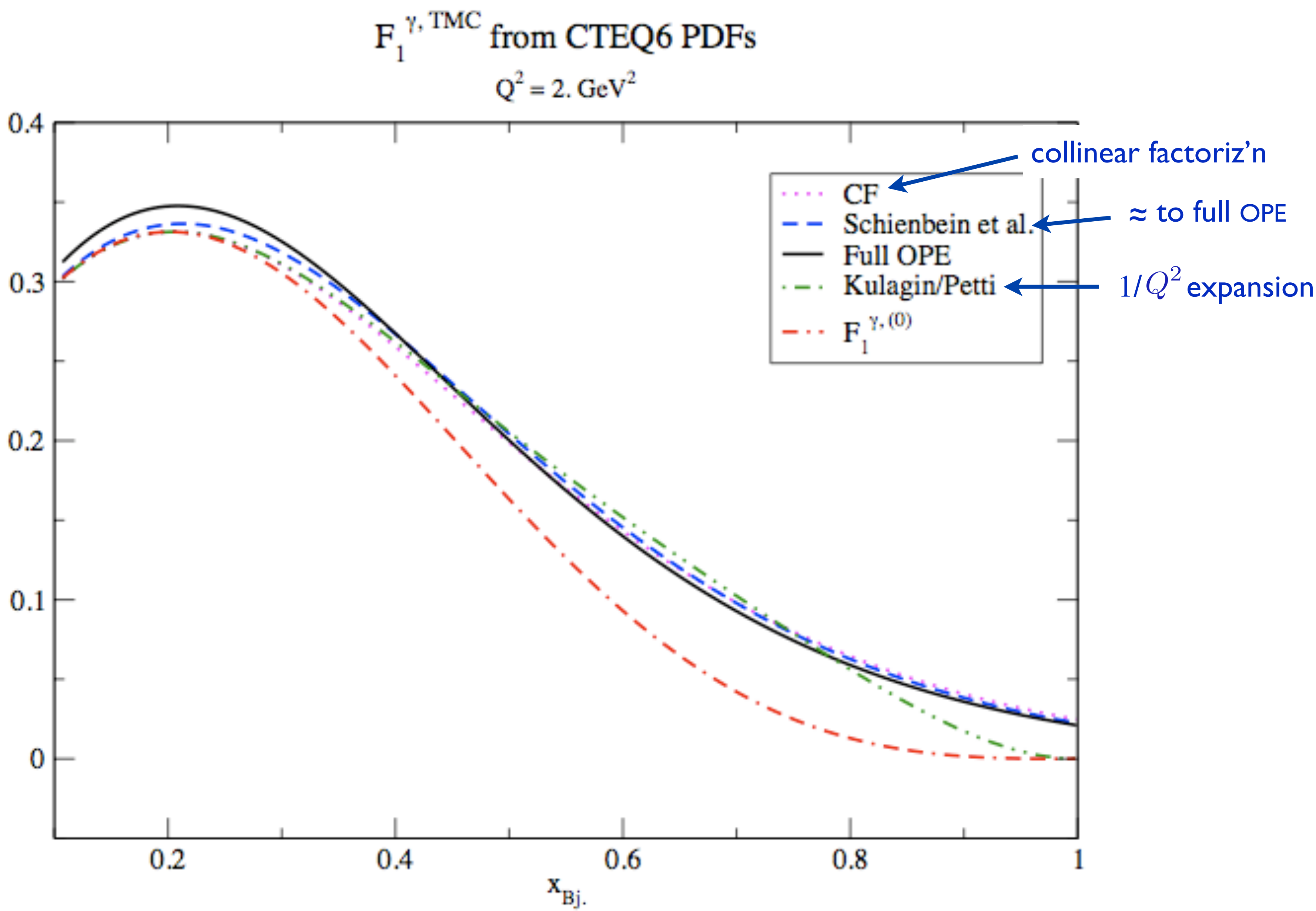
  $\longrightarrow$ most implementations exhibit "threshold problem"

$$F(x=1) \neq 0$$

  $\longrightarrow$ uncertainties not overwhelming, except at very large x

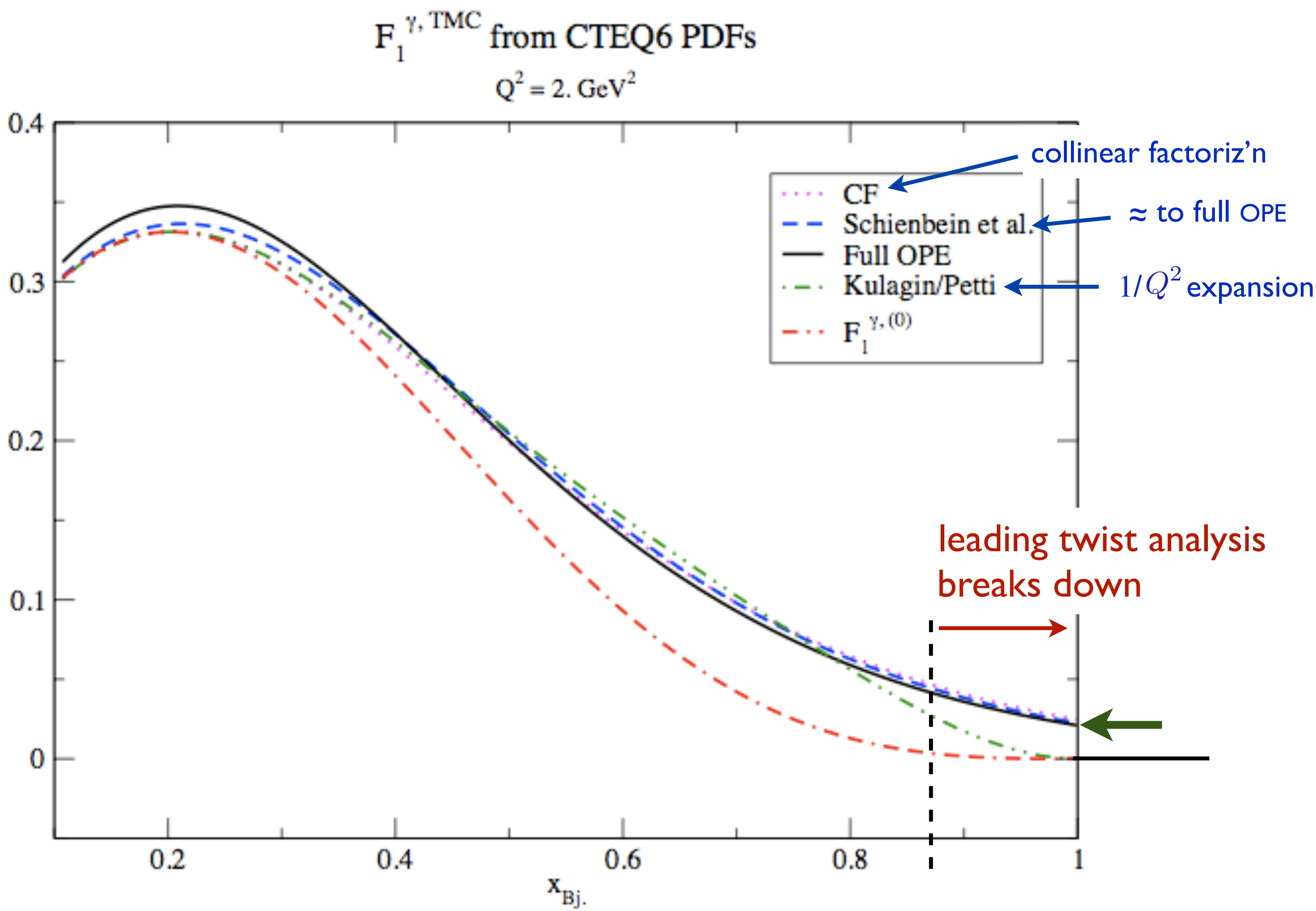
  $\longrightarrow$ new ("Nachtmann") scaling variable $\xi = \dfrac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$

