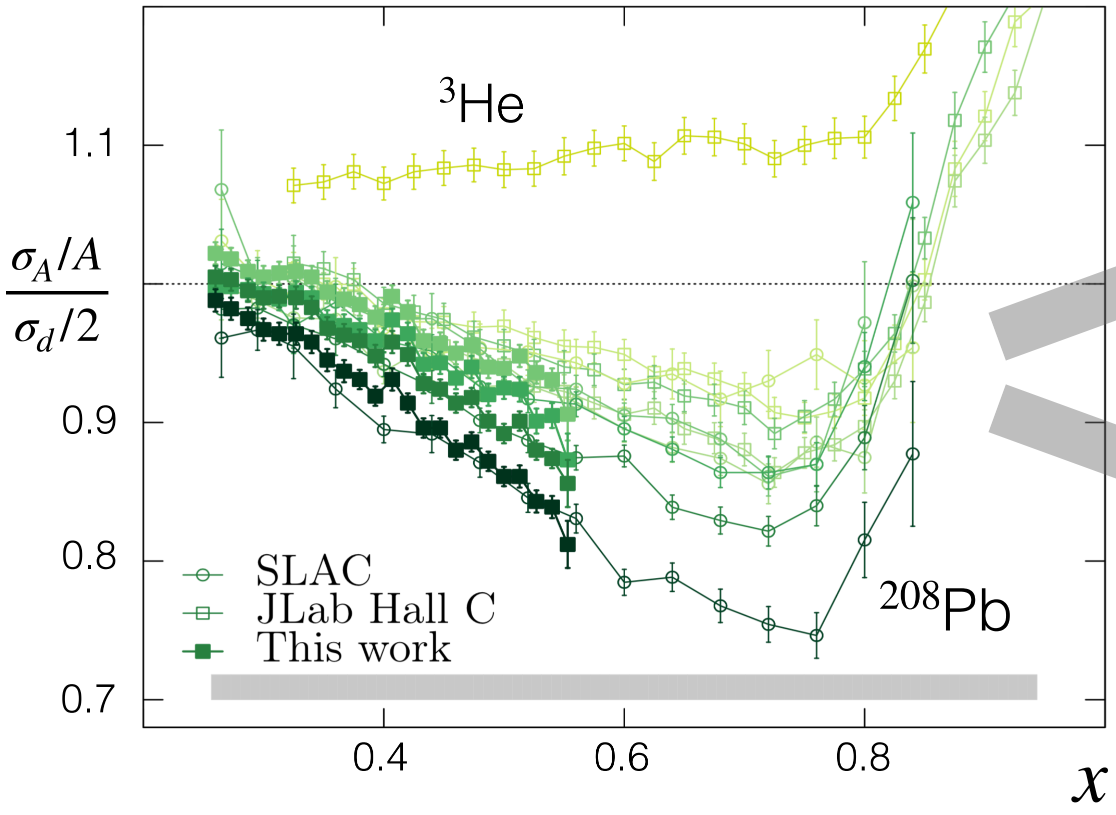
EMC Effect and Free Neutron Structure

