Nuclear modification of nucleon structure functions

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Outline

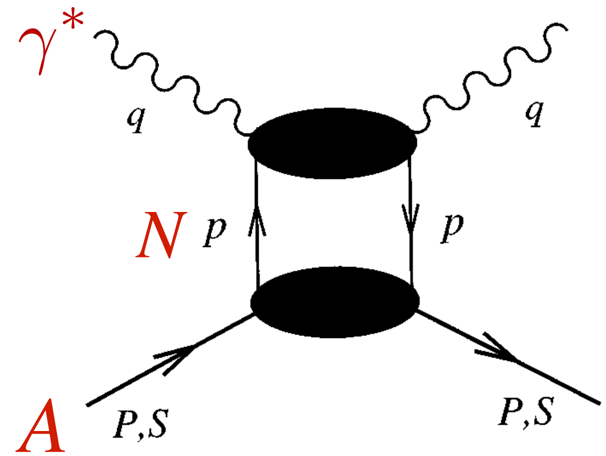
- Nuclear ($\rightarrow$ deuteron) structure functions
  - $\rightarrow$ smearing functions & quasielastic scattering
  - $\rightarrow$ nucleon off-shell effects
  - $\rightarrow$ nuclear effects on neutron structure function
- Extraction of neutron resonance structure from nuclear data
  - $\rightarrow$ new "unsmearing" method
  - $\rightarrow$ quark-hadron duality
  - $\rightarrow$ constraints on off-shell effects from local duality, SRCs
- Outlook

Nuclear structure functions

Nuclear structure functions

- Incoherent scattering from nucleons in nucleus A $(x \gg 0)$

$$W^A_{\mu\nu}(P,q) = \int d^4p\,\mathrm{Tr}\left[\widehat{\mathcal{A}}(P,p)\cdot\widehat{W}^N_{\mu\nu}(p,q)\right]$$



$\longrightarrow$ truncated (off-shell) nucleon tensor

$$\widehat{W}^N_{\mu\nu}(p,q) = g_{\mu\nu}\left(I\,\widehat{W}_0 + \not{p}\,\widehat{W}_1 + \not{q}\,\widehat{W}_2\right)$$

bound nucleon "structure functions"

$\longrightarrow$ (off-shell) nucleon$-$nucleus scattering amplitude

$$\widehat{\mathcal{A}}(P,p) = I\,\mathcal{A}_S + \gamma_\alpha\,\mathcal{A}^\alpha_V$$

scalar, vector amplitudes include sum over residual $A{-}1$ nuclear states

Nuclear structure functions

- (Spin-averaged) structure function of nucleus given by sum of *three* terms

$$F_2^A = \int d^4p \left(\mathcal{A}_S \widehat{W}_0 + p \cdot \mathcal{A}_V \widehat{W}_1 + q \cdot \mathcal{A}_V \widehat{W}_2 \right)$$

$\longrightarrow$ cannot be written (in general) as 1-dimensional convolutions:

$$\boxed{\begin{array}{l}\text{factorization of amplitudes}\\ \not\Rightarrow \text{ factorization of structure functions}\end{array}}$$

WM, Schreiber, Thomas, PRD ***49****, 1183 (1994)*

- Taking selective on-shell or nonrelativistic limits, one *can* identify convolution component *plus* off-shell corrections

$$F_2^A = \sum_N f_{N/A} \otimes F_2^N \; + \; \delta^{(\mathrm{off})} F_2$$

nucleon (light-cone) momentum distribution
("smearing function")

Deuteron structure functions

- For *deuteron*, nucleon momentum distribution can be computed "exactly" (relativistically or nonrelativistically), and form of off-shell corrections identified

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

WM, Schreiber, Thomas, PLB ***335****, 11 (1994)*
Kulagin, Piller, Weise, PRC ***50****, 1154 (1994)*

with relativistic ("MST") smearing function

$$f_{N/d}(y) = \frac{M_d^2}{2M} \int \frac{d^3p}{(2\pi)^3} \frac{y}{p_0} \theta(p_0)\, \delta\left(y - \frac{p_0 + p_z}{M}\right) |\psi_d(p)|^2$$

$\longrightarrow$ at $Q^2 \to \infty$, function of light-cone momentum fraction y of d carried by N, with normalization $\int dy\, f_{N/d}(y) = 1$

Deuteron structure functions

- Expanding in powers of $\boldsymbol{p}^2/M^2$ and binding energy ε_d/M ("weak binding approximation"), smearing function reduces to

$$f_{N/d}(y,\gamma) = \int \frac{d^3p}{(2\pi)^3} \left(1 + \frac{\gamma p_z}{M}\right) \mathcal{C}(y,\gamma)\, |\psi_d(p)|^2\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

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

$\longrightarrow$ at finite Q^2, additional dependence on photon "velocity"

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

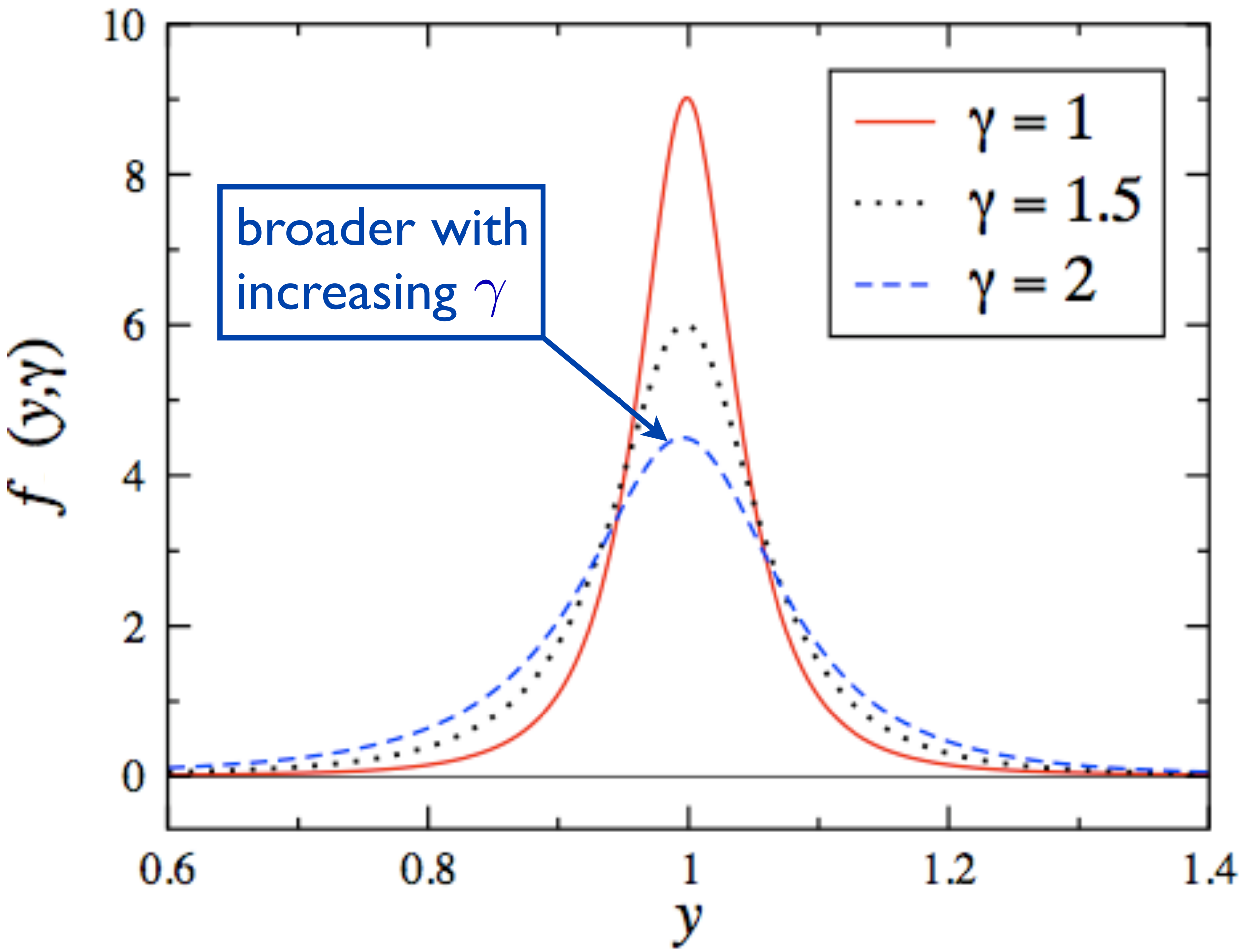
$\longrightarrow$ finite-Q^2 correction factor

$$\mathcal{C}(y,\gamma) = \frac{1}{\gamma^2}\left[1 + \frac{(\gamma^2-1)}{y^2}\left(1 + \frac{2\varepsilon}{M} + \frac{3p_\perp^2 - 2\mathbf{p}^2}{2M^2}\right)\right]$$

$\rightarrow 1 \quad \text{for} \quad \gamma \rightarrow 1$

separation energy $\varepsilon = p_0 - M$
$\approx \varepsilon_d - \mathbf{p}^2/2M$

Finite-Q^2 smearing function



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

→ for most kinematics $\gamma \lesssim 2$

→ effectively more smearing for larger x or lower Q^2

Finite-Q^2 smearing function

- Can we measure / constrain smearing function (and its Q^2 dependence) in other reactions?

  $\longrightarrow$ quasielastic electron−deuteron scattering (in IA) directly probes nucleon distribution function (multiplied by nucleon form factor)

$$F_2^{N(\mathrm{el})}(x/y, Q^2, p^2) = \left[\frac{G_{EN}^2 + \tau G_{MN}^2}{1+\tau}\right] y\,\delta(y - x/x_{\mathrm{th}})$$

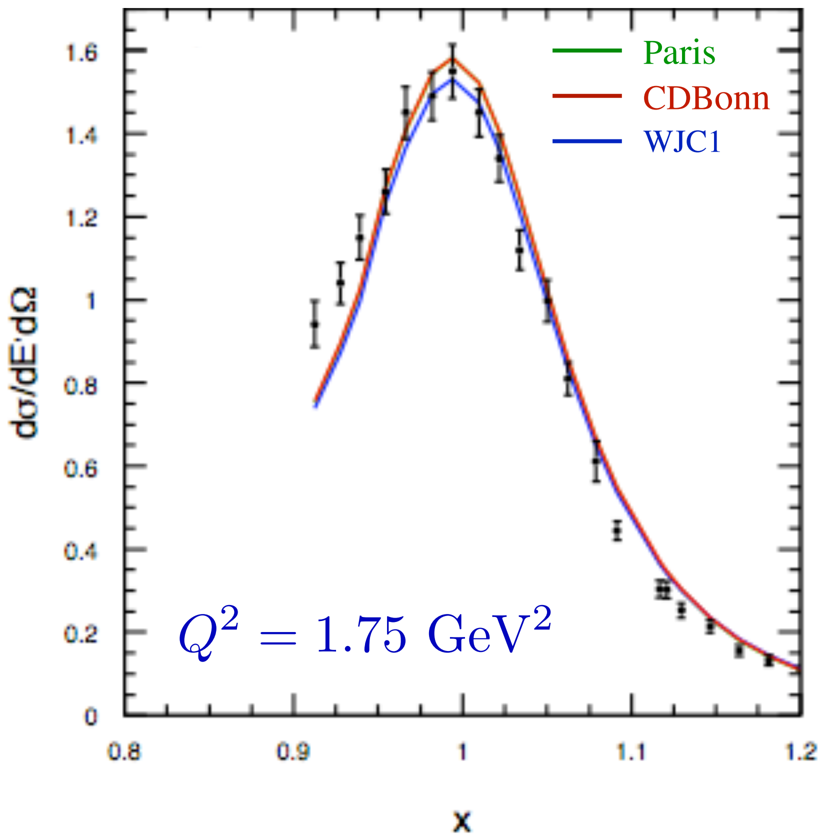
  with $x_{\mathrm{th}} = \left[1 - (p^2 - M^2)/Q^2\right]^{-1}, \ \tau = Q^2/4M^2$

  $\longrightarrow$ quasielastic contribution to deuteron structure function

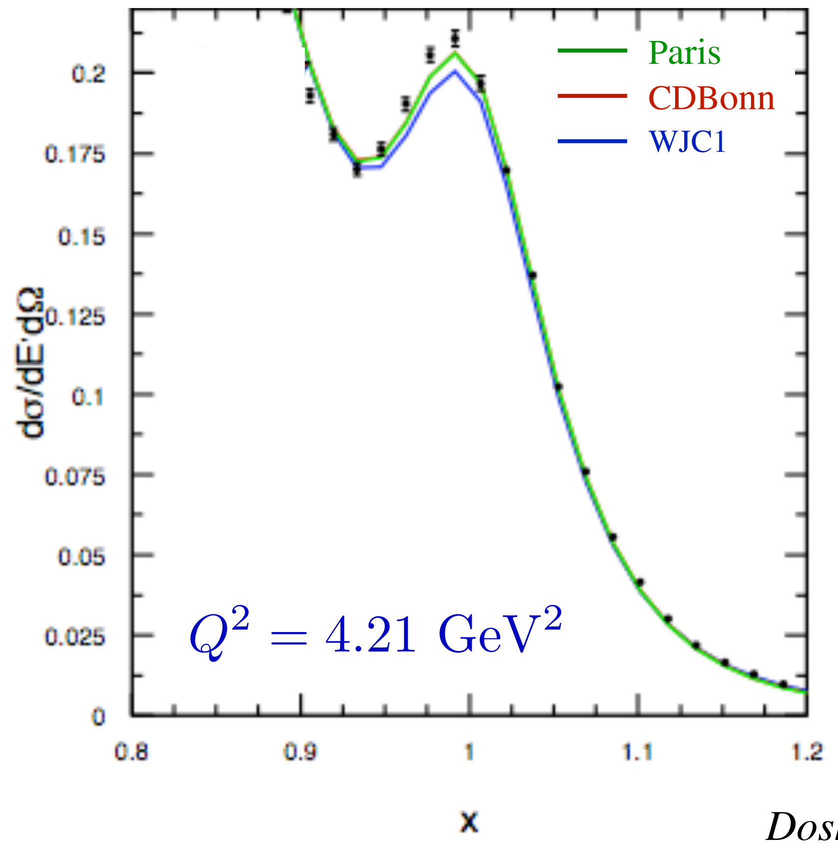
$$F_2^{d(\mathrm{QE})}(x, Q^2) \ \to \ \sum_N \left[\frac{G_E^{N2} + \tau G_M^{N2}}{1+\tau}\right] x\, f_{N/d}(x, \gamma)$$