Target mass corrections



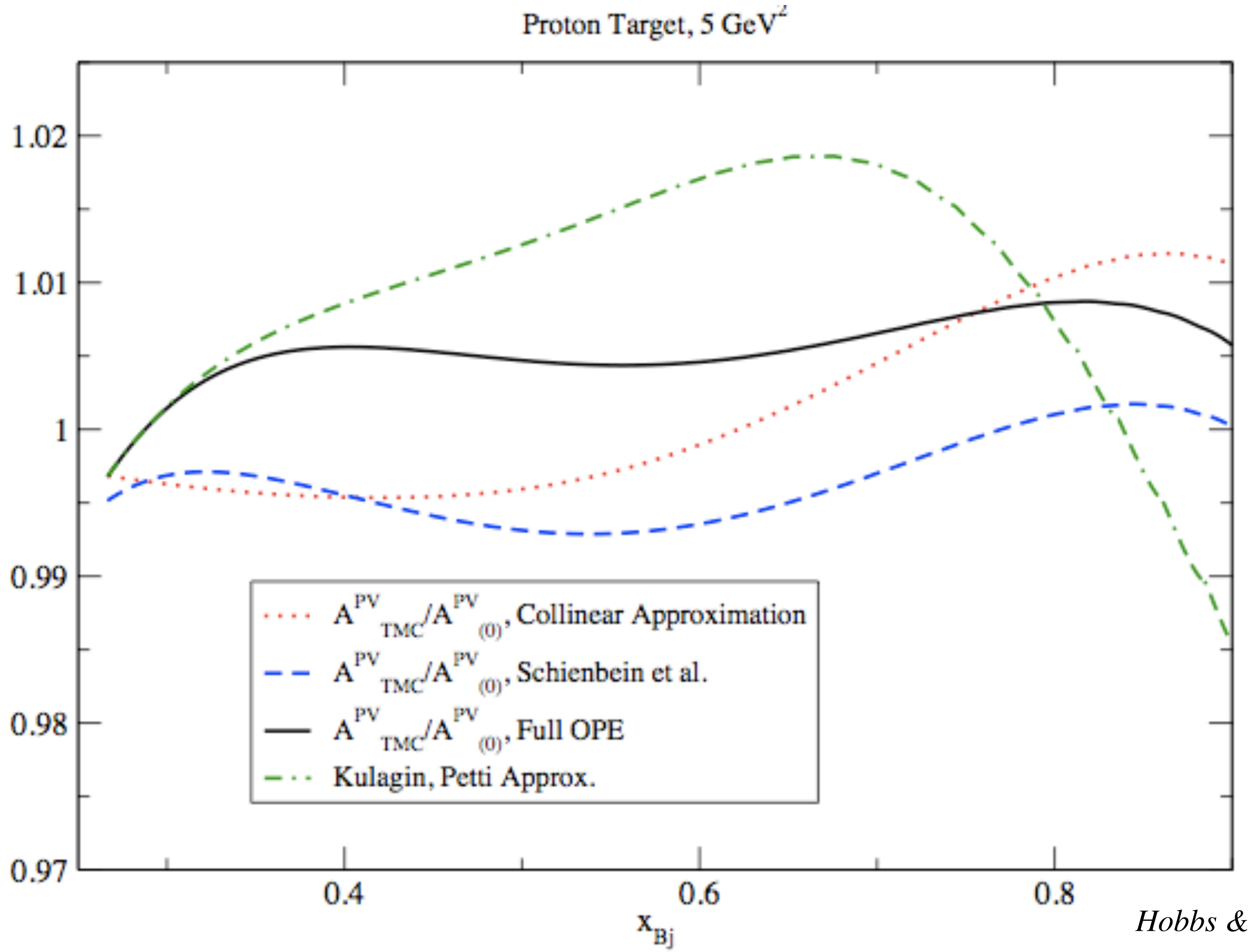
Hobbs & Melnitchouk (2008)

Target mass corrections



Hobbs & Melnitchouk (2008)

Target mass corrections

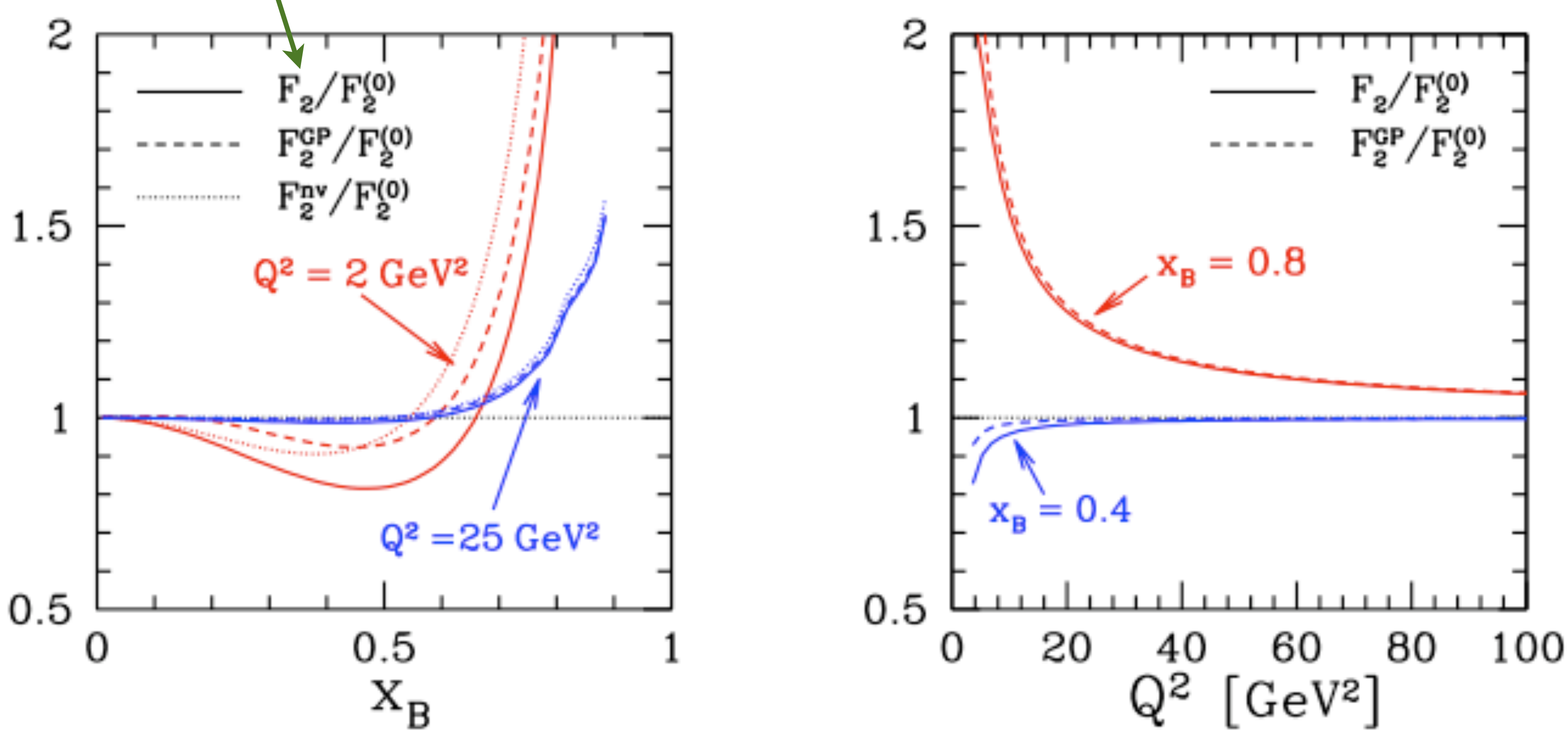


Hobbs & Melnitchouk (2008)

- → TMC effects ~ $1-2\%$ in PV asymmetry
- → larger in absolute structure functions

Target mass corrections

collinear factorization



*Accardi & Qiu, JHEP **0807**, 090 (2008)*

→ TMC important at large x even for large Q^2

Target mass corrections

- Important to implement in pQCD data analyses, if large-x (low-W) & low-Q^2 data incorporated into global PDF fits

  $\longrightarrow$ greatly expanded data set, especially with high-precision JLab data

- Currently working with CTEQ (J. Owens) to study effects of TMCs on W and Q^2 cuts on data
  (A. Accardi, E. Christy, C. Keppel, P. Monaghan)