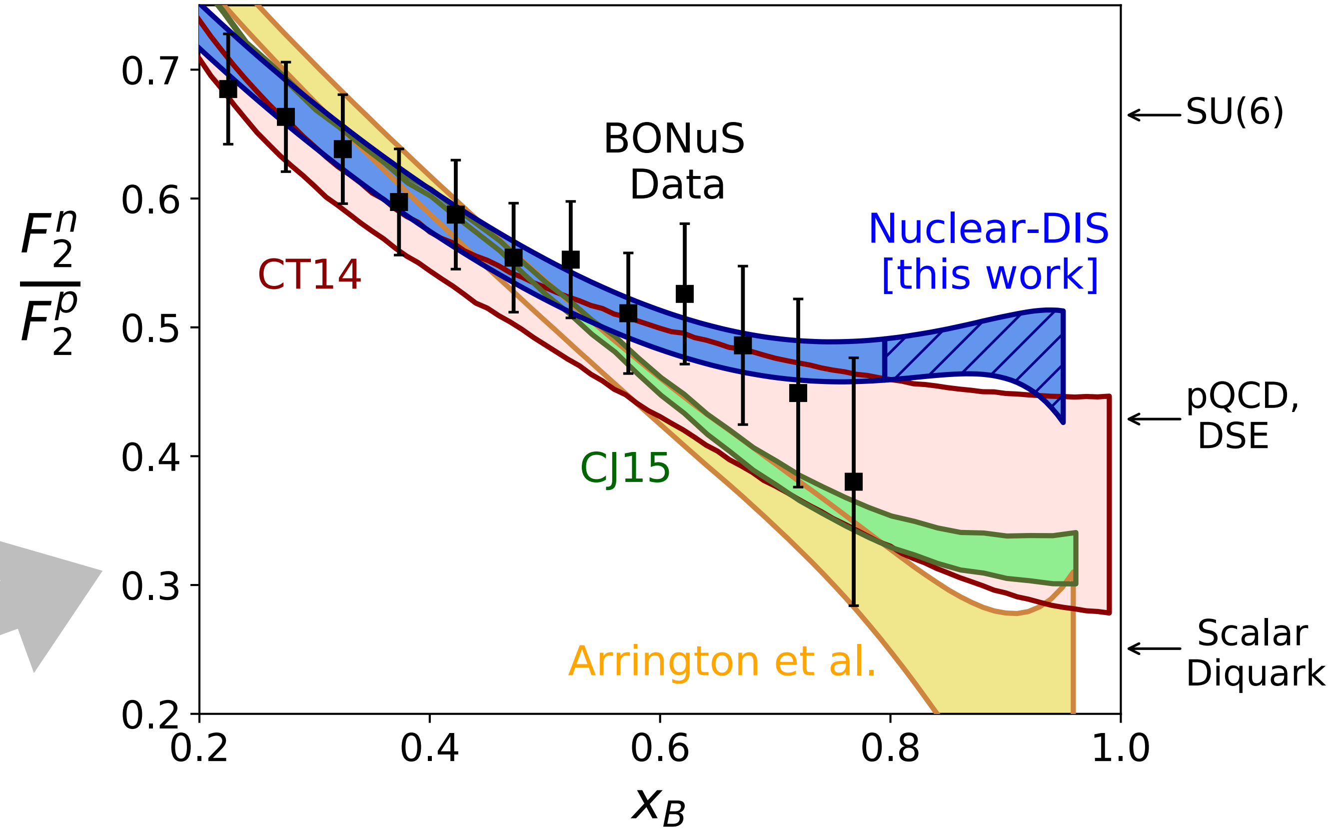
Efrain Segarra

From EMC to F_2^n and off-shell nature