Finite-Q^2 smearing function

Arnold et al., PRL ***61****, 806 (1988)*



Arrington et al., PRL ***82****, 2056 (1999)*



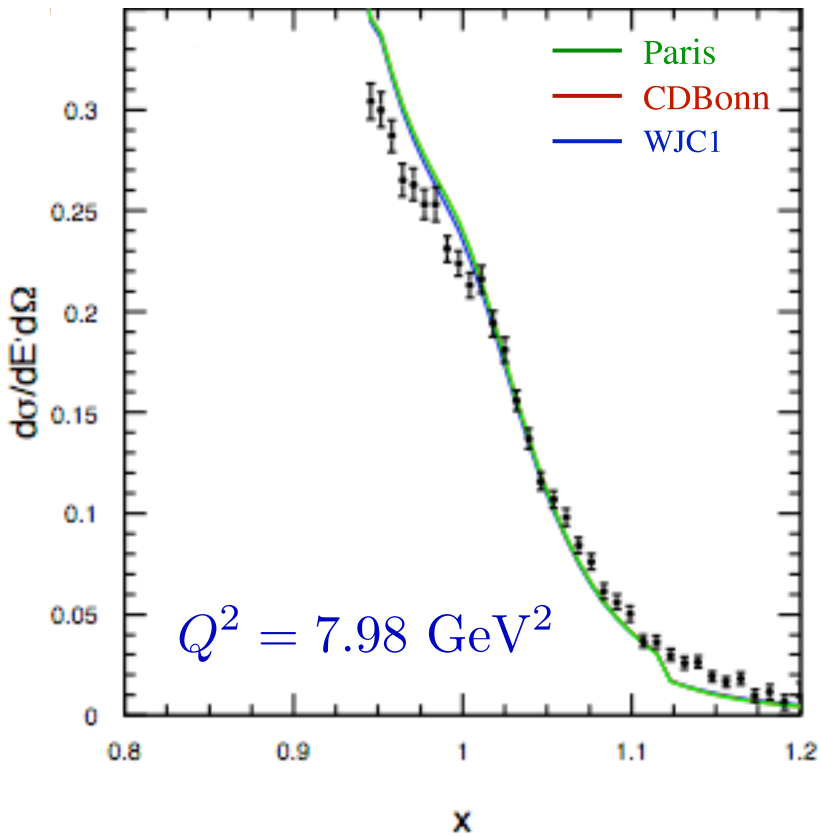
Doshi, WM (2012)

$\longrightarrow$ most data can be described by WBA smearing function

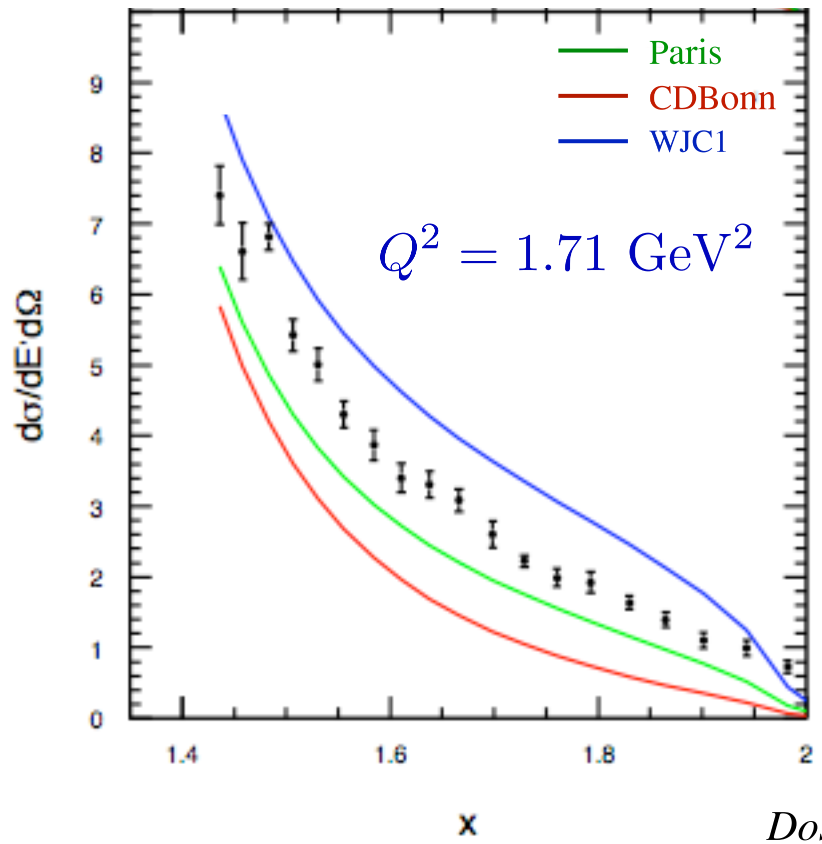
$\longrightarrow$ γ dependence crucial for describing Q^2 variation

Finite-Q^2 smearing function

*Rock et al., PRD **46**, 24 (1992)*



*Schutz et al., PRL **38**, 259 (1977)*



Doshi, WM (2012)

→ most data can be described by WBA smearing function

→ γ dependence crucial for describing Q^2 variation

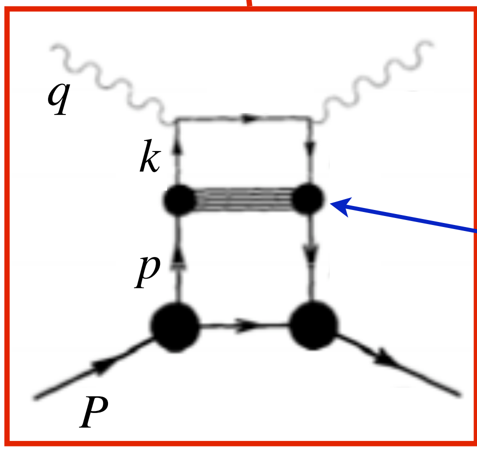
→ wave function dependence mild, except for $x \gg 1$ tails

Nucleon off-shell corrections

- In relativistic (MST) model, two sources of off-shellness

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

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



$$\Phi(p,k) = N(p^2)\frac{k^2 - m_q^2}{(k^2 - \Lambda^2)^n}$$

quark-diquark vertex functions

Nucleon off-shell corrections

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

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

$$\delta^{(\Psi)} F_2^d \sim \int dy \int dp^2 \left\{ \left[\frac{1}{2}(1 - E_p/p_0) F_2^N(x/y) \left(\frac{E_p}{M_d} \widehat{W}_1^{\text{on}} - \frac{P \cdot q}{M_d^2} \widehat{W}_2^{\text{on}} \right) \underline{(p^2 - M^2)} \right] |\psi_d(p)|^2 \right.$$

$$+ \left[-2M\widehat{W}_0^{\text{on}} + 2\mathbf{p}^2 \widehat{W}_1^{\text{on}} + \left(1 - y - \frac{E_p}{M_d}\right) P \cdot q \widehat{W}_2^{\text{on}} \right] \underline{(v_t^2 + v_s^2)}$$

$$\left. + \left[M\widehat{W}_0^{\text{on}} + M^2 \widehat{W}_1^{\text{on}} + \frac{M^2}{\mathbf{p}^2} \left(1 - y - \frac{E_p}{M_d}\right) P \cdot q \widehat{W}_2^{\text{on}} \right] \frac{2|\mathbf{p}|}{\sqrt{3}M} \left(u(\underline{v_s - \sqrt{2}v_t}) + w(\underline{v_t + \sqrt{2}v_s}) \right) \right\}$$

$$\delta^{(p^2)} F_2^d \sim \int dy \int dp^2 \left\{ \mathcal{A}_s \underline{\widehat{W}_0^{\text{off}}} + \mathcal{A}_v \cdot p\, \underline{\widehat{W}_1^{\text{off}}} + \mathcal{A}_v \cdot q\, \underline{\widehat{W}_2^{\text{off}}} \right\}$$

$$\widehat{W}_i^{\text{off}} = \widehat{W}_i - \widehat{W}_i^{\text{on}}$$

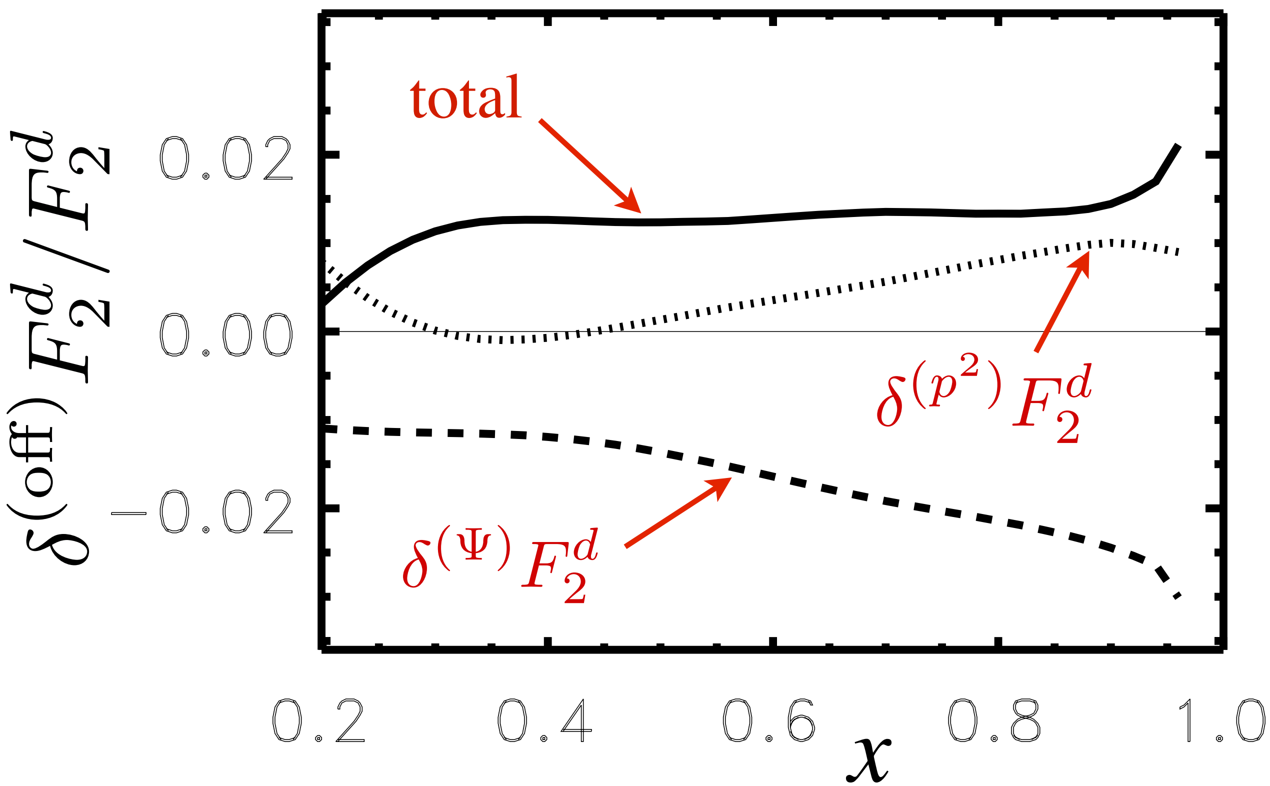
$$\mathcal{A}_{s,v} = \mathcal{A}_{s,v}(u, w, v_s, v_t)$$

Nucleon off-shell corrections

- In relativistic (MST) model, two sources of off-shellness

$\delta^{(\mathrm{off})} F_2^d \;\longrightarrow\; \delta^{(\Psi)} F_2^d$ negative energy components of ψ_d

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



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

$\longrightarrow\;\; \lesssim 1-2\%$ effect

Nucleon off-shell corrections

- In relativistic (MST) model, two sources of off-shellness

$$\delta^{(\mathrm{off})} F_2^d \quad \longrightarrow \quad \delta^{(\Psi)} F_2^d \quad \text{negative energy components of } \psi_d$$

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

- High degree of model dependence

$\longrightarrow$ require *quark*-level description of nuclear (bound nucleon) structure

$\longrightarrow$ *see Cloët talk*

$\longrightarrow$ in practice easier to implement off-shellness at *hadron* level through WBA approach

Nucleon off-shell corrections

- In WBA model, nuclear structure function factorizes to $\mathcal{O}(\mathbf{p}^2/M^2)$ into a 2-dimensional convolution (in y & p^2)

  $\longrightarrow$ expand off-shell structure function about $p^2 = M^2$

$$F_2^{N(\text{off})}(x, p^2) = F_2^N(x)\left(1 + \delta f(x)\frac{p^2 - M^2}{M^2}\right)$$

  with coefficient function

$$\delta f(x) = \left.\frac{\partial \log F_2^{N(\text{off})}}{\partial \log p^2}\right|_{p^2=M^2}$$

- "Phenomenological" model

  $\longrightarrow$ assume δf is independent of nucleus, and *fit* to F_2^A/F_2^d data

$$\delta f^{(\text{fit})} = C_N(x - 0.05)(x - x_0)(1 + x_0 - x)$$

$\longrightarrow$ *see Petti talk*

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

Nucleon off-shell corrections

- "Microscopic" model – off-shell spectral function $\Phi(k^2, \Lambda(p^2))$

$\longrightarrow$ in valence approximation $F_2^N(x) \sim x q_v(x)$

$$\delta f(x) \;\to\; \frac{\partial \log q_v}{\partial x} h(x) \;+\; \int dx \frac{\partial q_v}{\partial x} h(x)$$

$$h(x) = x(1-x)\frac{(1-\lambda)(1-x)M^2 + \lambda s_0}{(1-x)M^2 - s_0}$$

parameter
$s_0 \sim 2\ \mathrm{GeV}^2$

$$\lambda = \left.\frac{\partial \log \Lambda^2}{\partial \log p^2}\right|_{p^2=M^2} \longrightarrow \Lambda^{-1} \sim \text{ confinement radius } R_N$$