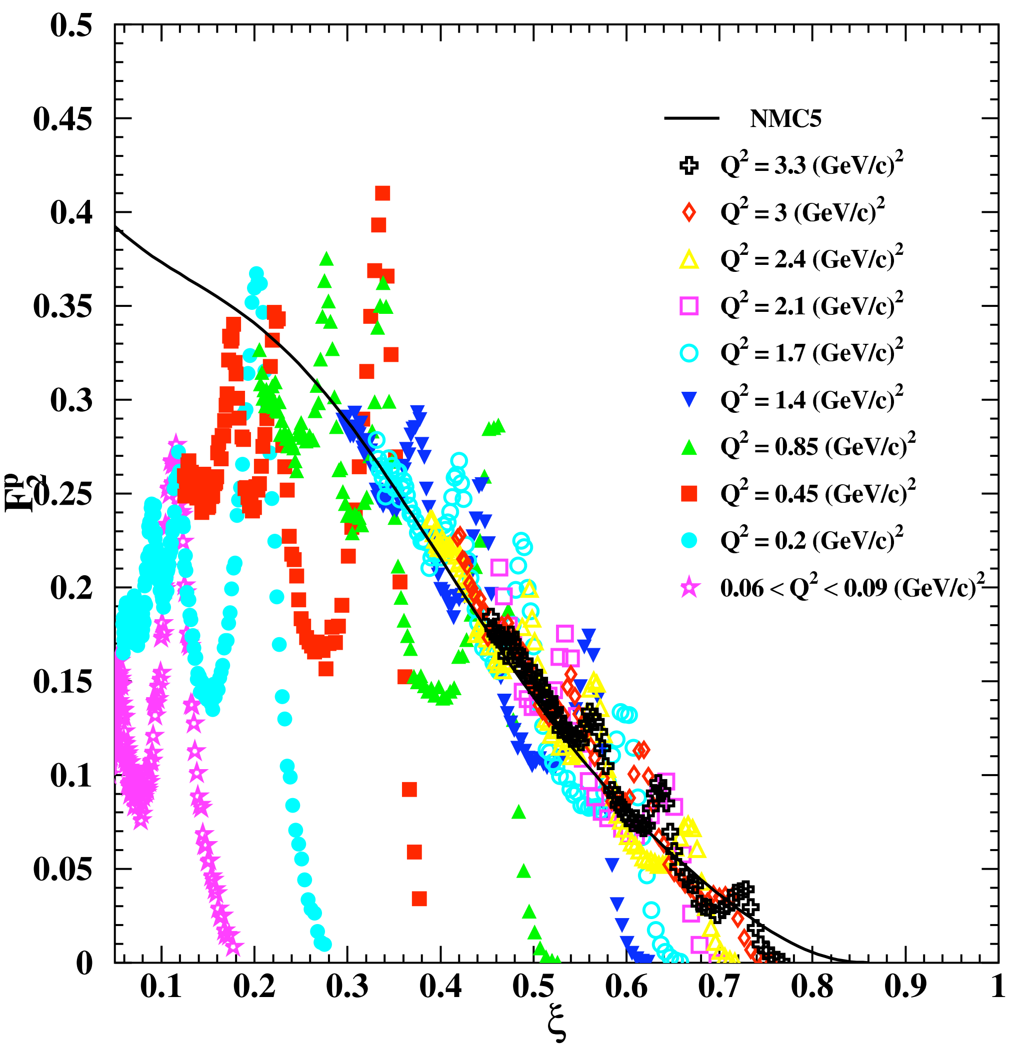
  $\longrightarrow$ crucial for neutrino scattering and oscillations

  $\longrightarrow$ important for "new physics" searches at colliders

Duality & truncated moments

(with Ales Psaker et al.)

Bloom-Gilman duality



Jefferson Lab (Hall C)

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

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

Truncated moments

- complete moments can be studied in QCD via twist expansion

  → Bloom-Gilman duality has a precise meaning

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

- for local duality, difficult to make rigorous connection with QCD

  → *e.g.* need prescription for how to average over resonances

- *truncated* moments allow study of restricted regions in x (or W) within QCD 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

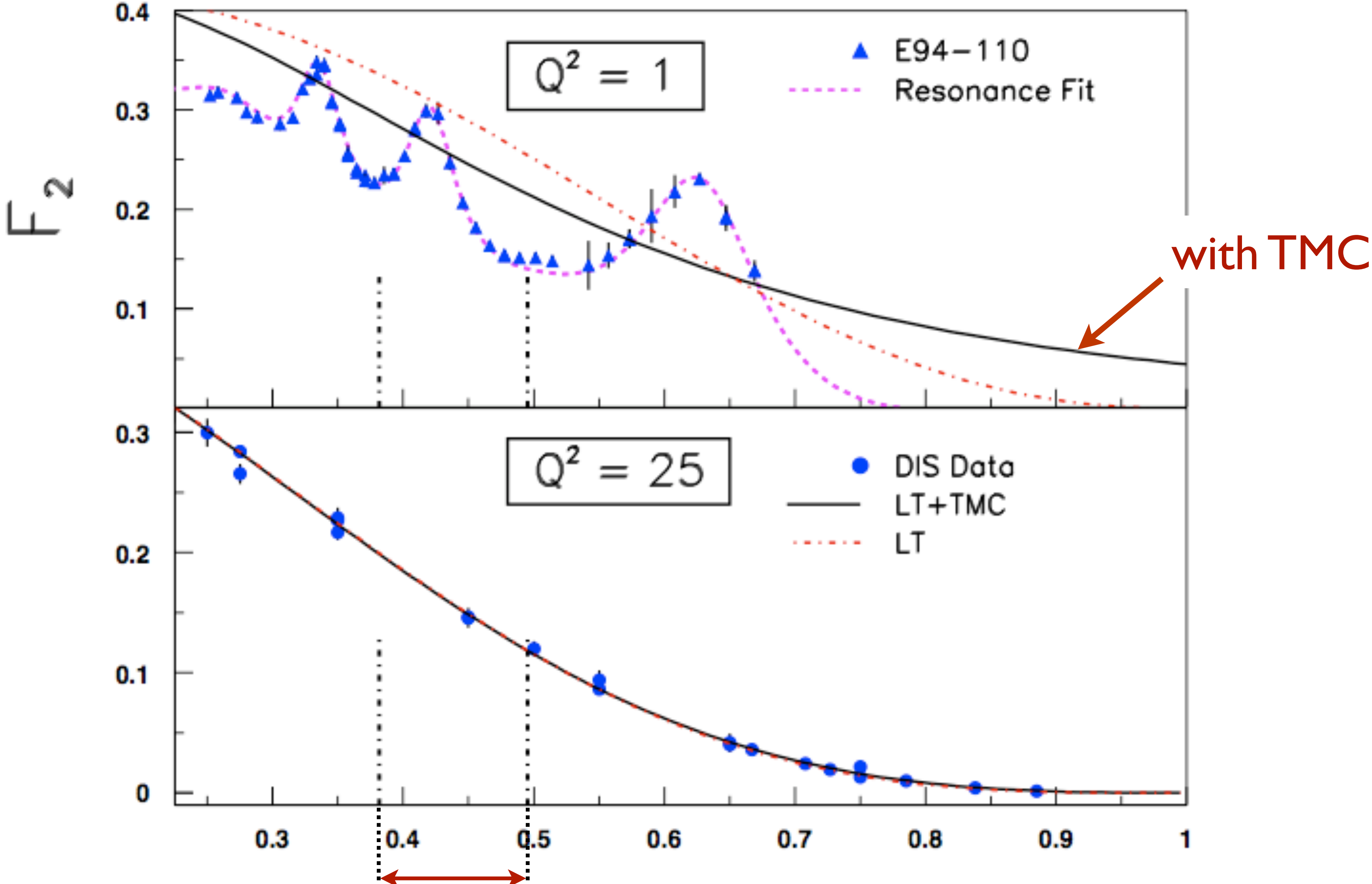
$$\frac{d\overline{M}_n(\Delta x, Q^2)}{d\log Q^2} = \frac{\alpha_s}{2\pi}\left(P'_{(n)} \otimes \overline{M}_n\right)(\Delta x, Q^2)$$

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



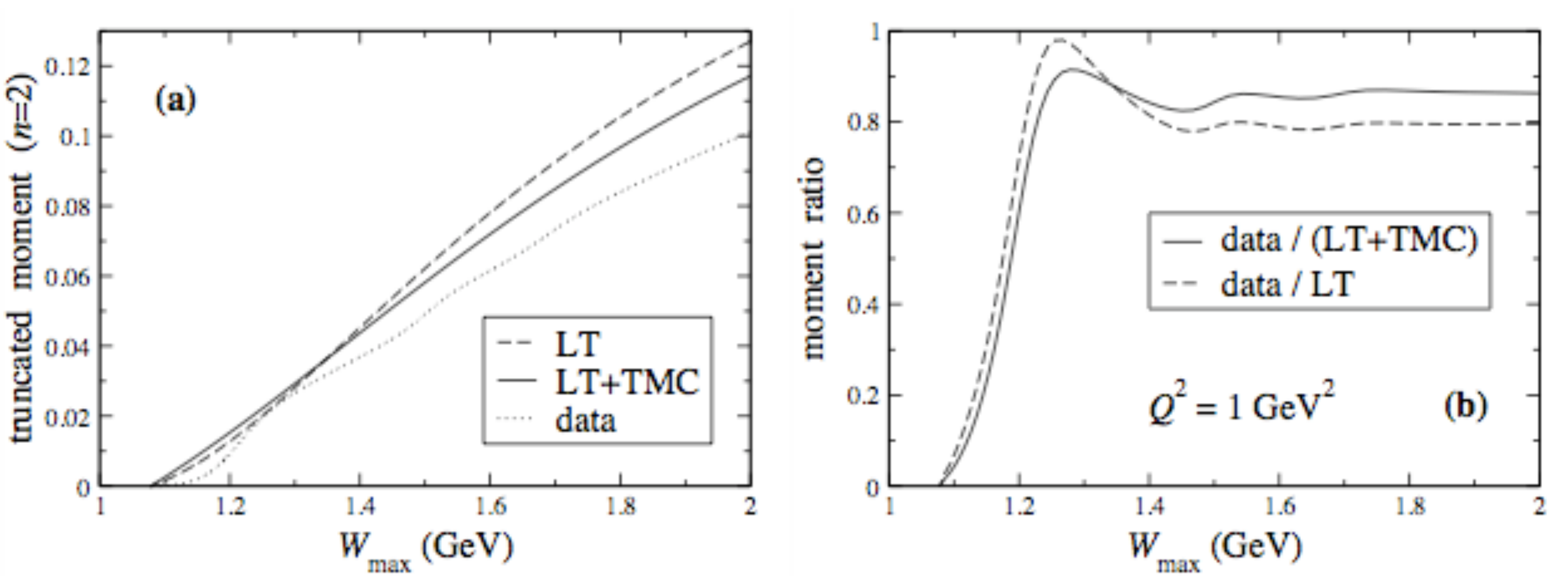
how much of this region is leading twist ?