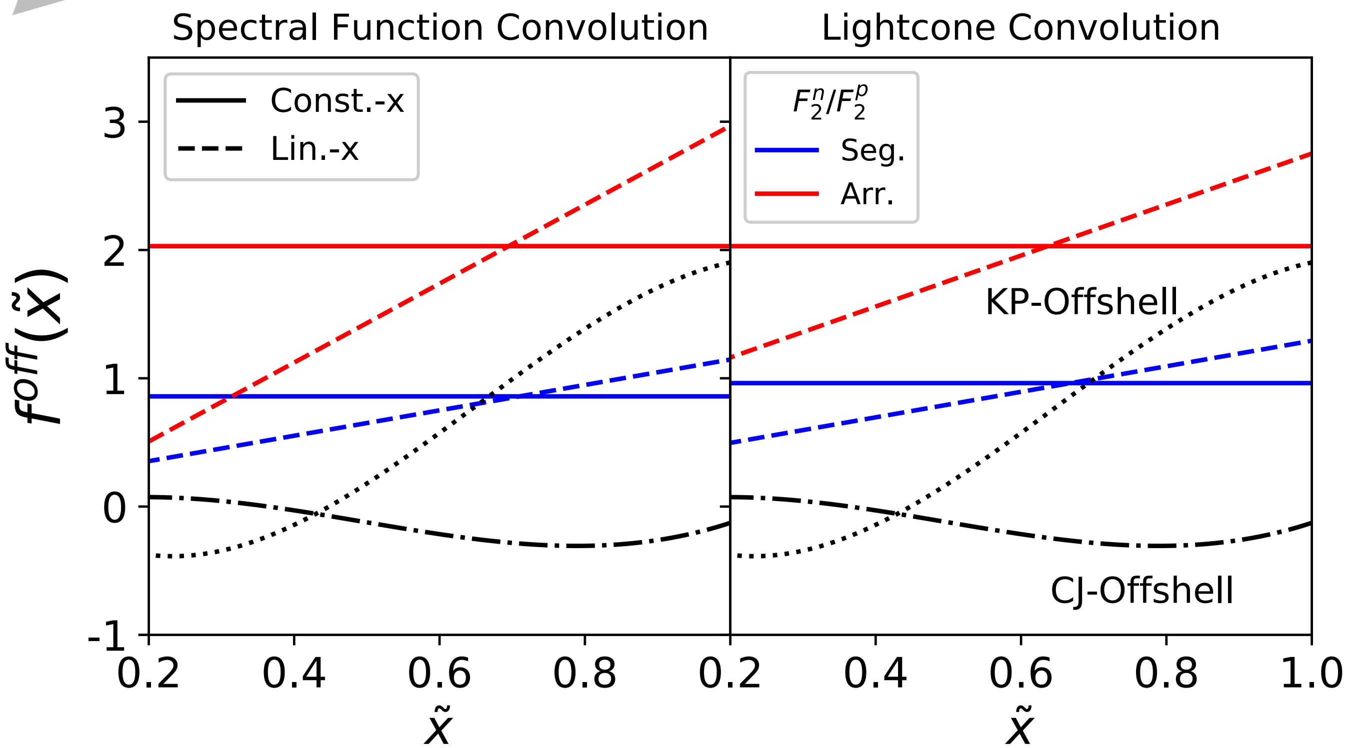
Nuclear EMC



Free neutron structure



Off-shell modification