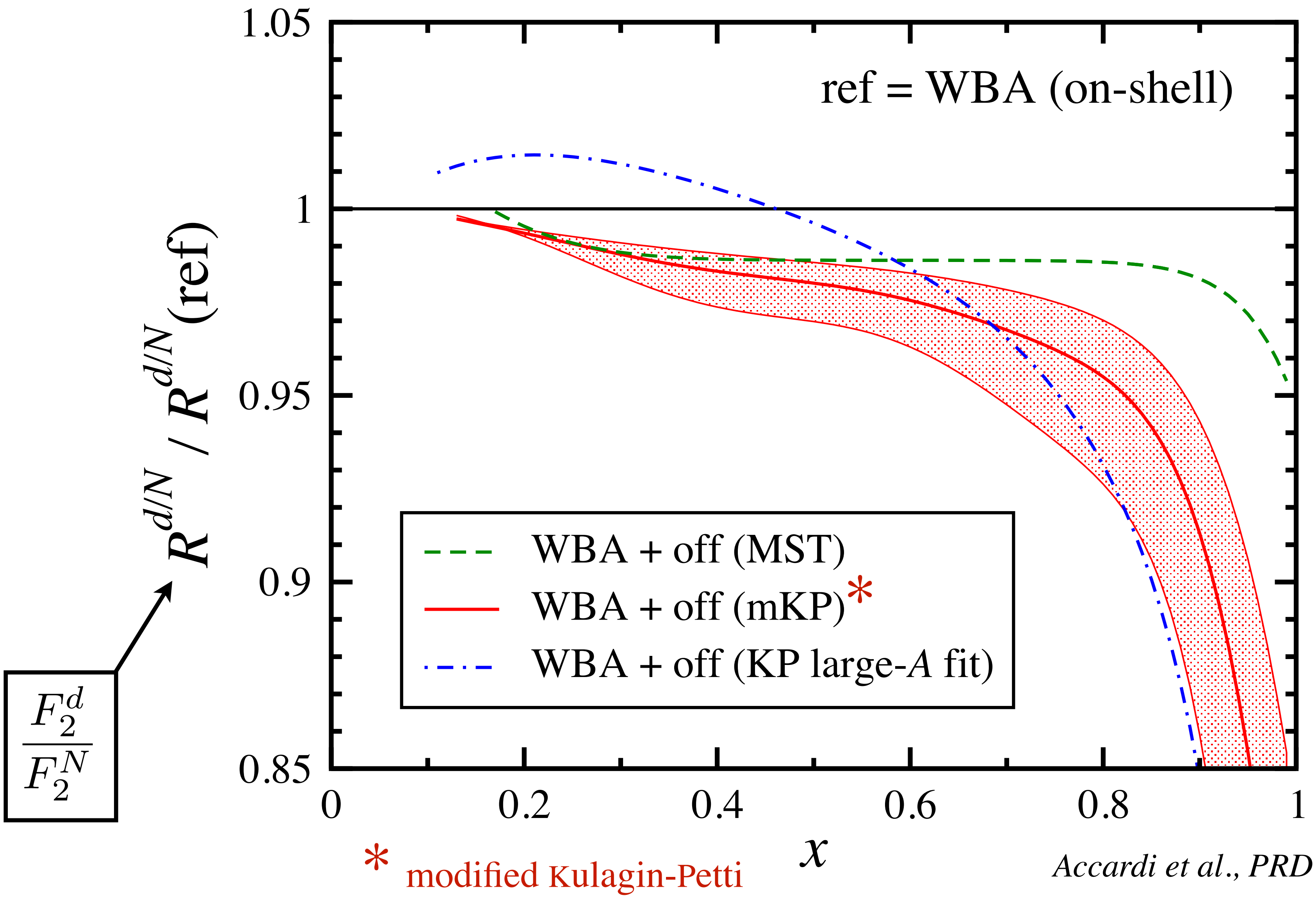
$$= -\frac{2\,\delta R_N}{R_N}\,\frac{\delta p^2}{M^2} \longrightarrow \underline{\underline{\delta R_N/R_N}} = 1.5\% - 1.8\%$$

Close et al., PRD ***31****, 1004 (1985)*

$$\sim 0.46 - 1.00 \qquad \underline{\underline{\delta p^2/M^2}} \approx -3.7\% \text{ to } -6.2\%$$

AV18, CD-Bonn, WJC

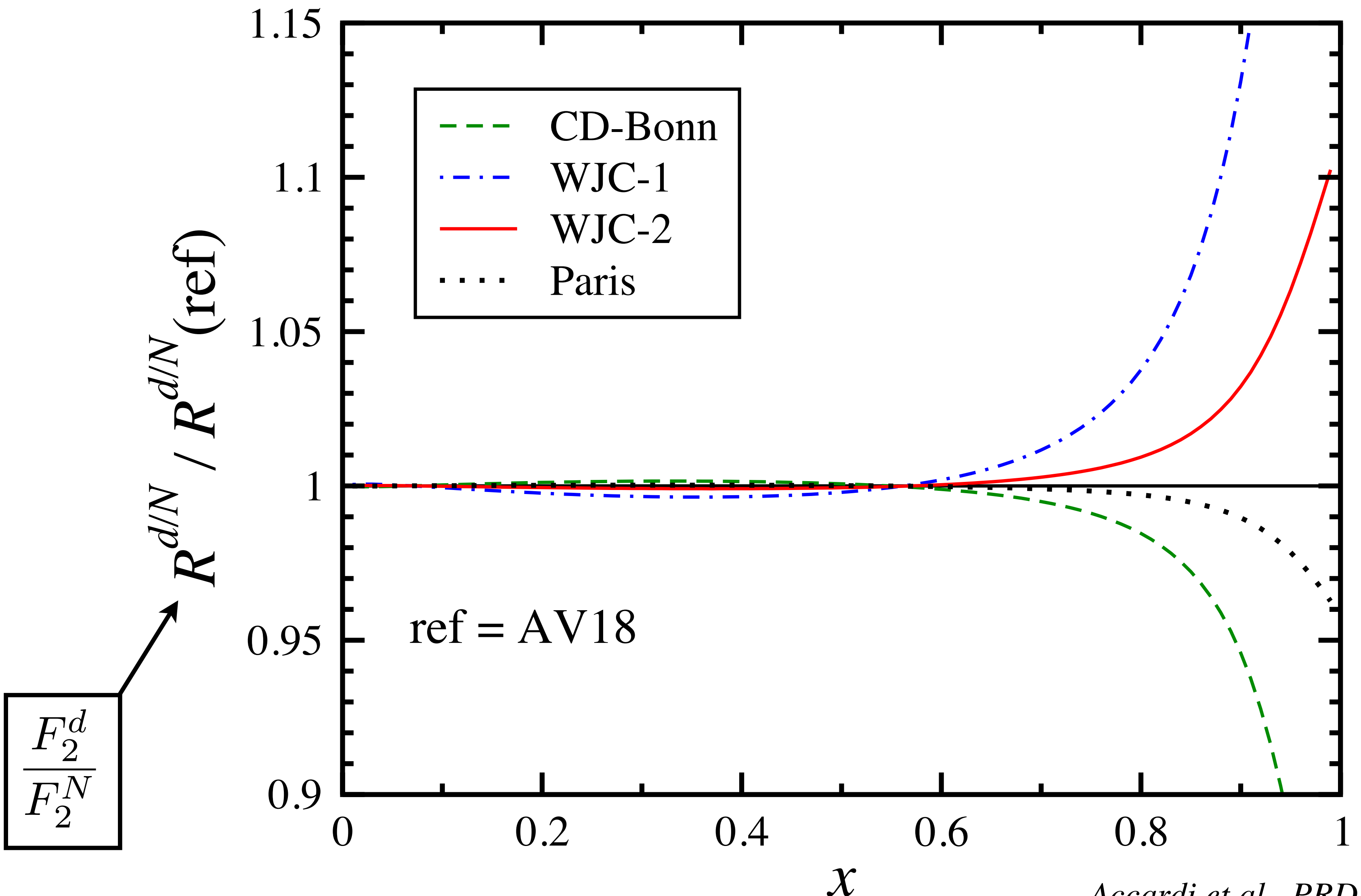
Model dependence: off-shell corrections



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

→ increasing nucleon off-shell suppression at large x

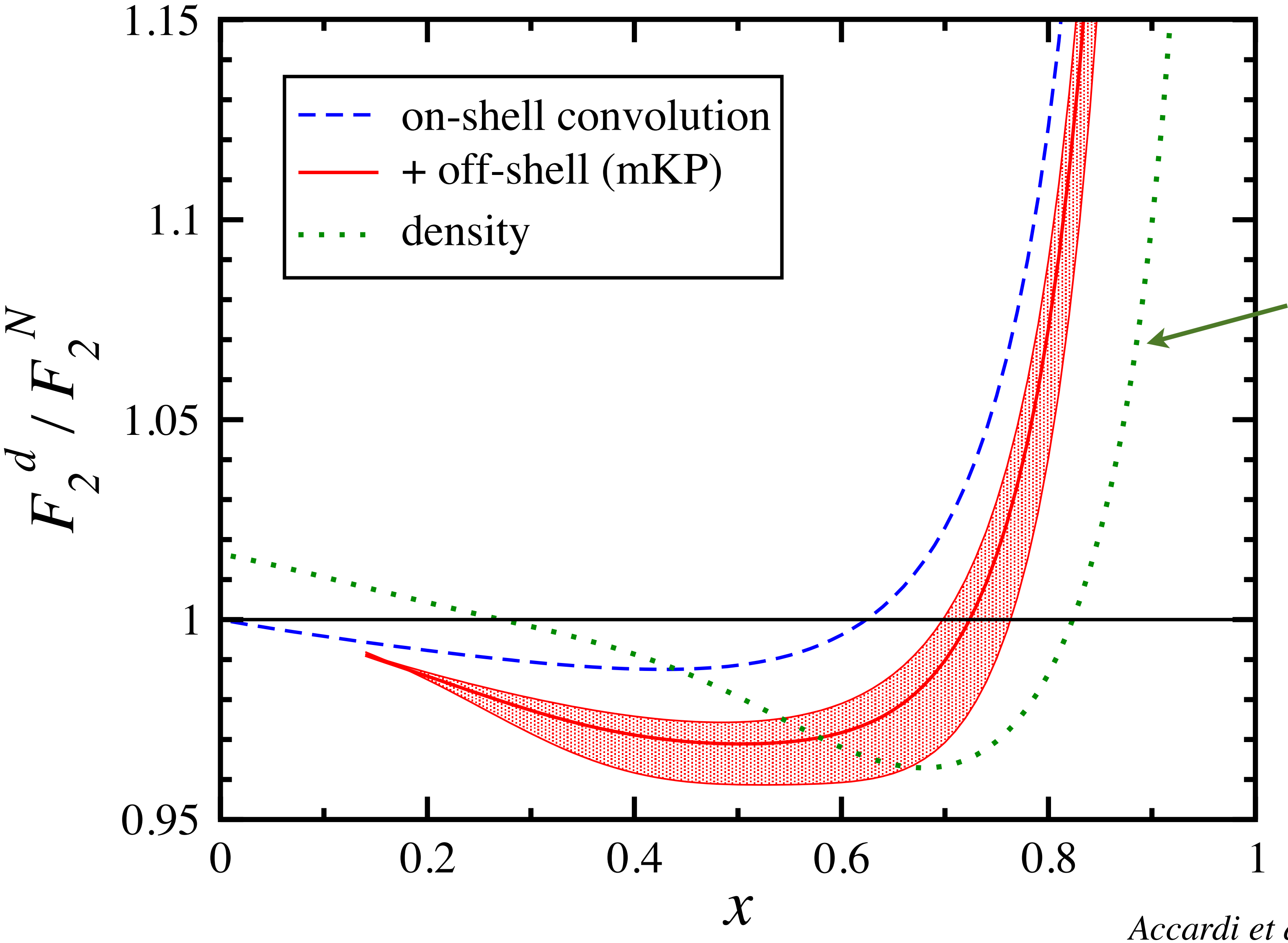
Model dependence: deuteron wave function



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

→ uncertainty in large-y tail of momentum distribution
(short-range NN interaction)

EMC effect in deuteron



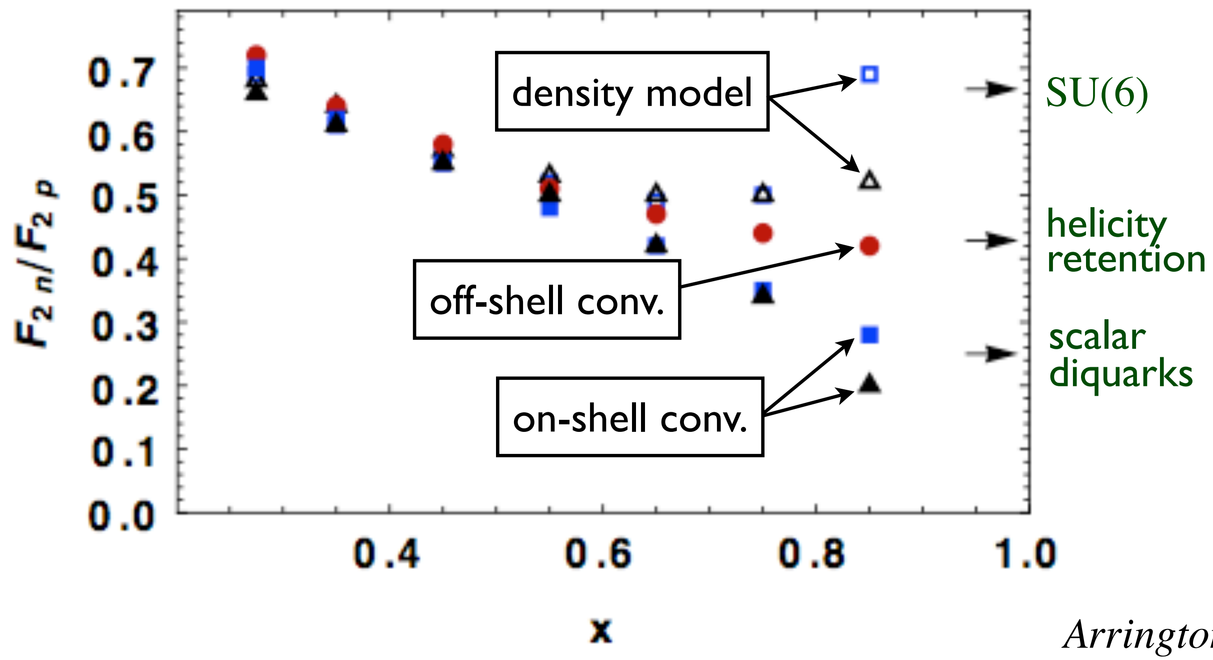
$$\frac{F_2^d}{F_2^N} - 1 \approx \frac{1}{4}\left(\frac{F_2^{\rm Fe}}{F_2^d} - 1\right)$$

assumes EMC effect scales with density; extrapolated from Fe $\longrightarrow$ deuterium