Psaker et al., arXiv:0803.2055, Phys. Rev. C (2008)

Data analysis

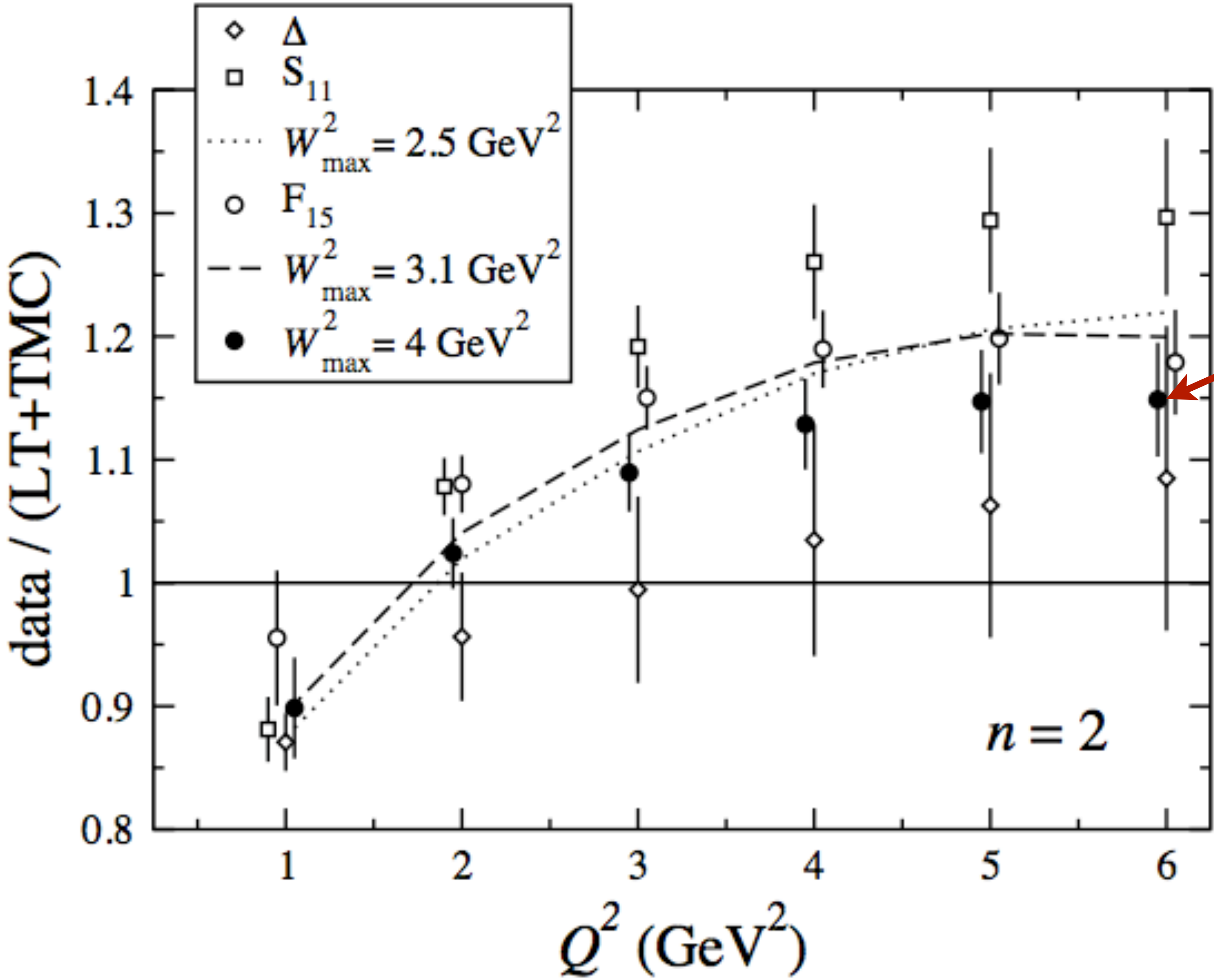
- assume data at large Q^2 is entirely leading twist
- evolve fit to data (as NS) at large Q^2 down to lower Q^2

$\longrightarrow$ apply TMC, and compare with data at lower Q^2



Psaker et al., arXiv:0803.2055, Phys. Rev. C (2008)