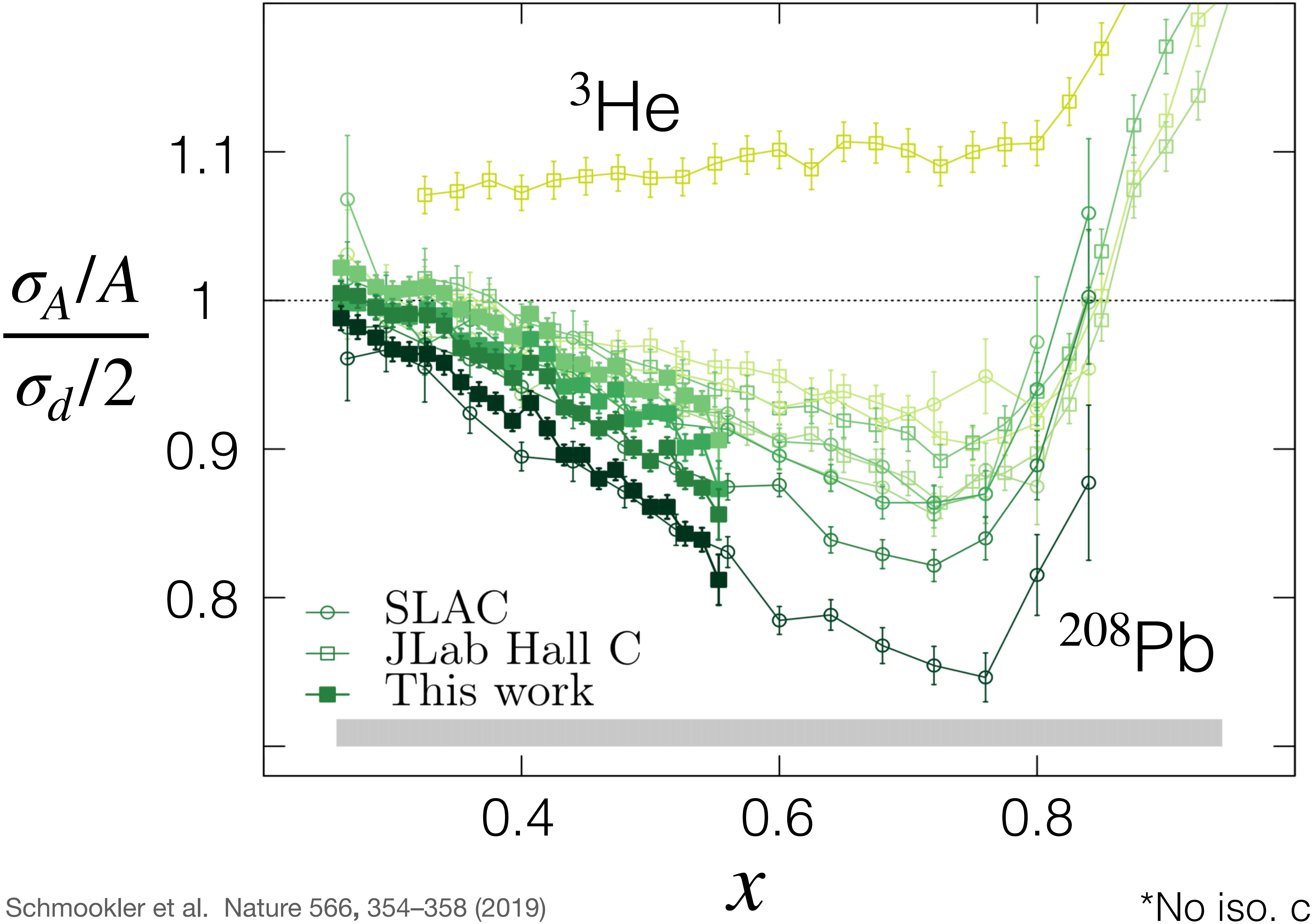


Schmookler et al. Nature 566, 354–358 (2019)