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

$\longrightarrow$ $\approx$ 2–4% depletion at $x \sim 0.4$–0.6, depending on model

Nuclear effects on neutron structure

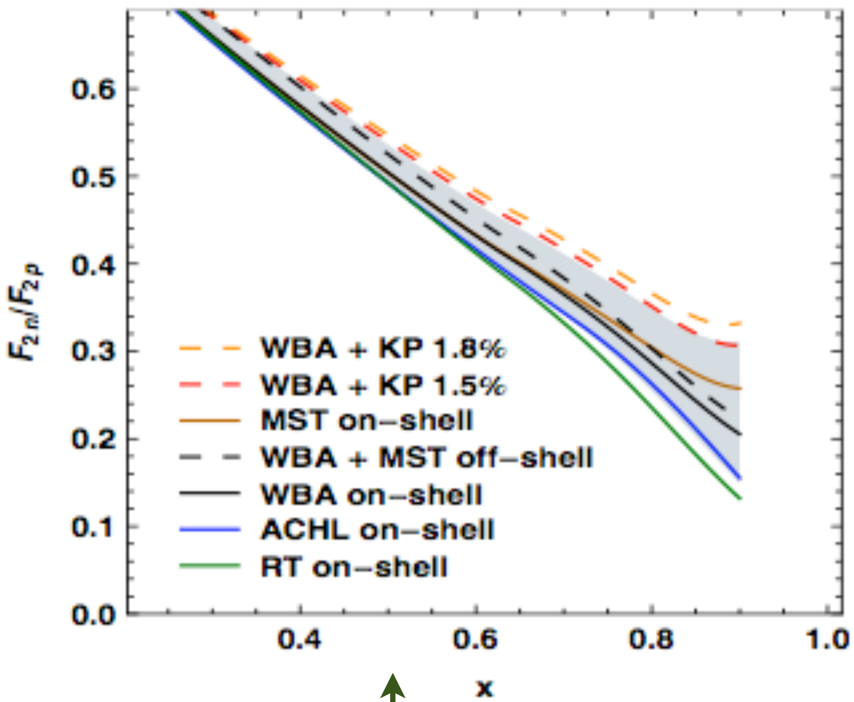


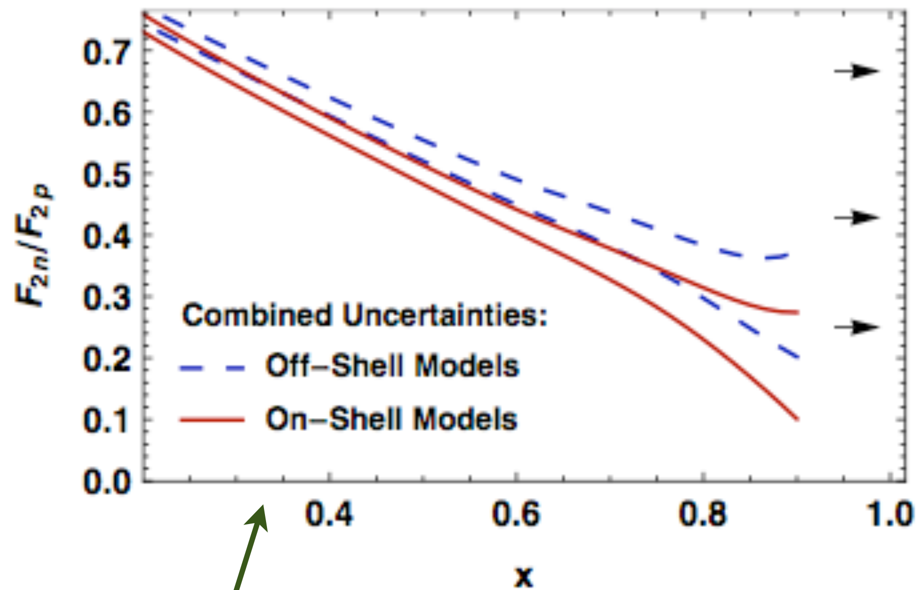
Arrington, Rubin, WM
PRL (2012) [arXiv:1110.3362]

→ large effect of nuclear model uncertainty on extracted neutron structure function at high x

→ cannot discriminate between predictions for $x \to 1$ behavior of F_2^n/F_2^p ratio

Nuclear effects on neutron structure





Arrington, Rubin, WM
PRL (2012) [arXiv:1110.3362]

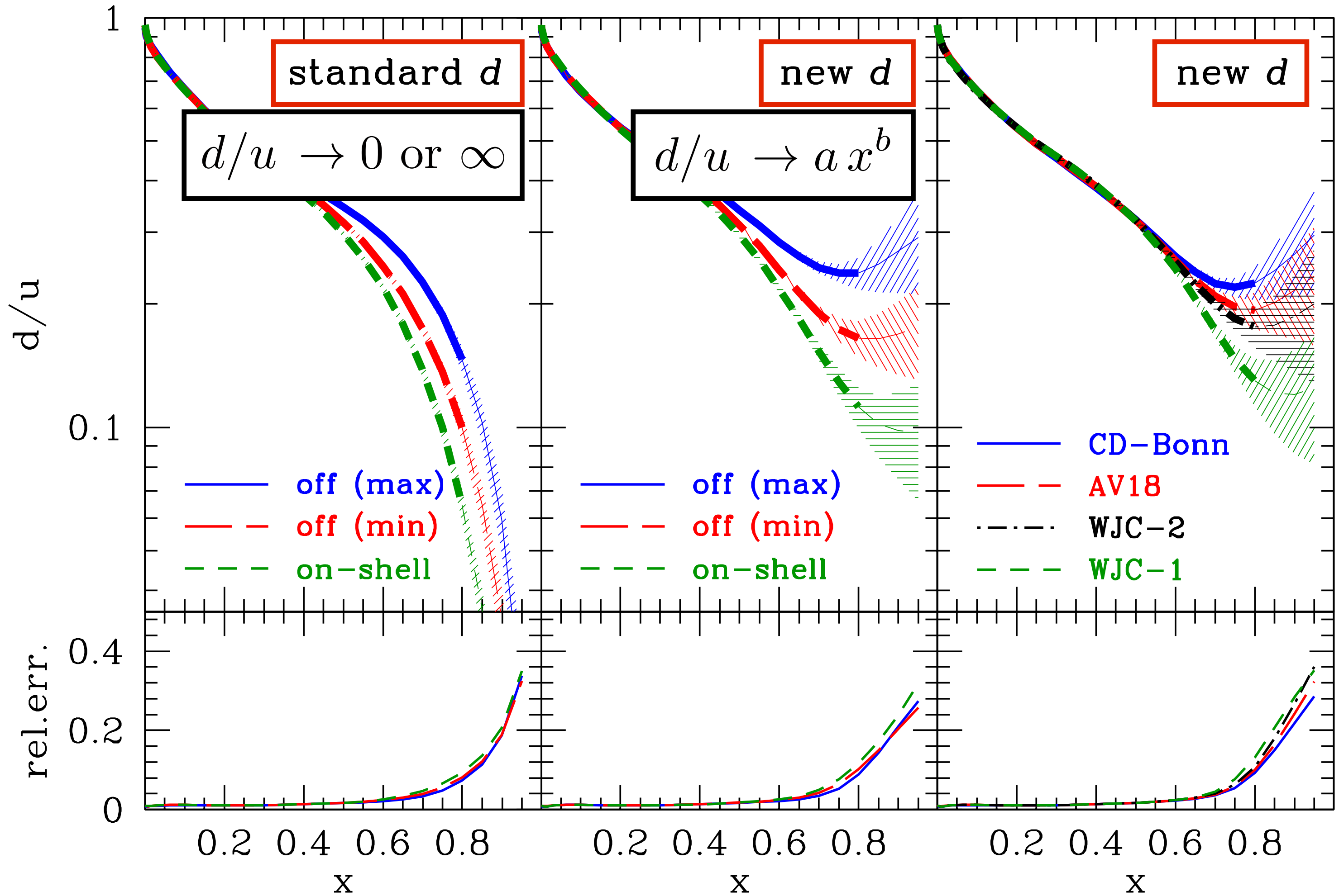
microscopic deuteron models

on-shell *vs.* off-shell models

→ SU(6) prediction disfavored by microscopic models

→ to disentangle *leading twist* need global pQCD analysis

Nuclear effects on PDF analysis



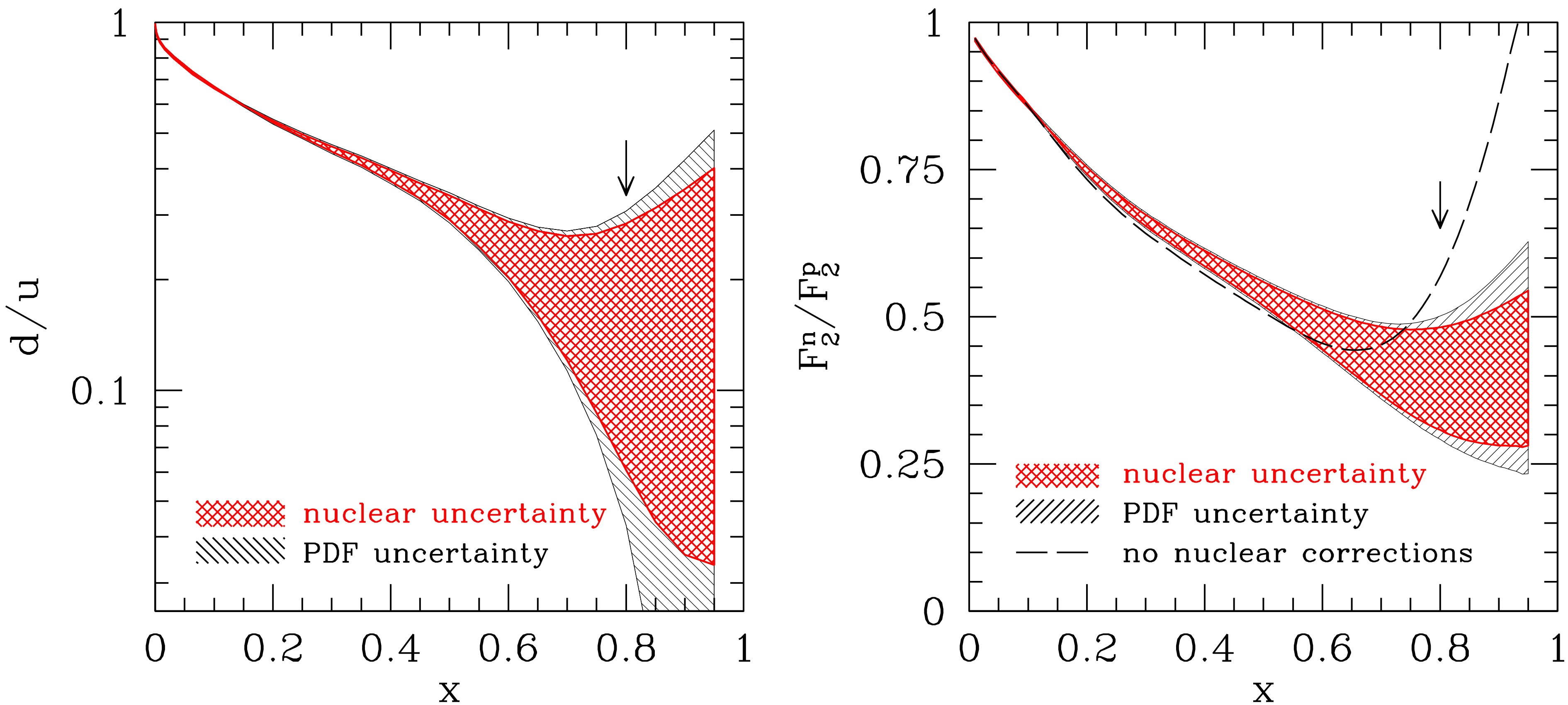
CTEQ-JLab (CJ) collaboration

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

→ larger off-shell effects → larger d/u ratio

→ precise $x \to 1$ limit depends on parametrization

Nuclear effects on PDF analysis



→ *see Accardi talk*

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

→ combined nuclear correction uncertainties sizable at $x > 0.5$

→ $x \rightarrow 1$ limiting value depends critically on deuteron model

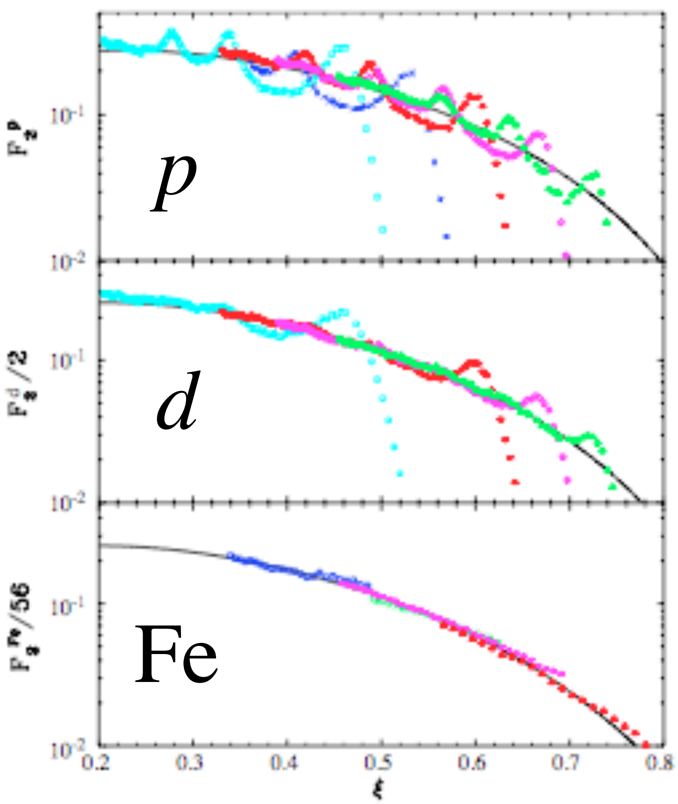
→ n/p ratio smaller at large x *cf.* no nuclear corrections fit