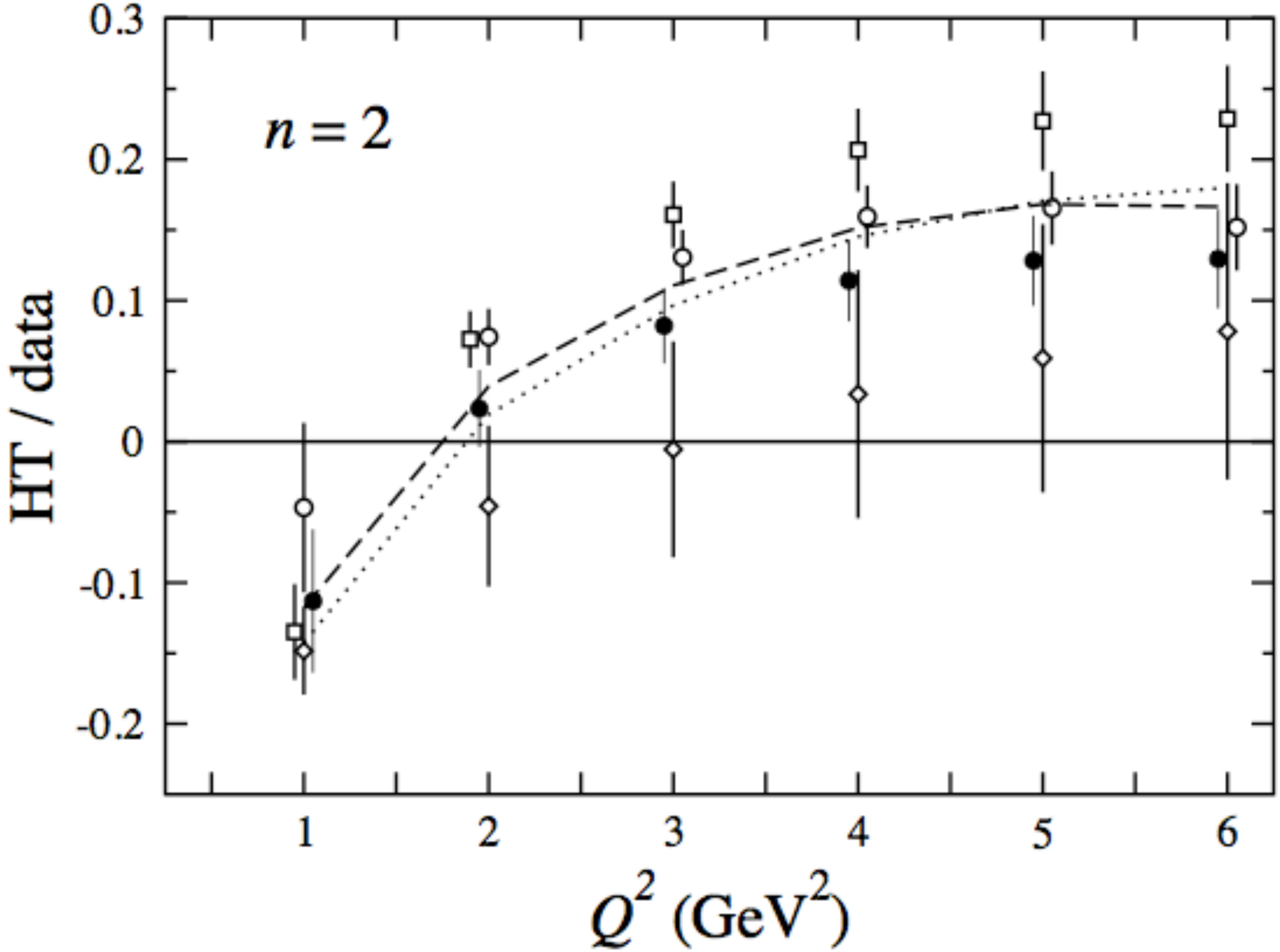
Data analysis



entire resonance region

Psaker et al., arXiv:0803.2055

Data analysis



Psaker et al., arXiv:0803.2055

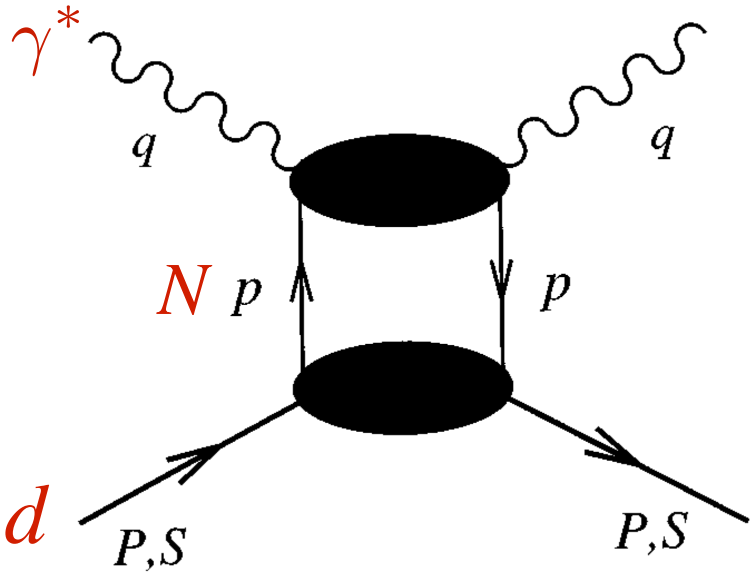
→ higher twists less than 10–15% for n=2 moment

→ also study higher twists in higher moments

Extracting neutron SFs from nuclear data

(with Yoni Kahn)

EMC effect in deuteron



Nuclear "impulse approximation"

⇒ incoherent scattering from individual nucleons in deuteron

$$F_2^d(x) = \int dy\ f_{N/d}(y)\ F_2^N(x/y)\ + \delta^{(\text{off})} F_2^d(x)$$

nucleon momentum distribution
("smearing function")

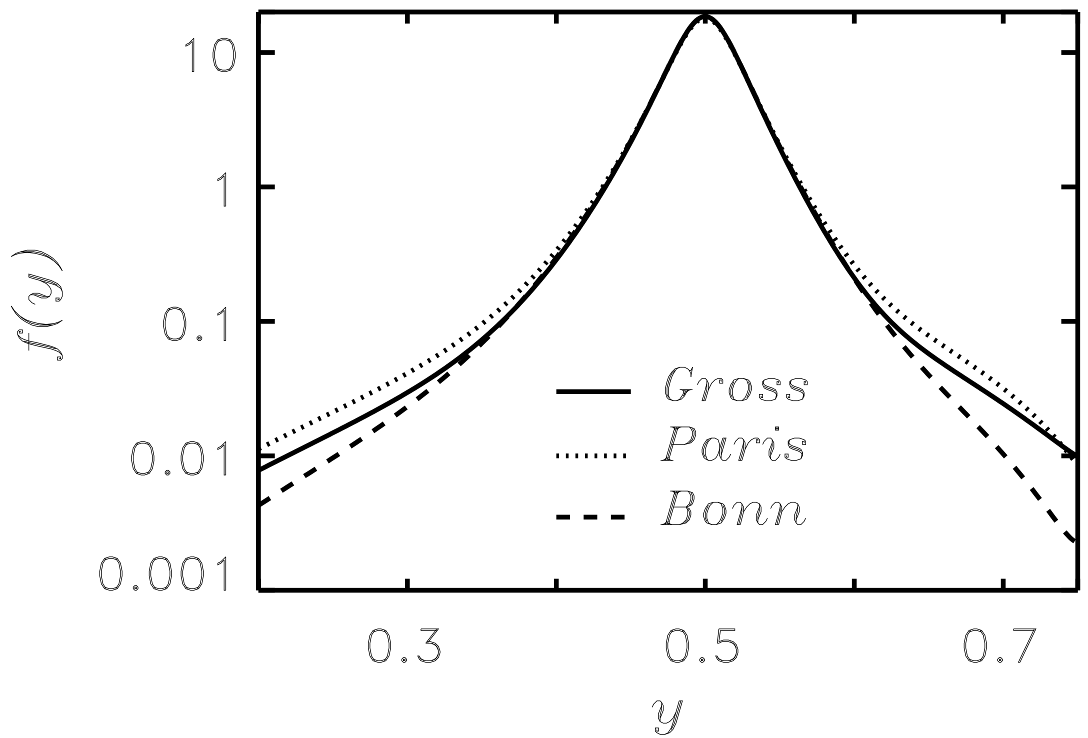
off-shell correction
(very small in d)

EMC effect in deuteron

Nucleon momentum distribution in deuteron

➡ computed from d wave function

$$f_{N/d}(y) = \frac{1}{4} M_d \; y \int_{-\infty}^{p^2_{\max}} dp^2 \, \frac{E_p}{p_0} \left| \Psi_d(\vec{p}^{\,2}) \right|^2$$



EMC effect in deuteron

- At finite Q^2, smearing function depends also on parameter

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

$\longrightarrow$ simple factorization of convolution formula breaks down

- For polarized SFs, have mixing between g_1 & g_2 at finite Q^2

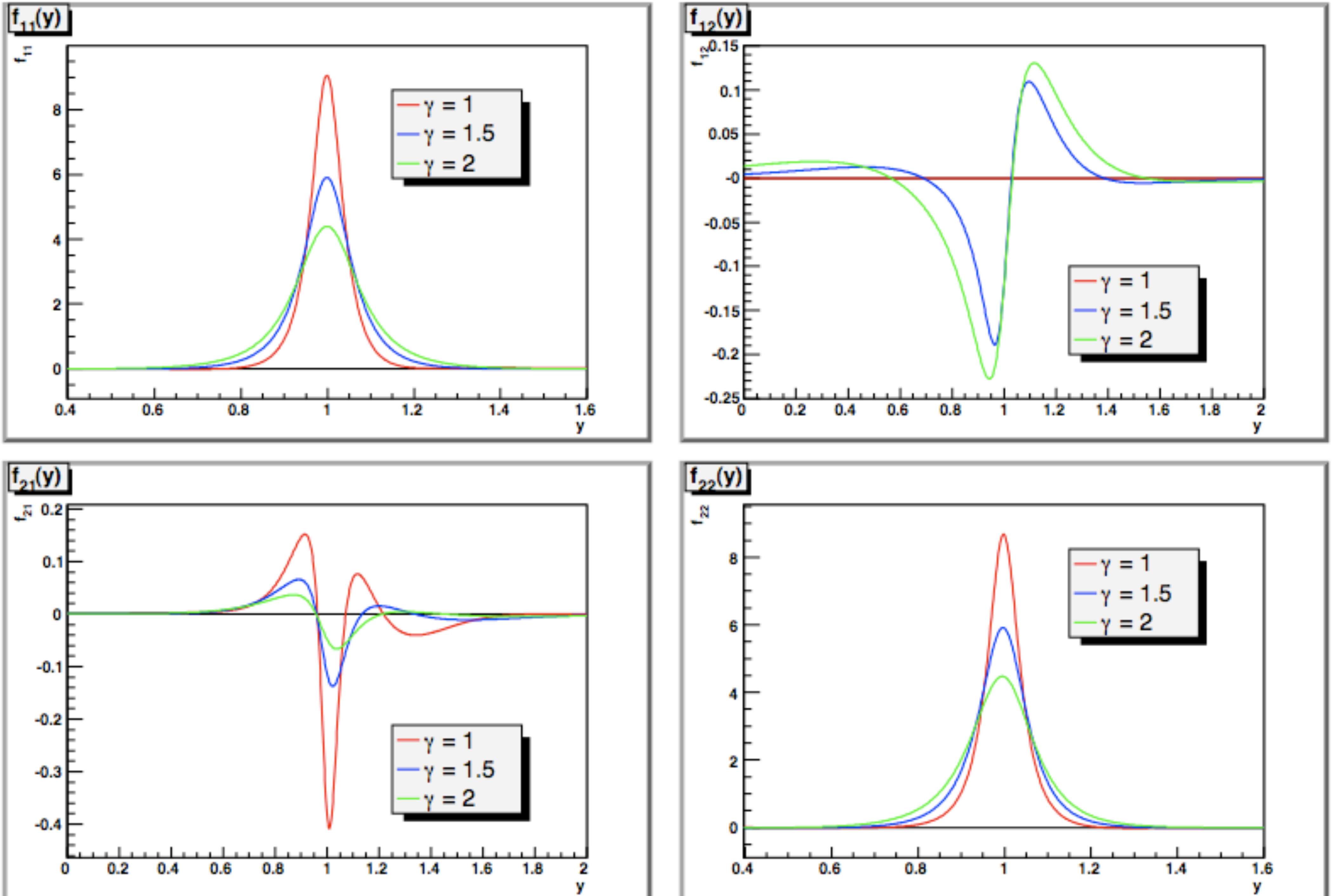
$$g_i^d(x, Q^2) = \int \frac{dy}{y} f_{ij}(y, \gamma)\ g_j^N(x/y, Q^2)\ , \qquad i, j = 1, 2$$