E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

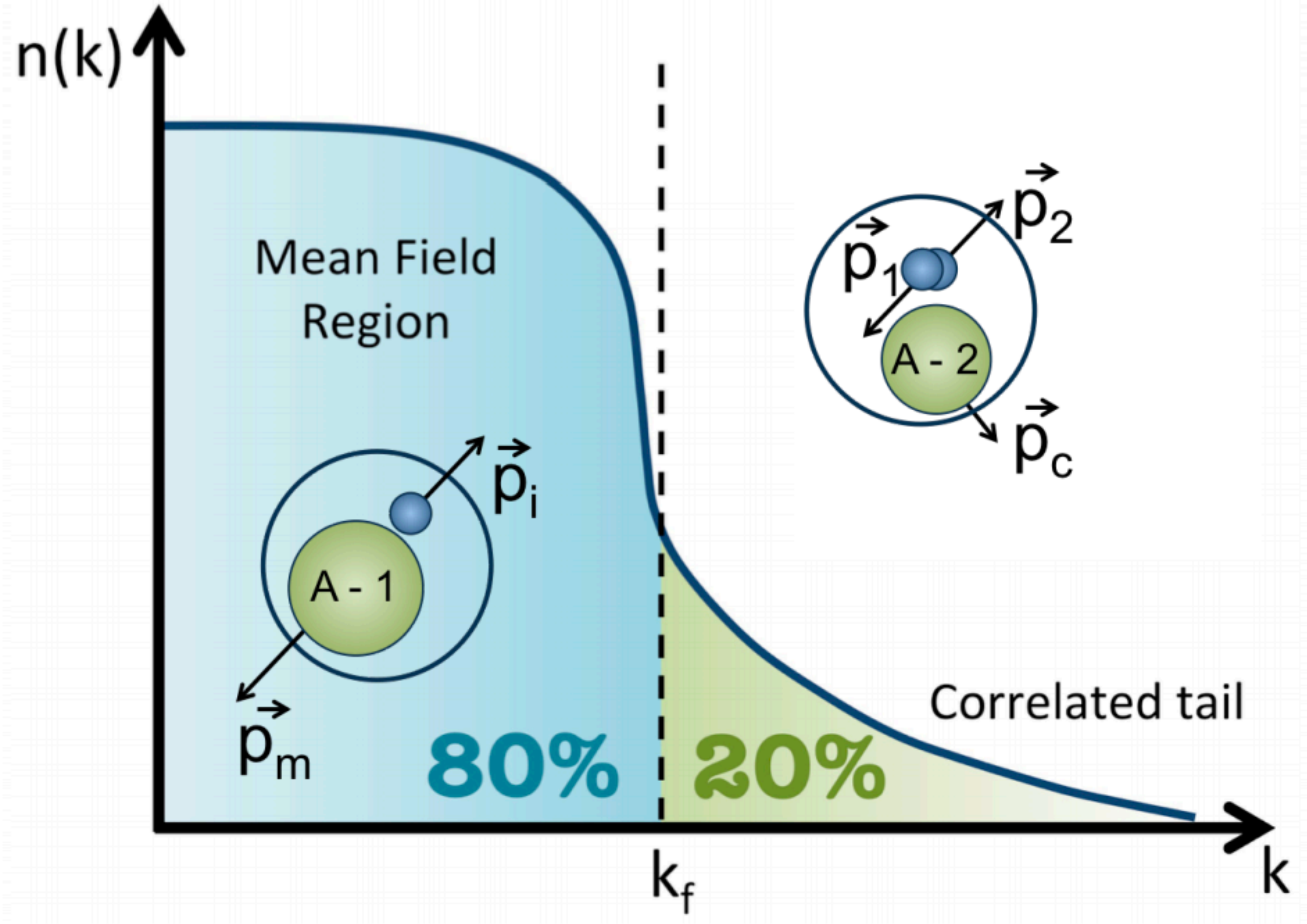
E.P. Segarra et al. arxiv 2006.10249 (submitted)