Nuclear effects on resonances

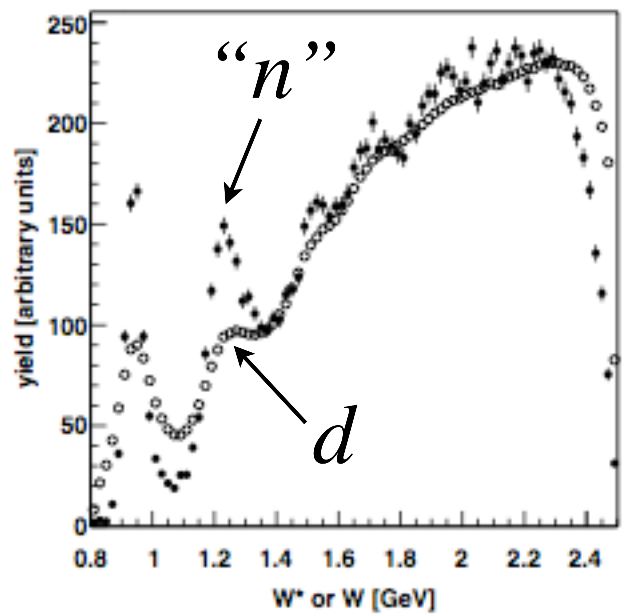
Neutron resonances

- Extraction of neutron information in *resonance* region is highly problematic

→ nuclear Fermi motion smears out resonance structures in neutrons bound in nuclei



*Arrington et al., PRC **64**, 014602 (2001)*



*Baillie et al., PRL **108**, 142001 (2012)*

Neutron resonances – unsmearing

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

  1. define difference 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 $F_2^{n(0)} \longrightarrow \Delta^{(0)} = \widetilde{F}_2^{n(0)} - F_2^n$

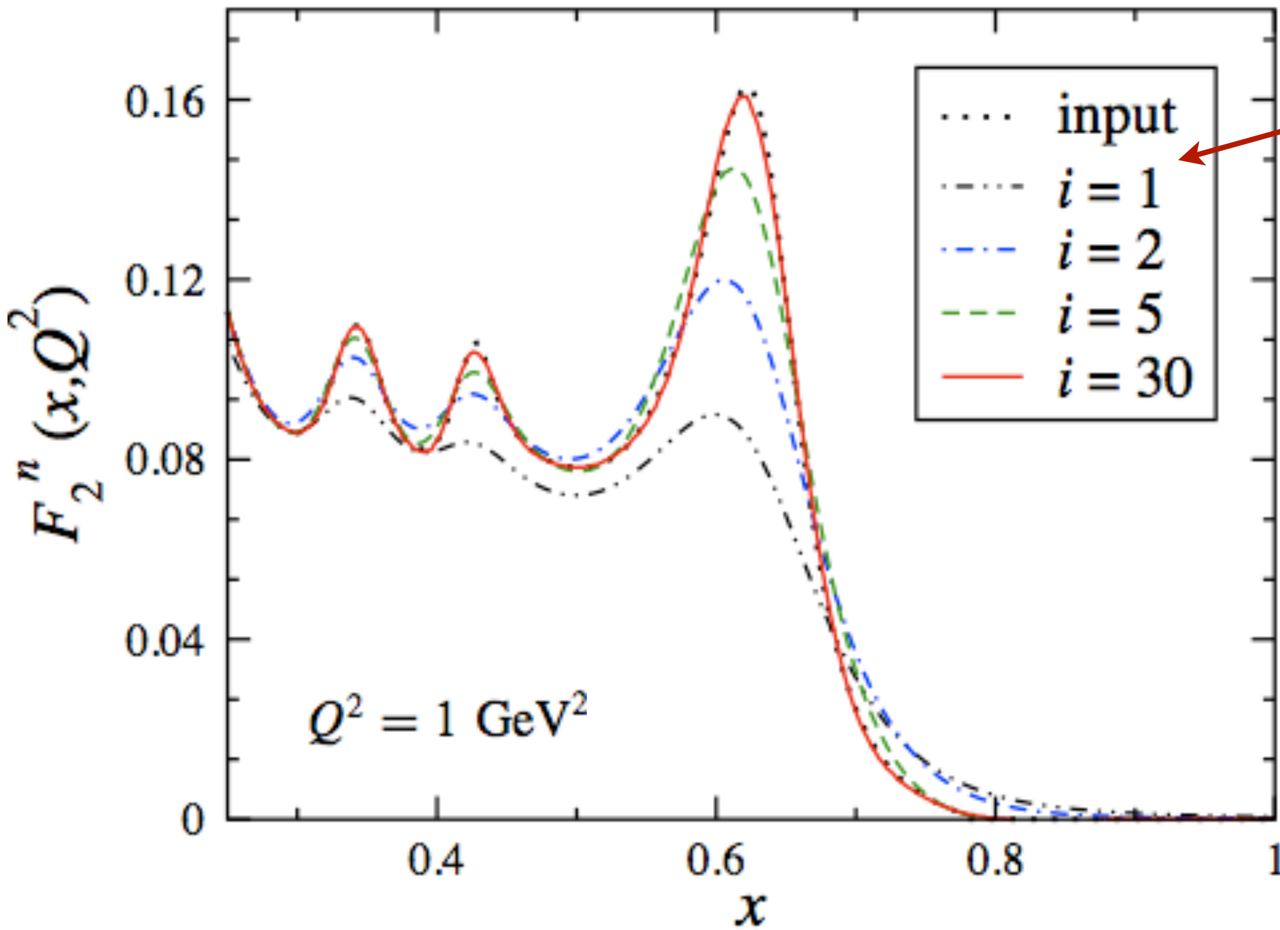
  3. after one iteration, gives

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

  4. repeat until convergence

Neutron resonances – unsmearing

- 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)*

$\longrightarrow$ can reconstruct almost arbitrary shape

Neutron resonances – unsmearing

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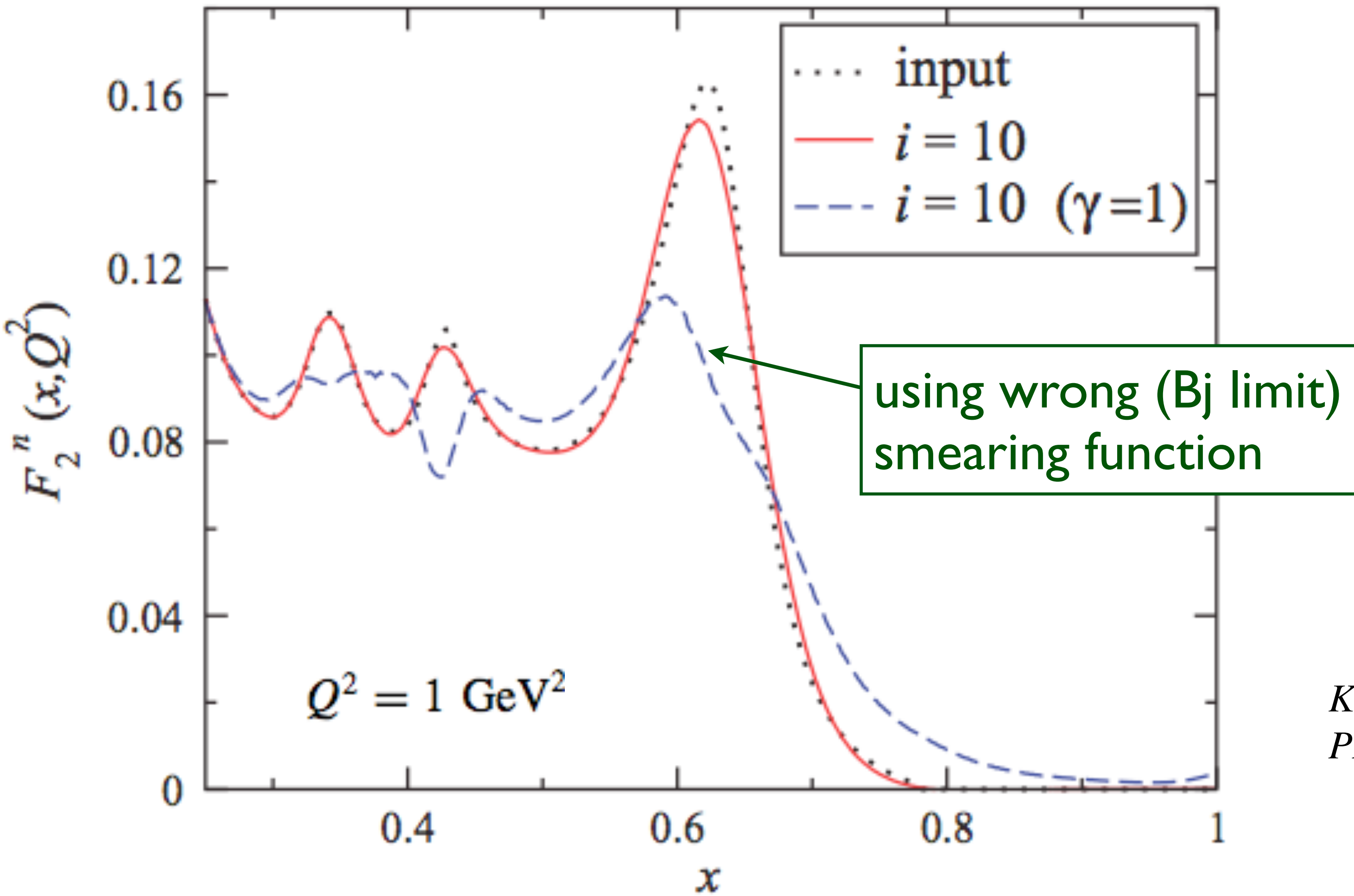
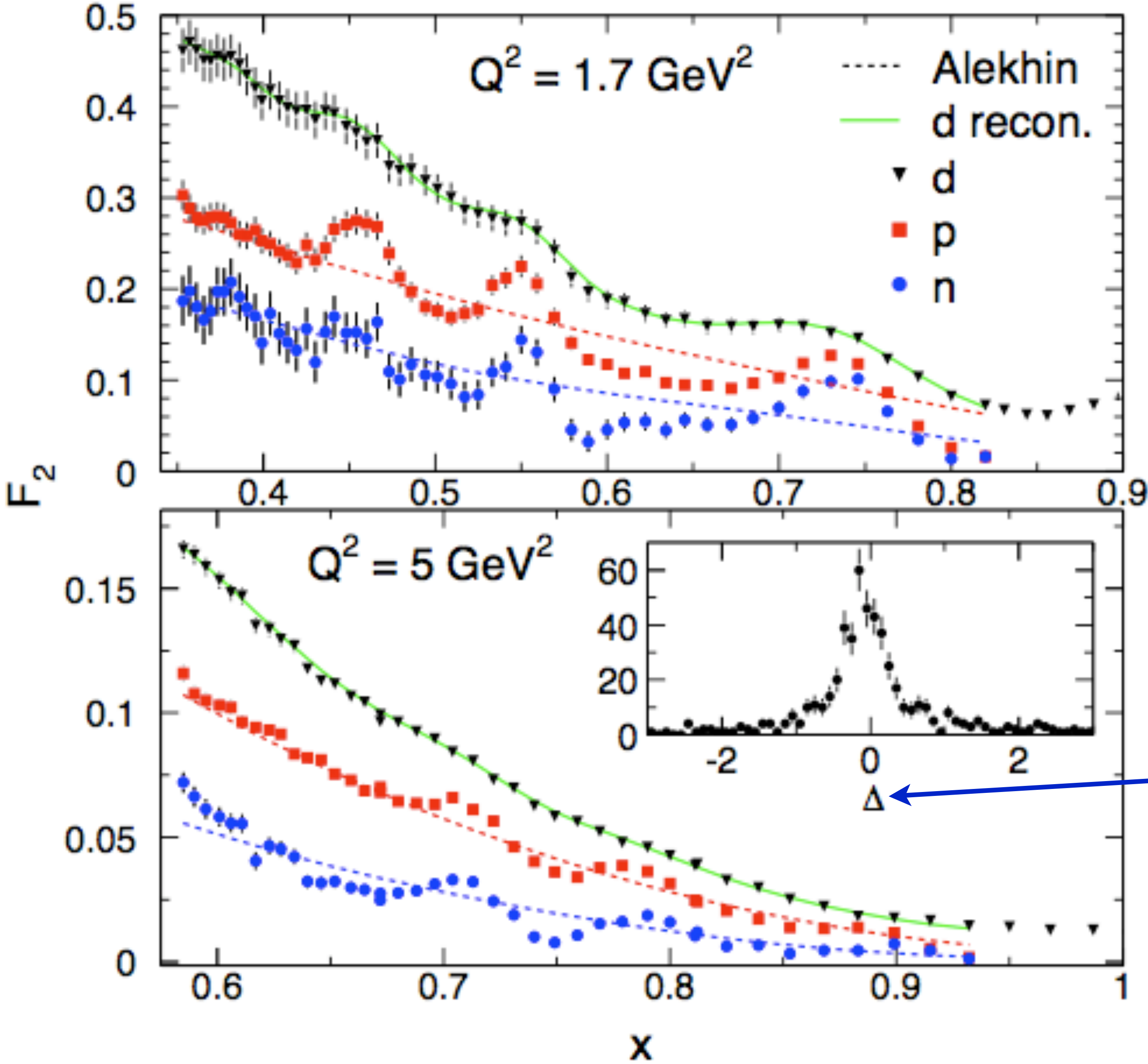