$\longrightarrow$ for most kinematics $\gamma \lesssim 2$

$\longrightarrow$ off diagonal functions small $|f_{12}|, |f_{21}| \ll f_{11}, f_{22}$

Kulagin, Melnitchouk
Phys. Rev. C ***77****, 015210 (2008)*

N momentum distributions in *d*



Unsmearing – multiplicative method

- calculated d/N ratio depends on input F_2^n

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

Solution: iteration procedure

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

1. smear F_2^p with $f_{N/d}$: $f_{N/d} \otimes F_2^p \equiv S_p^{-1} F_2^p$

2. extract neutron via $F_2^n = S_n (F_2^d - F_2^p / S_p)$

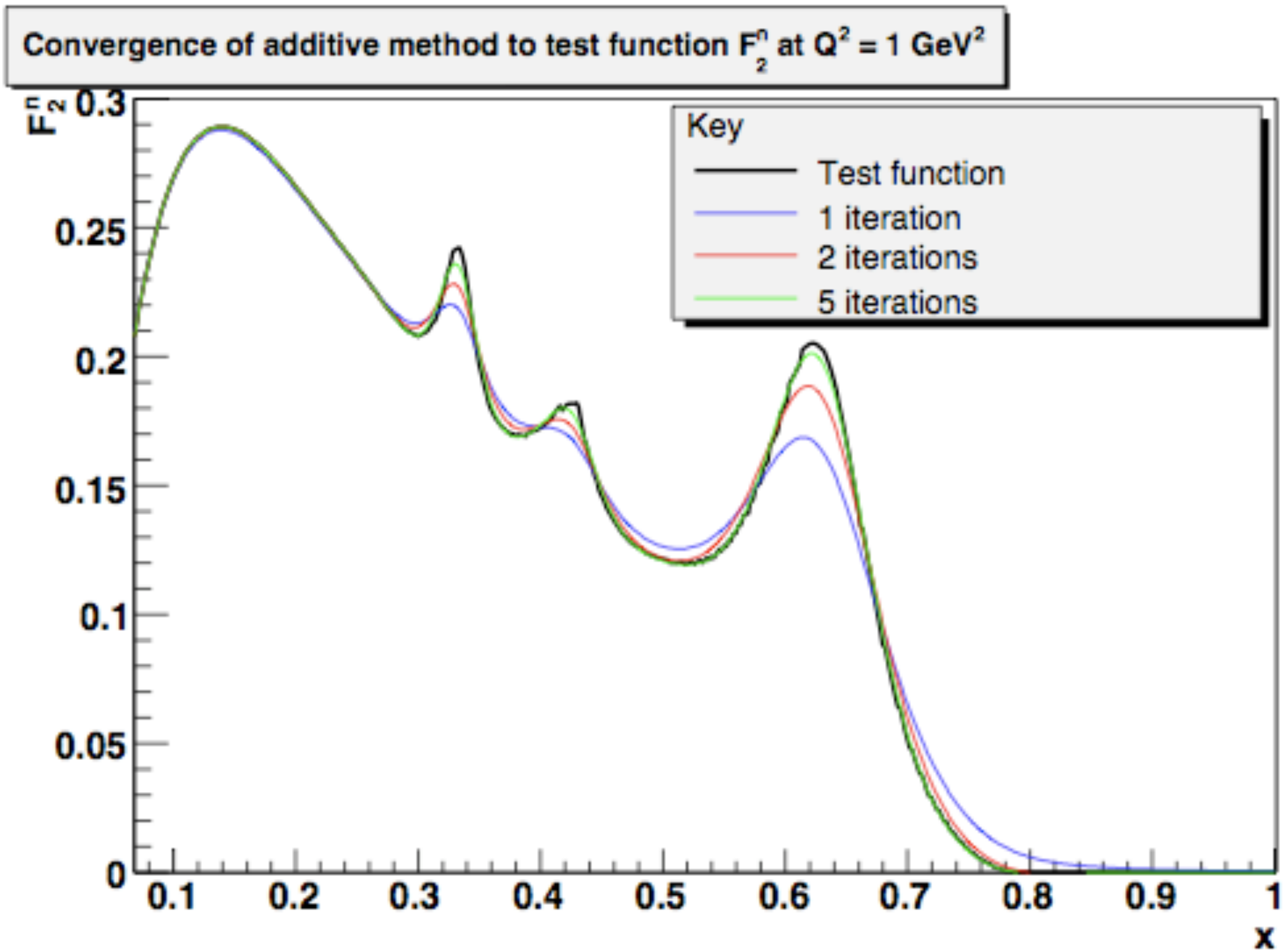
   starting with $e.g.$ $S_n = S_p$

3. smear F_2^n with $f_{N/d}$ to get new S_n

4. repeat 2-3 until convergence

Unsmearing – multiplicative method

- F_2^d constructed from F_2^p and F_2^n inputs
  (using Bosted/Christy parameterizations)



Kahn, WM (2008)

Unsmearing – additive method

- since g_1 & g_2 are not positive-definite, expect multiplicative method to fail for spin-dependent SFs

Solution: additive iteration procedure (avoids zeros)

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

$$\widetilde{F}_2^n = f_{N/d} \otimes F_2^n = F_2^n + \delta$$

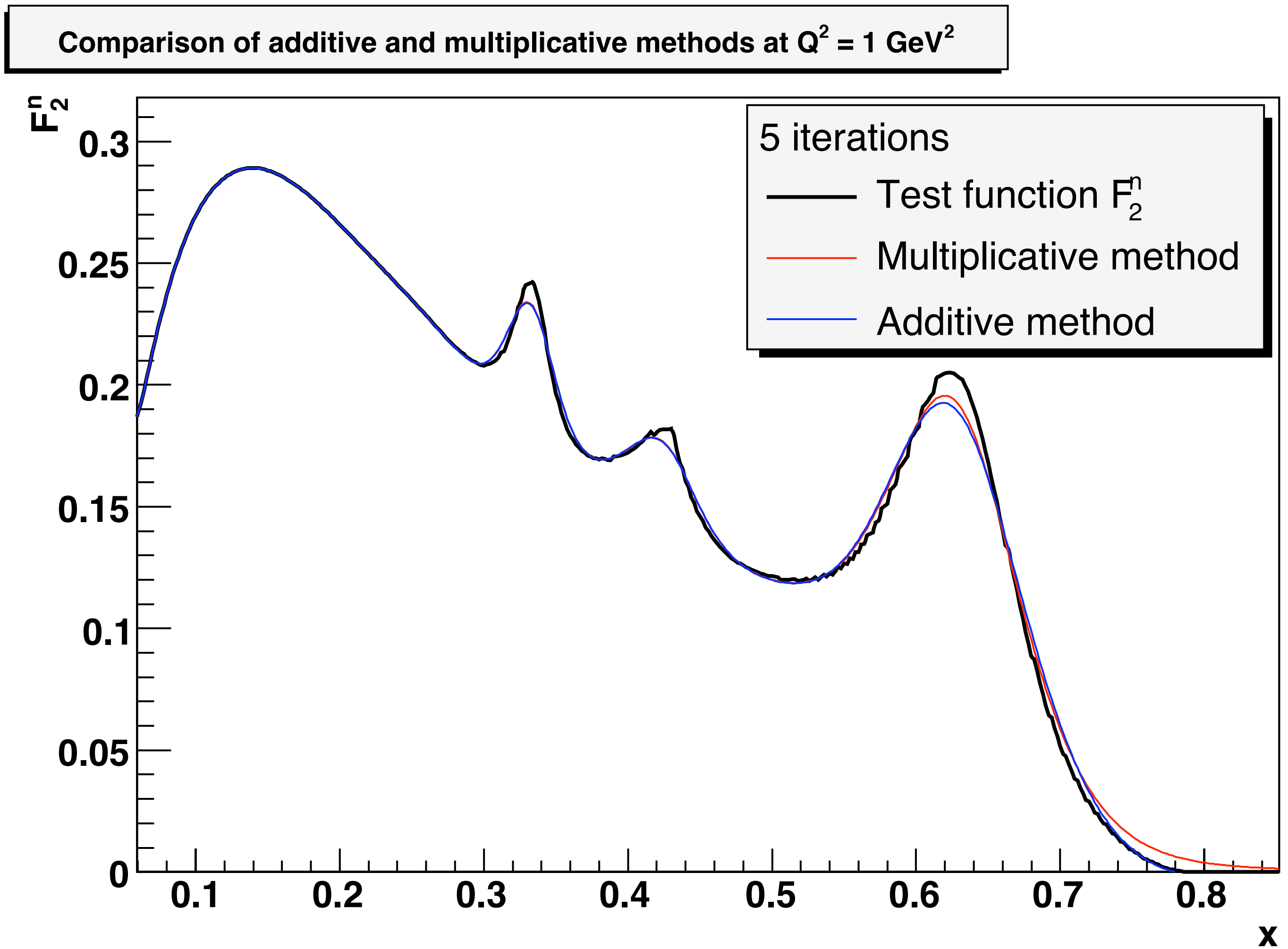
2. first guess for $F_2^{n(0)}$ $\longrightarrow$ $\delta^{(0)} = \widetilde{F}_2^{n(0)} - F_2^{n(0)}$