Bound nucleons are… well, complicated

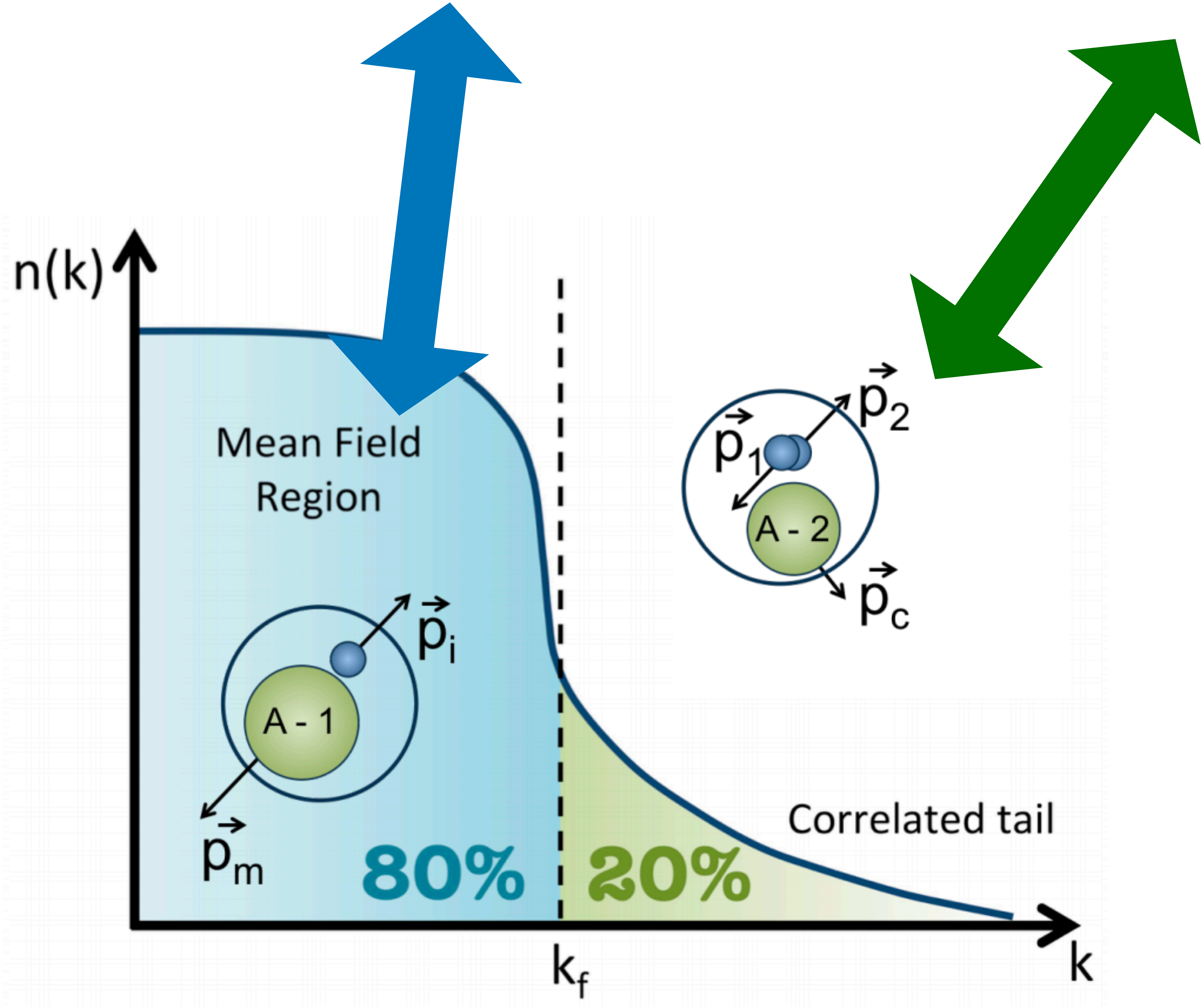


Schmookler et al. Nature 566, 354–358 (2019)