Kahn, WM, Kulagin
PRC ***79****, 035205 (2008)*

⟶ vital to use correct (Q^2-dependent) smearing function

Neutron resonances – unsmearing



→ JLab & SLAC data

→ 2 iterations with $n(0)=p$

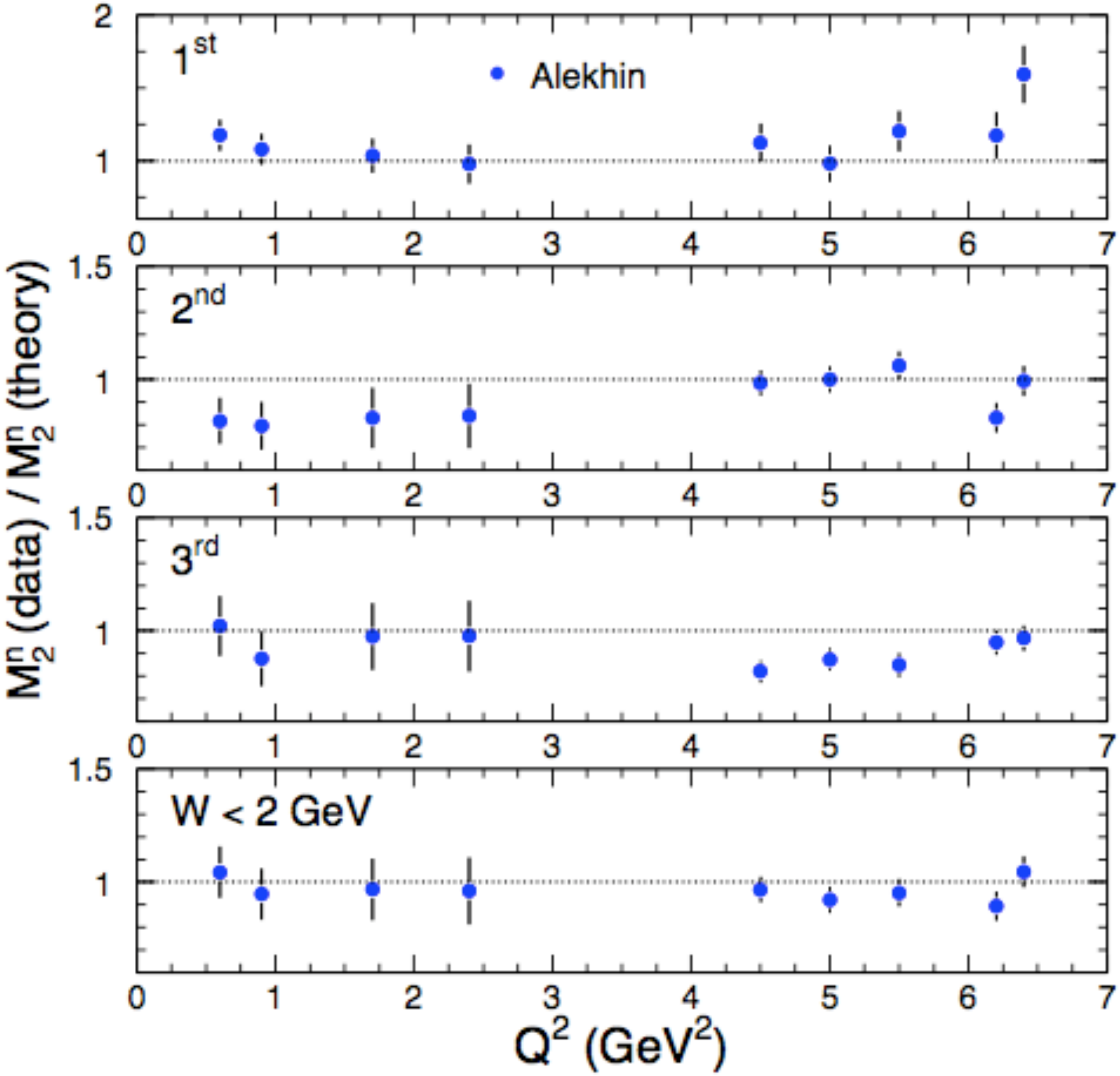
- clear neutron resonance structure observed
- weak dependence on input neutron

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

Malace, Kahn, WM, Keppel PRL ***104****, 102001 (2010)*

→ striking similarity with QCD fit to DIS data!

Neutron resonances – duality



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

Alekhin et al., 0908.2762 [hep-ph]

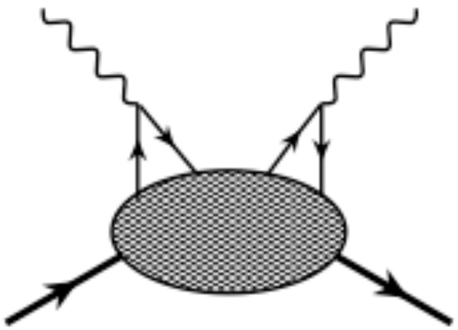
- *locally*, deviations in individual resonance regions $< 15-20\%$
- *globally*, deviations generally $< 10\%$

Malace, Kahn, WM, Keppel PRL ***104****, 102001 (2010)*

→ duality is *not accidental*, but a general feature of resonance–scaling transition!

Neutron resonances – duality

- Accidental cancellations of charges?



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 *incoherent*

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

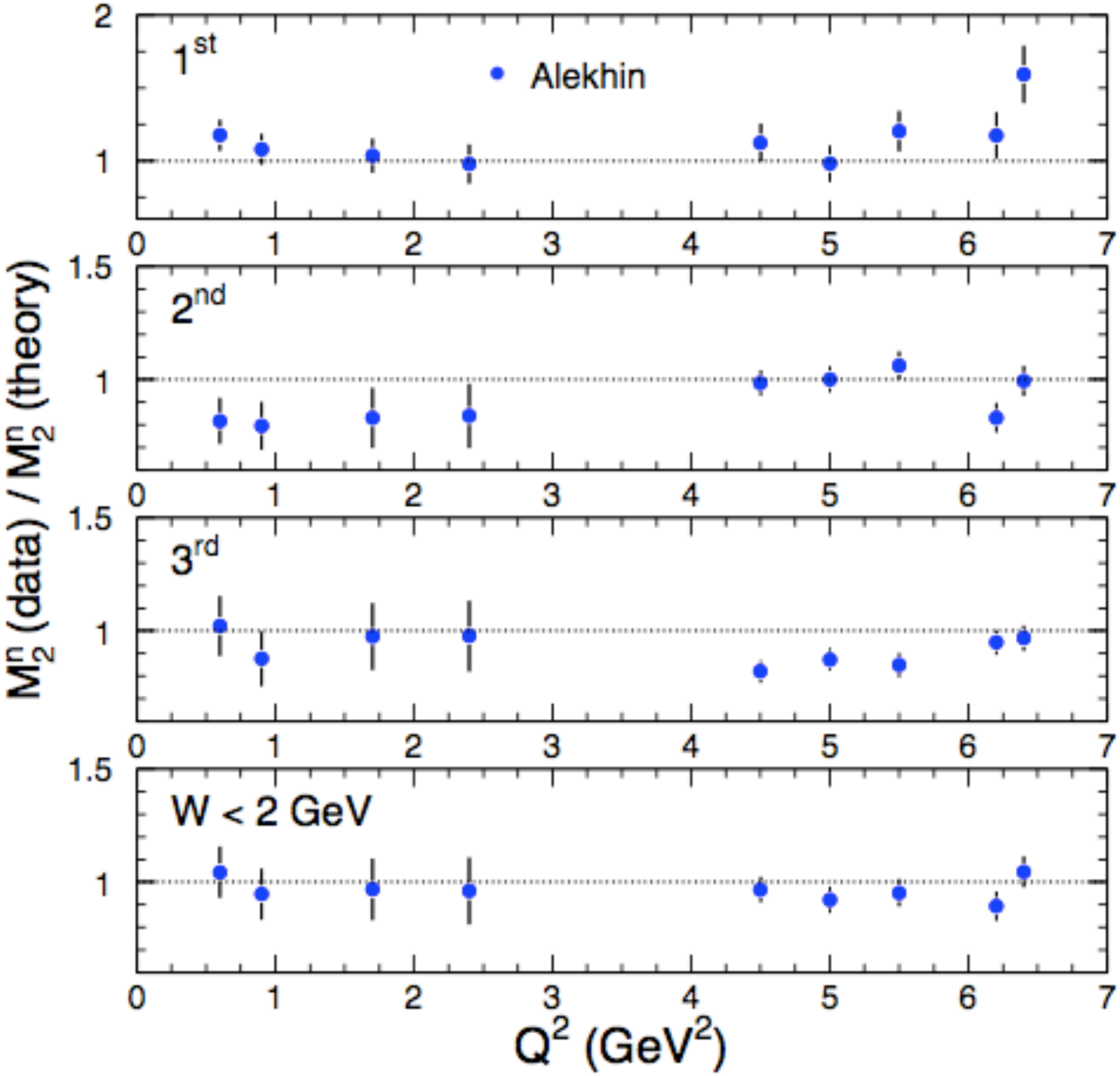
neutron $\mathrm{HT} \sim 0 - \left(\frac{4}{9} + 2 \times \frac{1}{9}\right) \neq 0$

→ duality in proton a *coincidence!*

→ should *not* hold for neutron

Brodsky, hep-ph/0006310

Neutron resonances – duality



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- *locally*, deviations in individual resonance regions < 15−20%
- *globally*, deviations generally < 10%

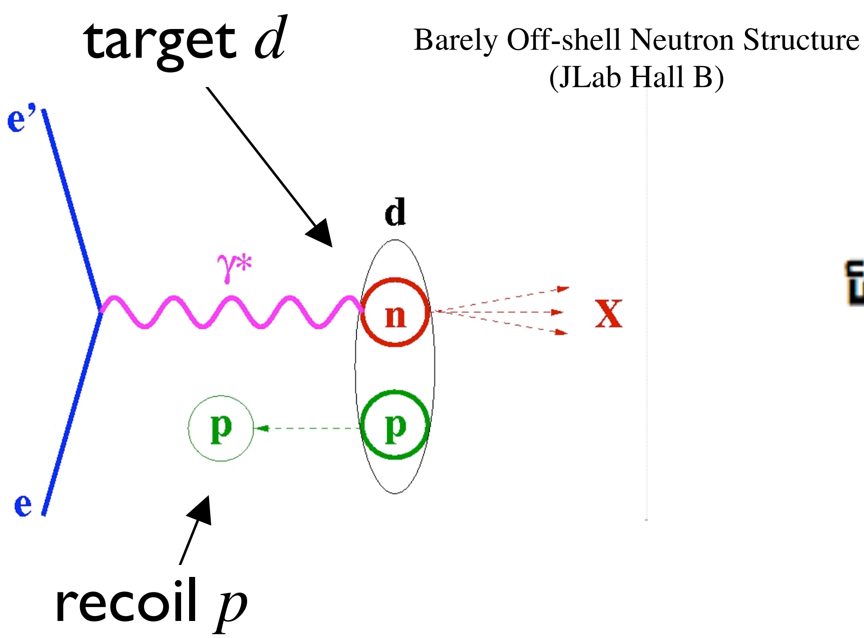
Malace, Kahn, WM, Keppel PRL ***104****, 102001 (2010)*

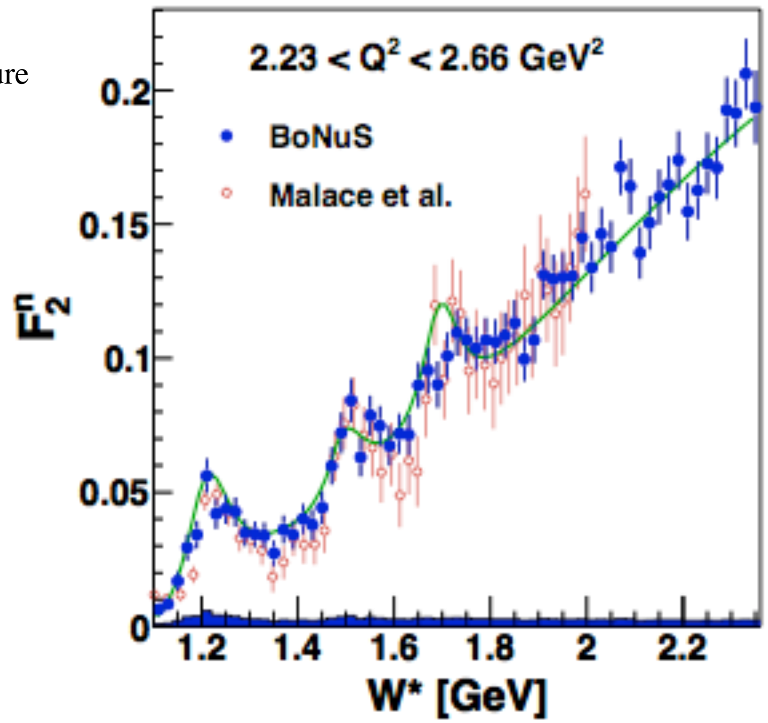
→ use resonance region data to learn about *leading twist* structure functions?