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

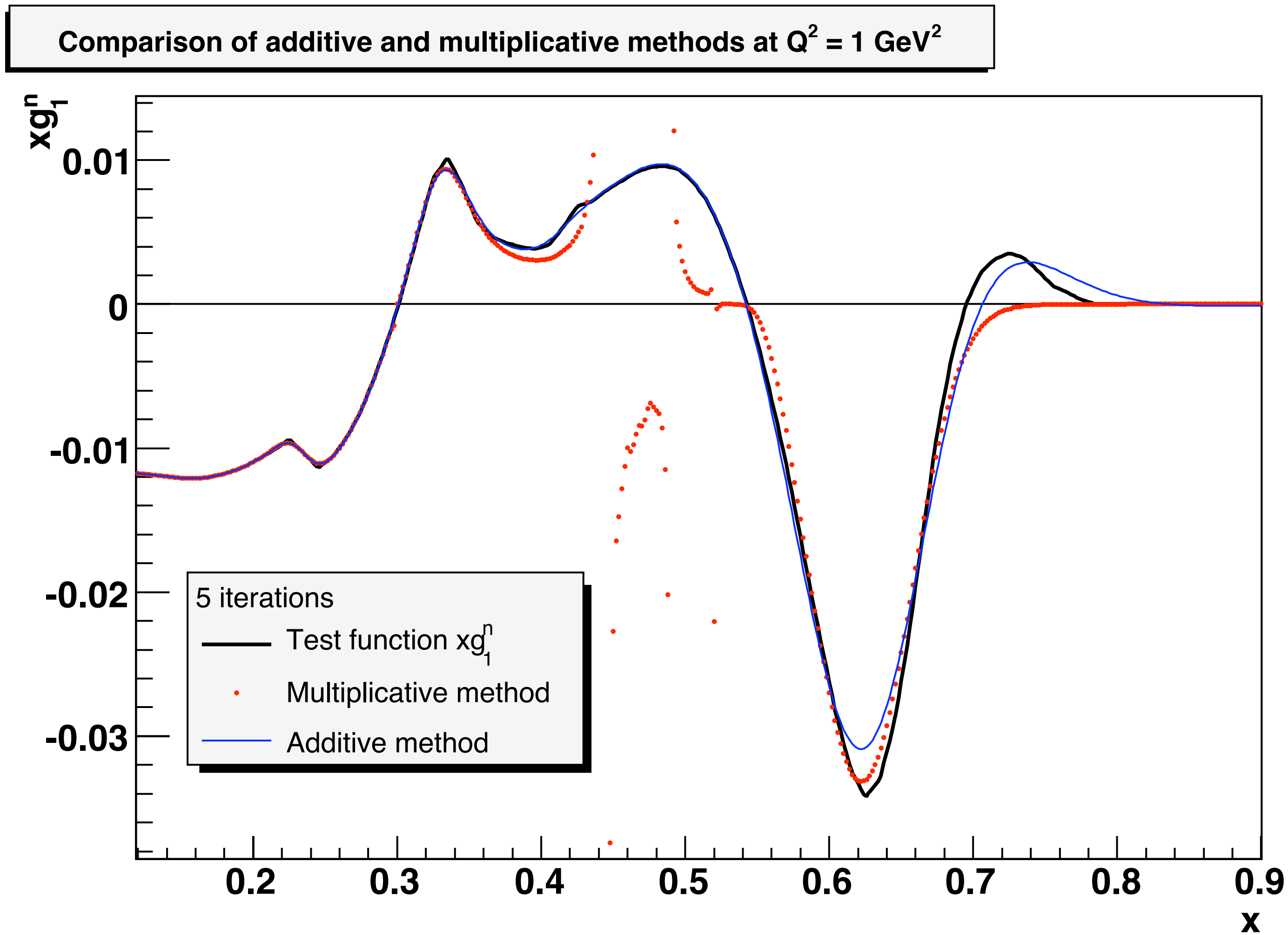
Unsmearing – additive vs. multiplicative



Kahn, WM (2008)

→ both methods work well for unpolarized SFs

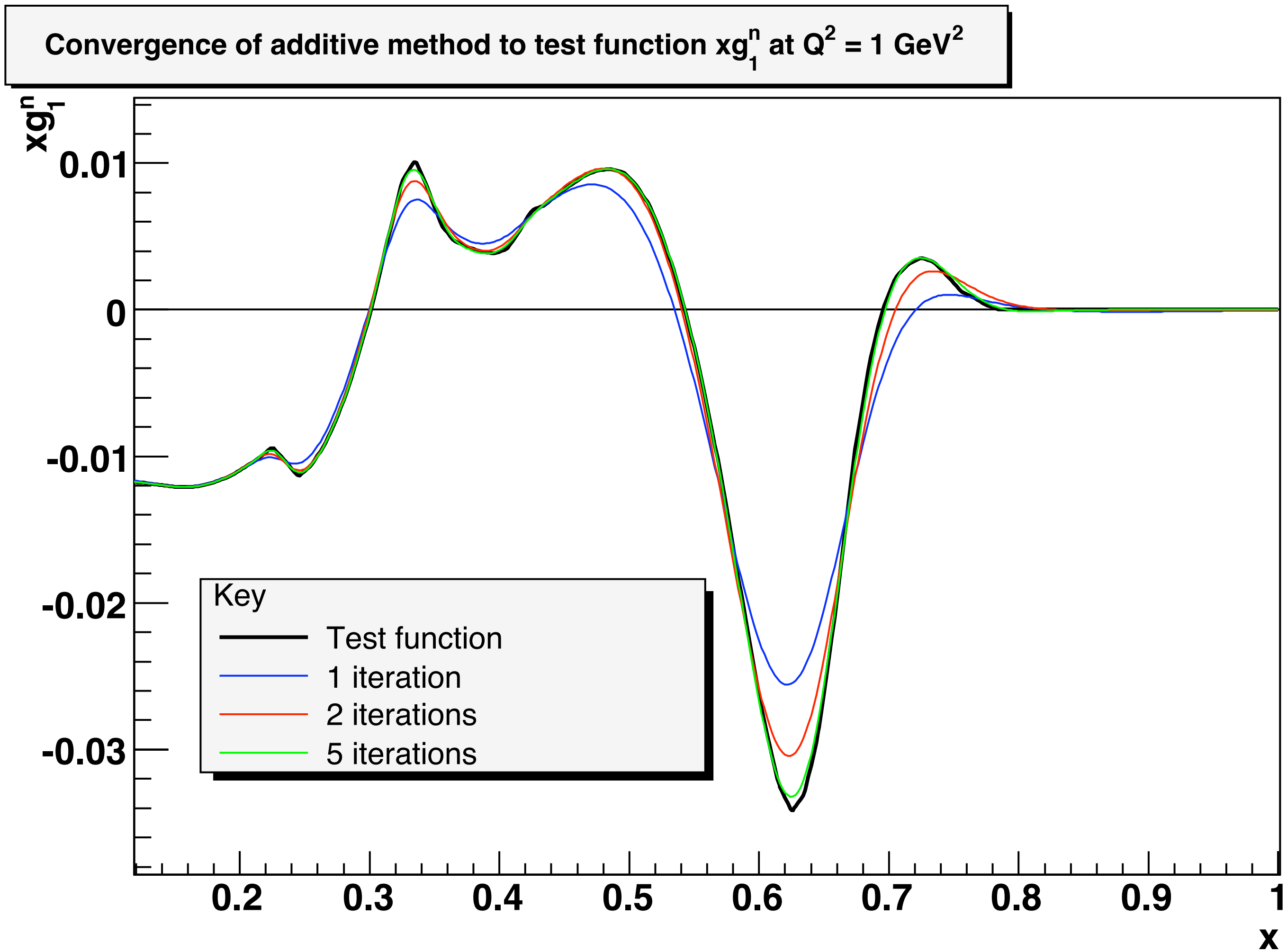
Unsmearing – additive vs. multiplicative



Kahn, WM (2008)