Neutron resonances – BoNuS

- (Almost) free neutron structure function extracted from semi-inclusive scattering from d with spectator p tagging

$\rightarrow$ slow, backward-moving proton ensures neutron is nearly on-shell, minimizes rescattering





Baillie et al., PRL ***108****, 142001 (2012)*

$\rightarrow$ agreement between extracted (inclusive) data and (more precise) BoNuS results

Neutron resonances – BoNuS

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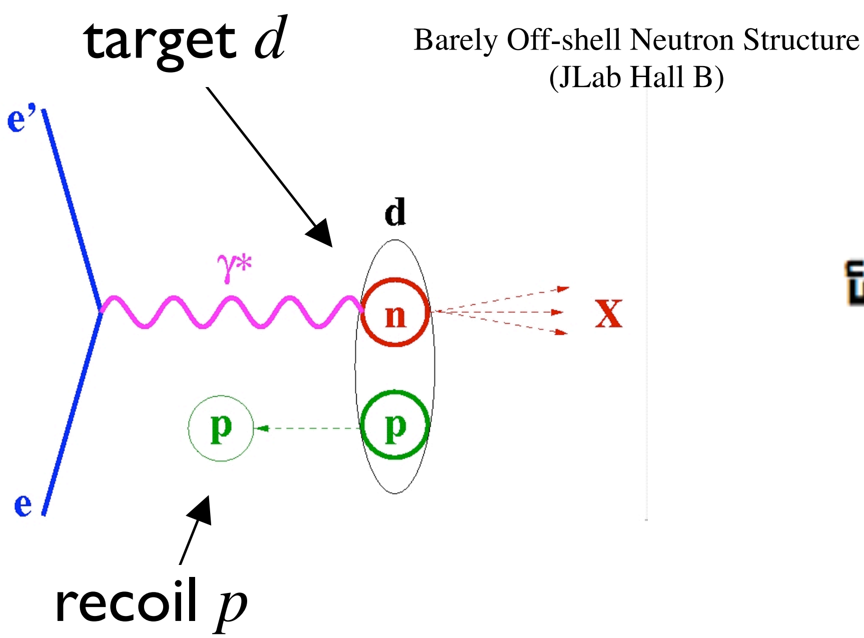
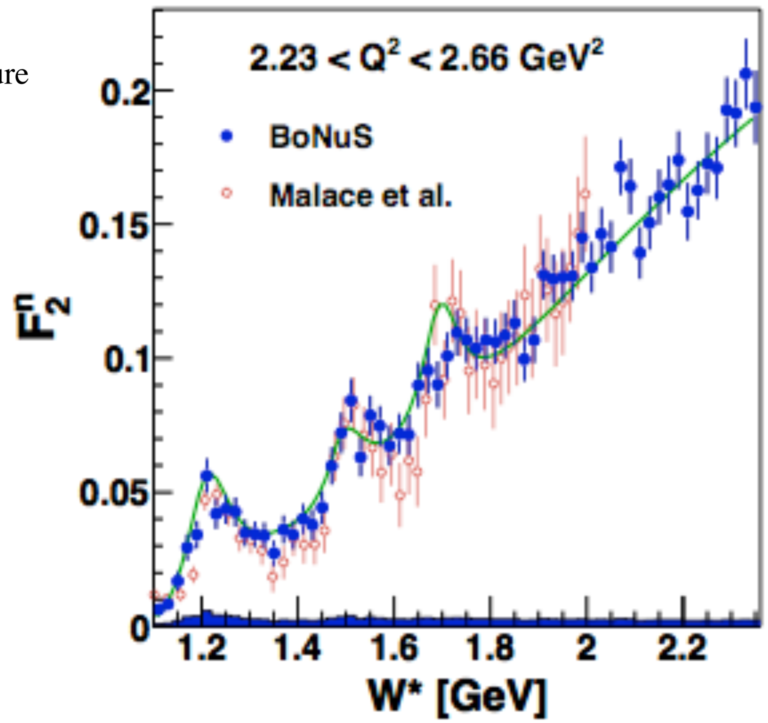
→ slow, backward-moving proton ensures neutron is nearly on-shell, minimizes rescattering





*Baillie et al., PRL **108**, 142001 (2012)*

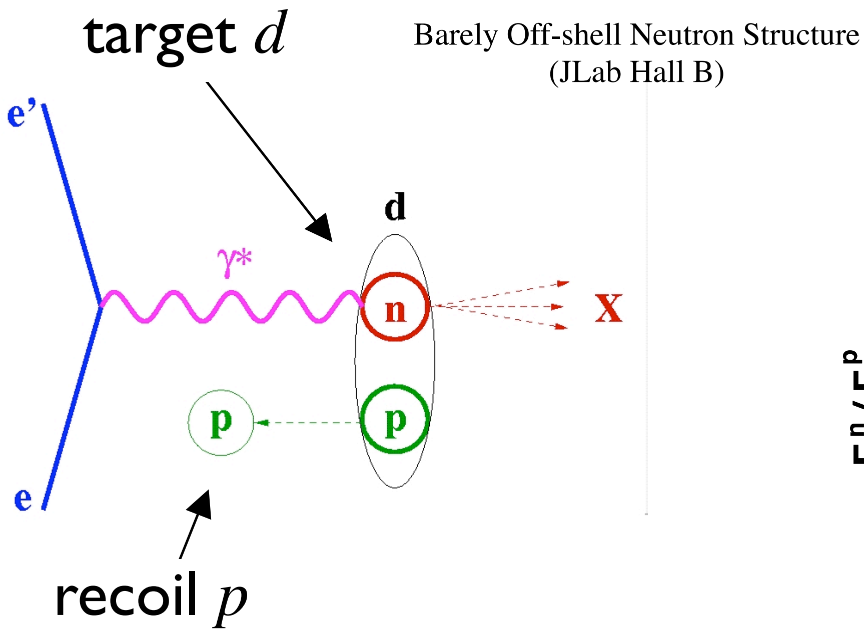
→ duality analysis in progress

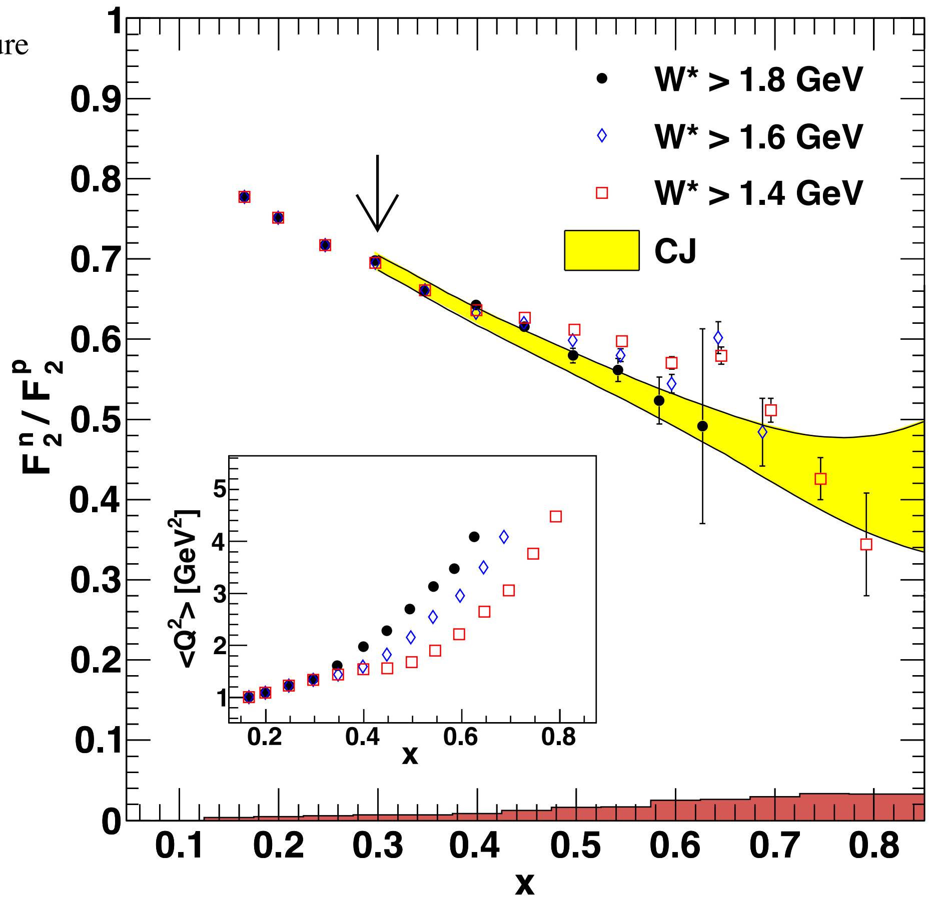
Niculescu, WM et al. (2012)

Neutron resonances – BoNuS

- (Almost) free neutron structure function extracted from semi-inclusive scattering from d with spectator p tagging

  → slow, backward-moving proton ensures neutron is nearly on-shell, minimizes rescattering





→ 12 GeV experiment will extend (DIS) range to $x \sim 0.8$

Constraints from local duality

- If validity (at ~15–20% level) of local duality holds also for extreme subthreshold region $M \leq W \leq M + m_\pi$

→ relate $x \to 1$ behavior of structure functions with $Q^2 \to \infty$ behavior of elastic (magnetic) form factors *

$$\frac{F_2^{N*}}{F_2^N} \longleftrightarrow \frac{d(G_M^{N*})^2/dQ^2}{d(G_M^N)^2/dQ^2}$$

*Bloom, Gilman, PRL **16**, 1140 (1970)*
*WM, PRL **86**, 35 (2001)*

* at finite Q^2, corrections also from G_E^N

→ $F_2^{N*},\ G_M^{N*}$ = off-shell N structure function, form factor

calculated in quark-meson coupling (QMC) model

Guichon, Thomas, Saito, Tsushima, ...

Constraints from local duality

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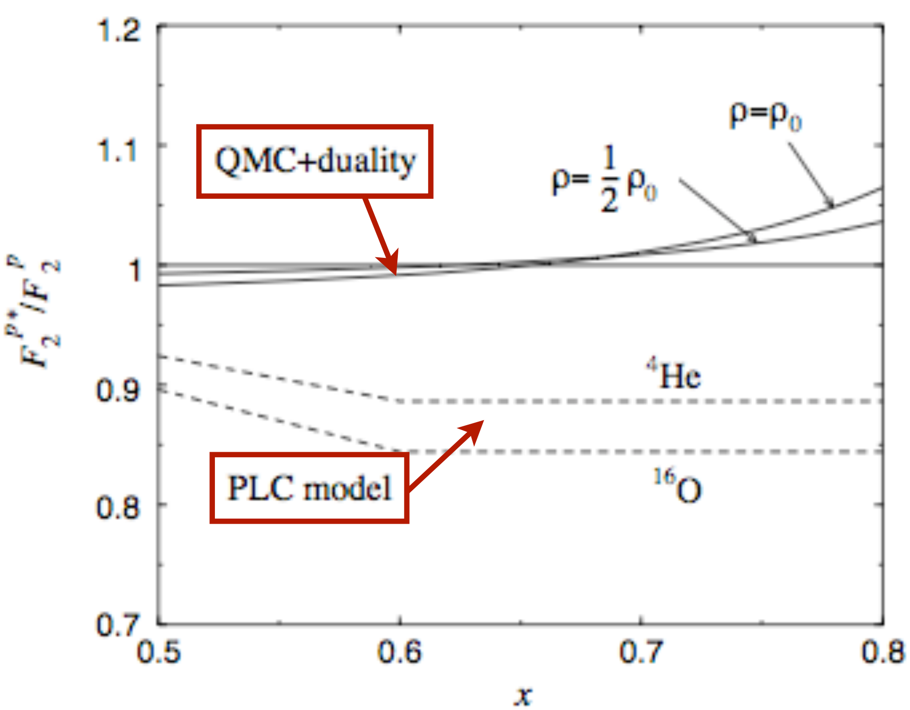


→ point-like configuration (PLC) suppression model ($x > 0.6$)

$$\frac{F_2^{N*}}{F_2^N} = 1 - \frac{2(k^2/2M + \epsilon_A)}{\Delta E_A}$$

→ most of EMC effect attributed to off-shell nucleon modification

Frankfurt, Strikman, NPB ***250****, 1585 (1985)*

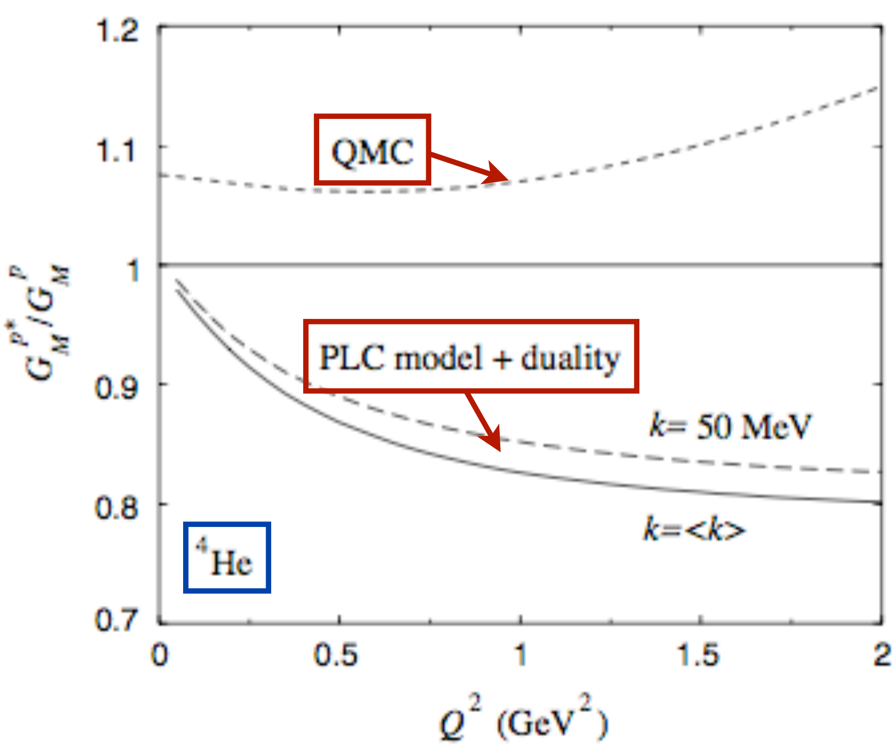
→ sign of off-shell effect in models *opposite* at large x

Constraints from local duality

- Using duality in reverse, extract elastic form factor from integral of structure function below threshold

$$(G_M^p)^2 \approx \frac{(2-\xi_0)}{\xi_0^2}\,\frac{(1+\tau)}{(1/\mu_p^2+\tau)}\int_{\xi_{\rm th}}^{1} d\xi\, F_2^p(\xi)$$

$\xi_0 = \xi(x=1)$



→ PLC model predicts in-medium *suppression* of G_M^p

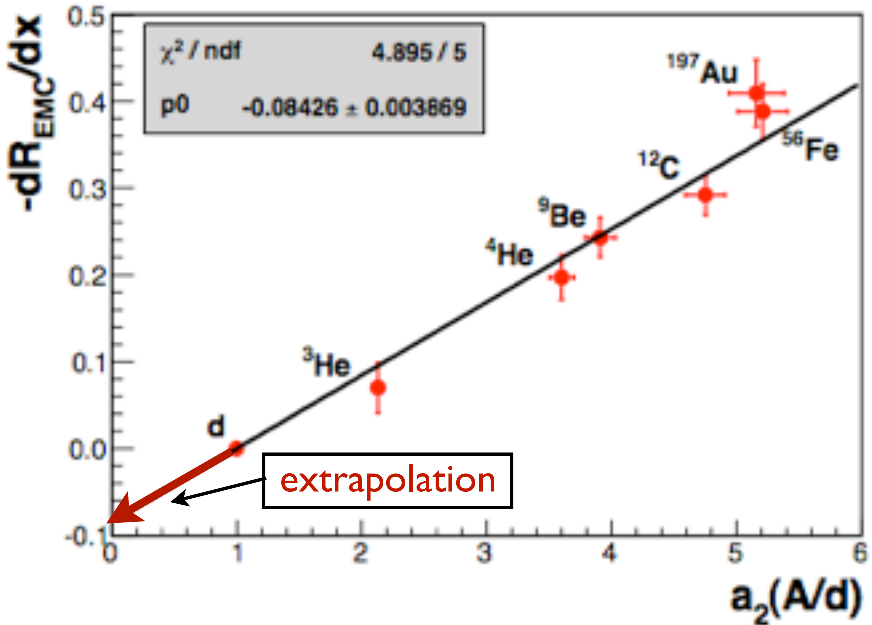
→ QMC (consistent with $(\vec{e}, e'\vec{p})$ data) implies small *enhancement*

WM, Tsushima, Thomas
*EPJA **14**, 105 (2002)*

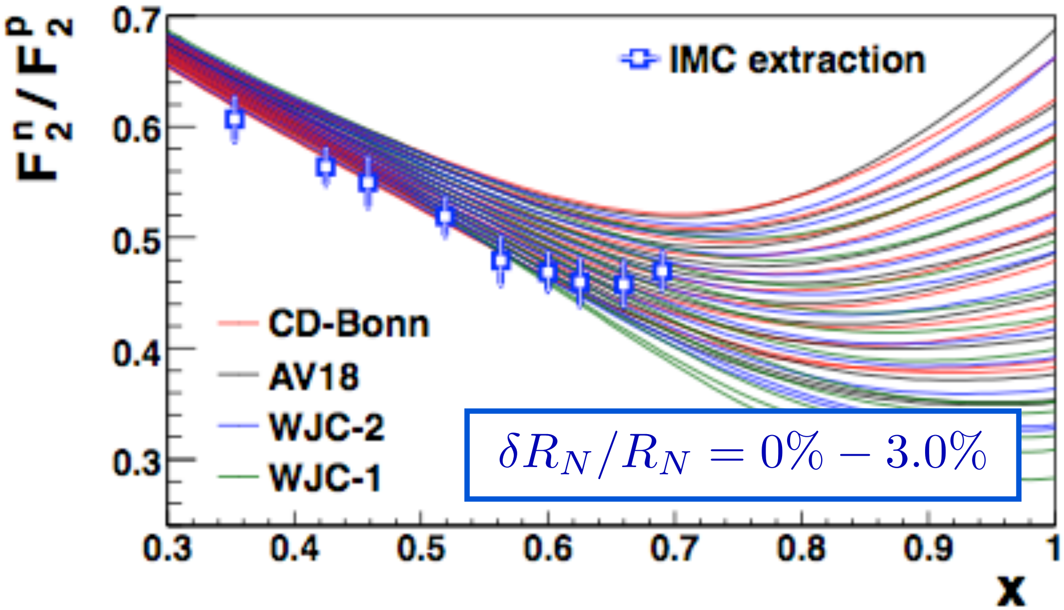
→ disfavors models with *large* medium modifications of SFs

Constraints from $x > 1$

- "IMC" extraction of F_2^n/F_2^p, assuming extrapolation of EMC–SRC correlation to A=1



Hen, Piasetzky, Weinstein
arXiv:1202.3452

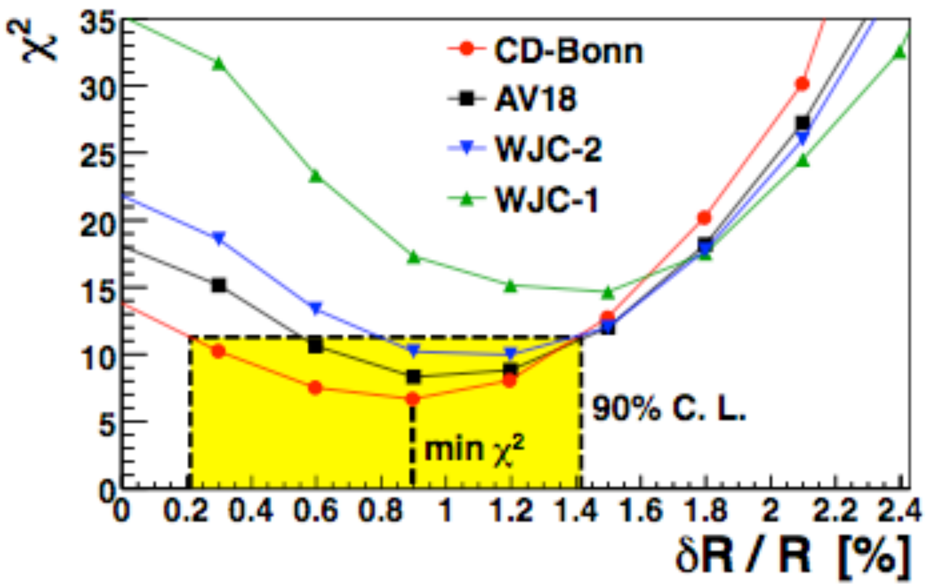


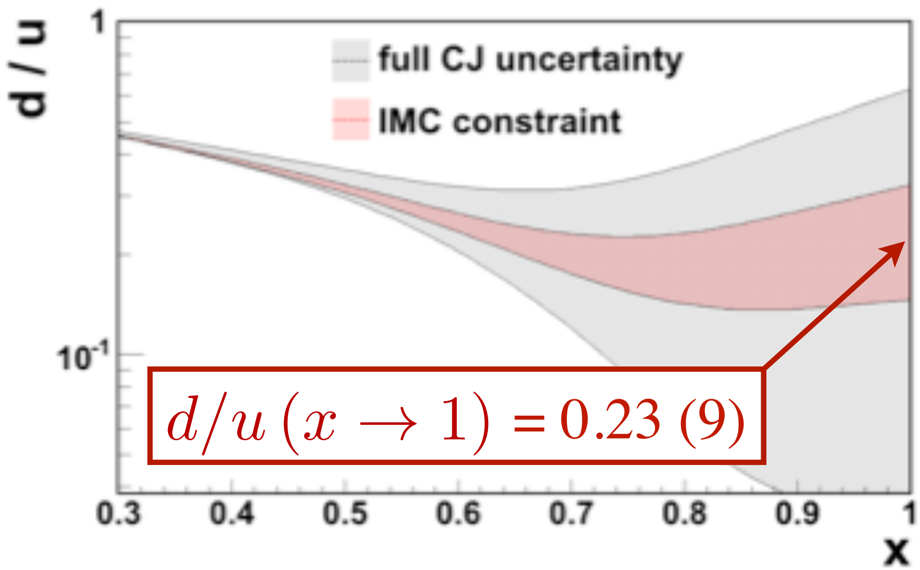
Hen, Accardi, WM, Piasetzky
PRD **84**, *117501 (2011)*

$\longrightarrow$ assuming validity of extrapolation, how would IMC F_2^n/F_2^p data constrain deuteron correction models?

Constraints from $x > 1$

- "IMC" extraction of F_2^n/F_2^p, assuming extrapolation of EMC–SRC correlation to A=1





Hen, Accardi, WM, Piasetzky
*PRD **84**, 117501 (2011)*

→ χ^2 fit constrains combination of d wave function and off-shell nucleon parameters (nucleon swelling)

→ WJC-1 disfavored, $\delta R_N / R_N = 0.2\% - 1.4\%$ (at 90% C.L.)

Future methods of determining d/u

- $e\ d \rightarrow e\ p_{\rm spec}\ X$ * — semi-inclusive DIS from d $\longrightarrow$ tag "spectator" protons
  "BoNuS"

- $e\ {}^3{\rm He}({}^3{\rm H}) \rightarrow e\ X$ * — ^{3}He-tritium mirror nuclei
  "MARATHON"

- $e\ p \rightarrow e\ \pi^{\pm}\ X$ * — semi-inclusive DIS as flavor tag

- $$\left.\begin{array}{l} e^{\mp}\ p \rightarrow \nu(\bar{\nu})X \\ \nu(\bar{\nu})\ p \rightarrow l^{\mp}\ X \\ p\ p(\bar{p}) \rightarrow W^{\pm}X, Z^0\ X \\ \vec{e}_L(\vec{e}_R)\ p \rightarrow e\ X^{*} \end{array}\right\}$$ weak current as flavor probe
  "PVDIS / SOLID"

* planned for JLab at 12 GeV

Future methods of determining d/u

- $e\ d \to e\ p_{\rm spec}\ X^*$ — semi-inclusive DIS from d $\longrightarrow$ tag "spectator" protons

  "BoNuS"

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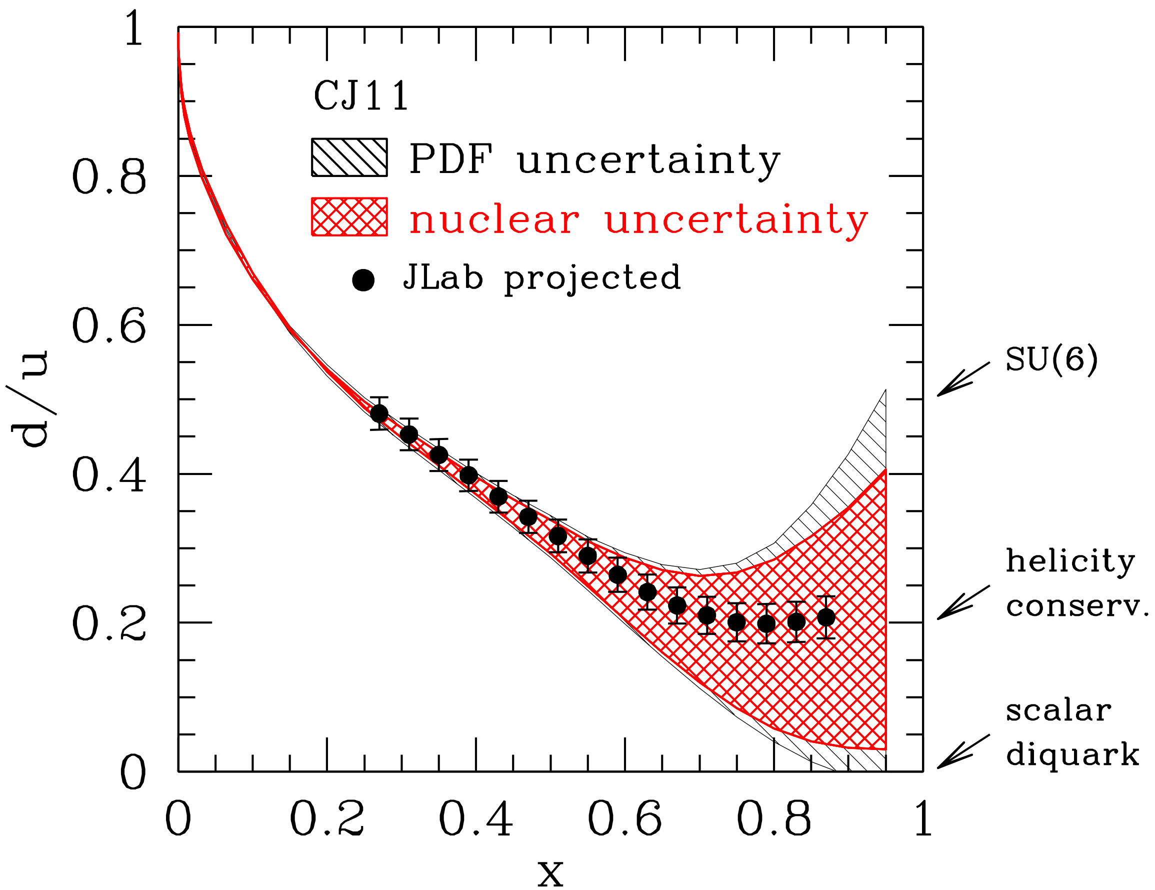

Summary

- Neutron structure at large x has remained elusive for > 40 years

  $\longrightarrow$ impact of nuclear effects on PDF analysis (CJ collaboration)

- First (model-independent) glimpse of neutron resonance spectrum from BoNuS experiment

  $\longrightarrow$ strong indication of validity of quark-hadron duality (*not* result of accidental cancellations)

- Model-dependent constraints give conflicting evidence for magnitude of nucleon off-shell effects
  (local duality $\longrightarrow$ small, IMC $\longrightarrow$ large)

  $\longrightarrow$ definitive tests will require JLab 12 GeV data (~ insensitive to nuclear effects)