→ multiplicative method problematic for polarized SFs

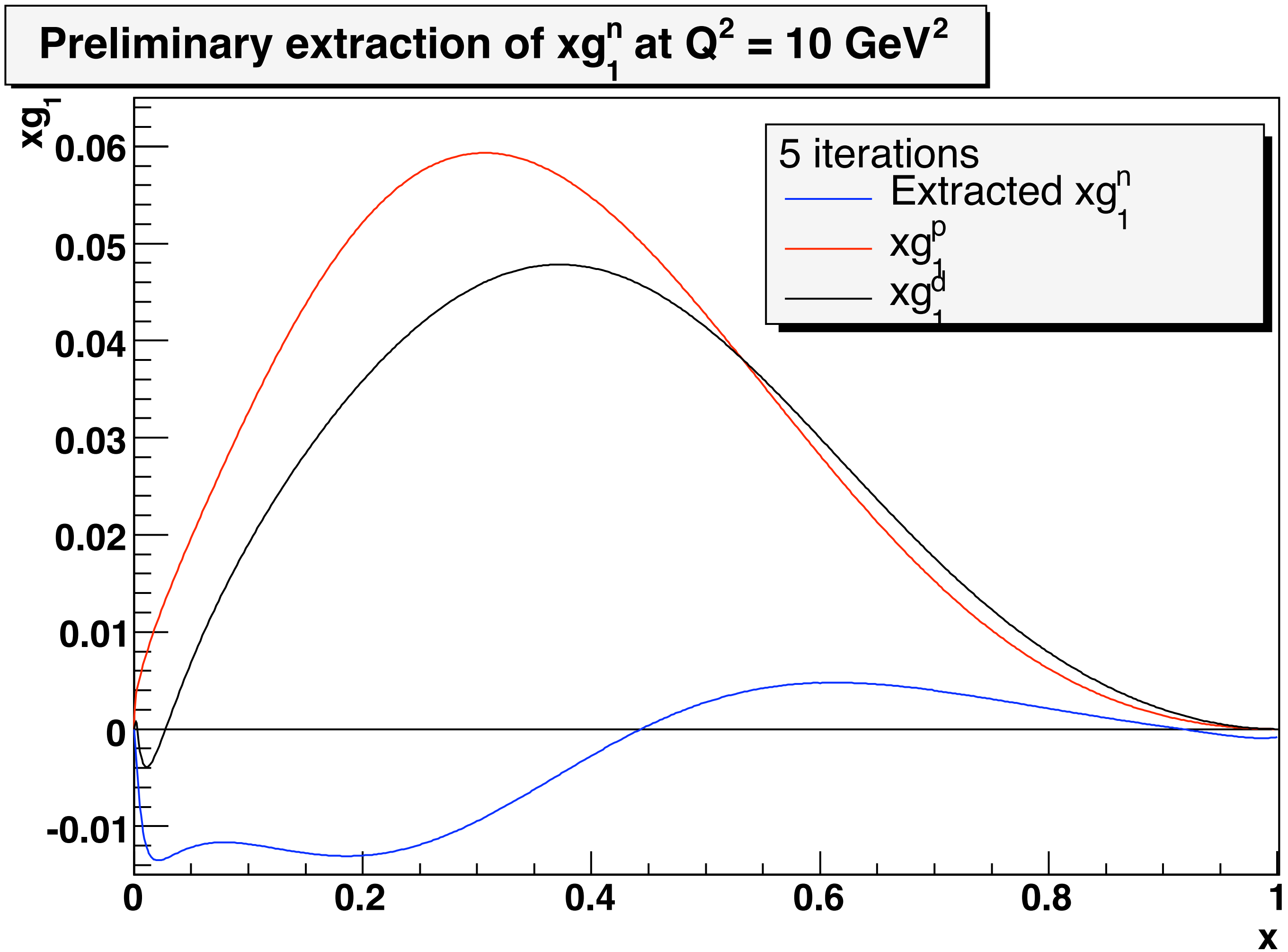
Unsmearing – additive method



Kahn, WM (2008)

→ additive method works well for polarized SFs

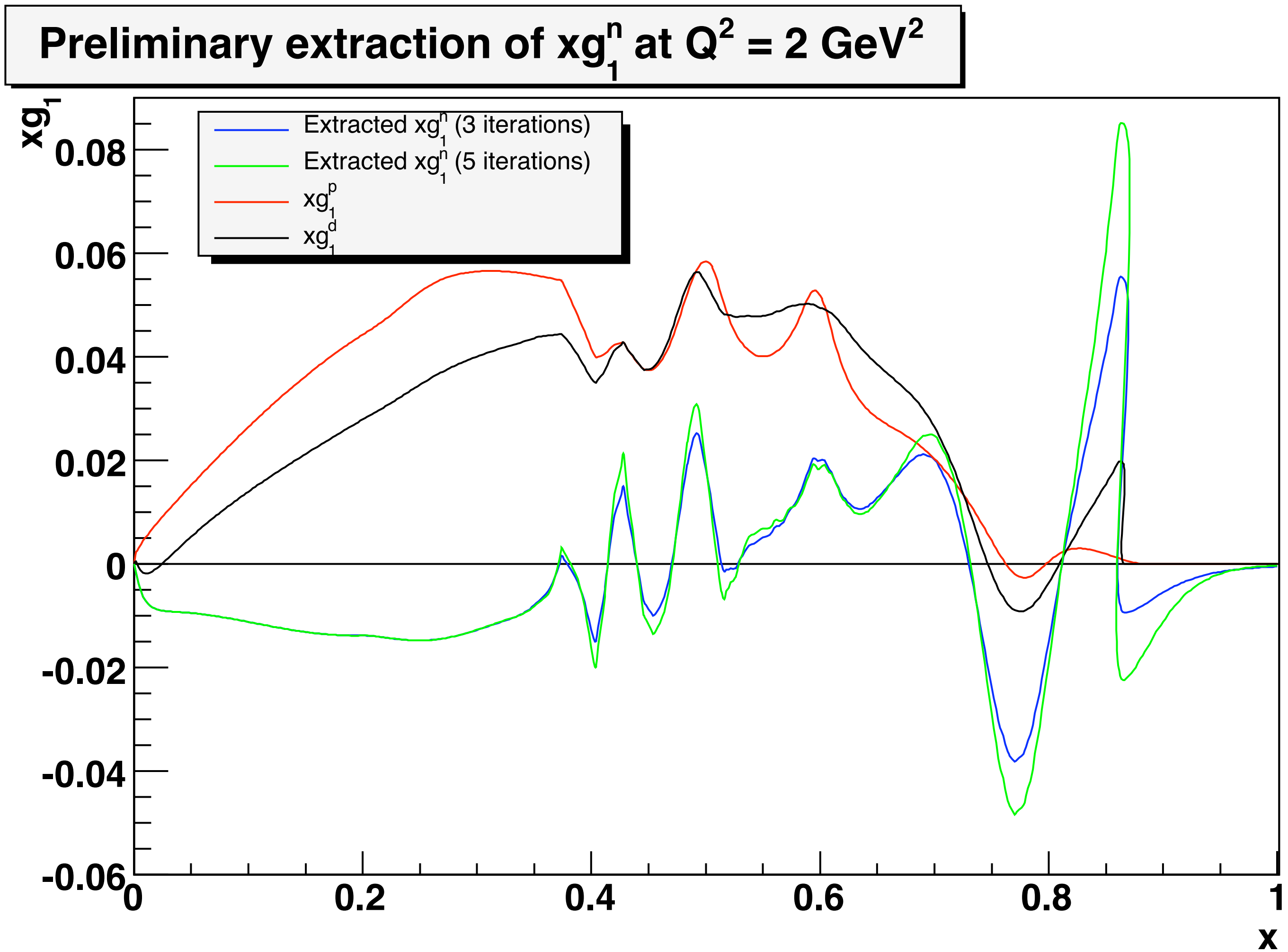
Unsmearing – additive method



Kahn, WM (2008)

→ additive method works well for polarized SF data at large Q^2

Unsmearing – additive method



Kahn, WM (2008)

→ extraction sensitive to discontinuities in *d* data

→ *cf.* future RSS data

Summary

- Fundamental questions remain to be addressed at large x
- Need to account for finite-Q^2 effects in PVDIS
  - $\longrightarrow$ quantify effects of $R^{\gamma Z}$, as well as higher twists
- Target mass corrections
  - $\longrightarrow$ joint analysis with CTEQ of global data under way
  - $\longrightarrow$ TMCs in polarized structure functions
- Truncated moments
  - $\longrightarrow$ firm foundation for study of local duality in QCD
  - $\longrightarrow$ higher twists $< 10\%$ for $Q^2 > 1$ GeV^2 in resonance region
- New method for extracting neutron SFs from nuclear data
  - $\longrightarrow$ await higher-precision nuclear data!

The End