*No iso. corrections

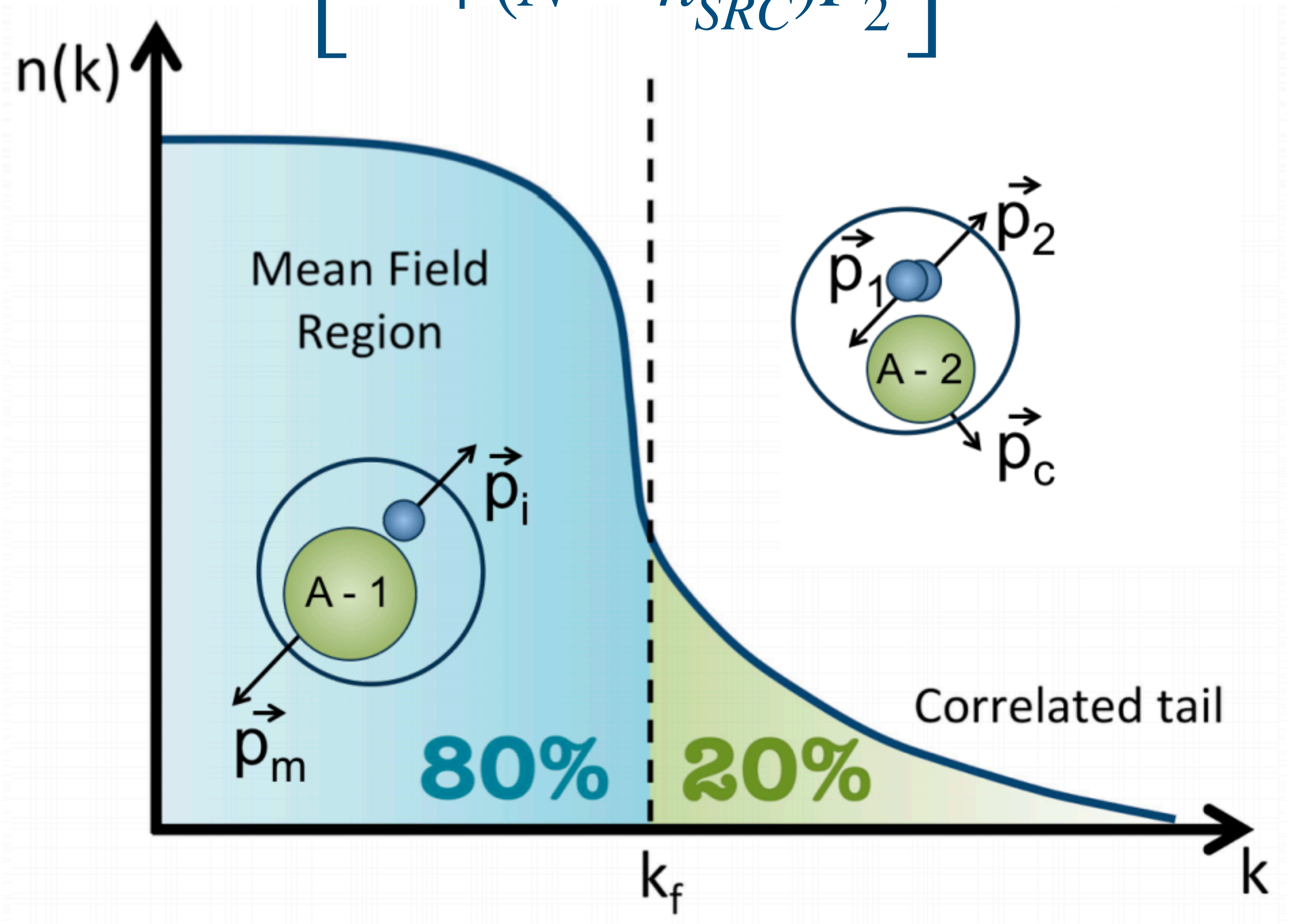

n(k)
Mean Field Region
$\vec{p}_i$
A - 1
$\vec{p}_m$
80%
$\vec{p}_2$
$\vec{p}_1$
A - 2
$\vec{p}_c$
Correlated tail
20%
k_f
k

“Bound” = “Quasi-Free” + “Modified SRC nucleons”



“Bound” = “Quasi-Free” + “Modified SRC nucleons”

$$F_2^A = \left[\begin{array}{l}(Z - n_{SRC}^A)F_2^p \\ \quad +(N - n_{SRC}^A)F_2^n\end{array}\right] + n_{SRC}^A\left(F_2^{p*} + F_2^{n*}\right)$$



EMC-SRC hypothesis proposes universal behavior

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \underbrace{\left(\Delta F_2^p + \Delta F_2^n\right)}_{\text{Nucleus-independent}}$$

EMC-SRC hypothesis proposes universal behavior

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \underbrace{\left(\Delta F_2^p + \Delta F_2^n\right)}_{\text{Nucleus-independent}}$$

If we want to extract modification,
we have to deal with F_2^n

EMC-SRC hypothesis proposes universal behavior

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \left(\Delta F_2^p + \Delta F_2^n \right)$$

$$F_2^d = F_2^p + F_2^n + n_{SRC}^d \left(\Delta F_2^p + \Delta F_2^n \right)$$

$$F_2^A = (Z - N)\, F_2^p + NF_2^d + \left(n_{SRC}^A - N n_{SRC}^d \right) \left(\Delta F_2^p + \Delta F_2^n \right)$$

Treat **all** bound nucleon structure **consistently** with **all** nuclear DIS and QE data

Extracting universal behavior in nuclei

$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

Universal function

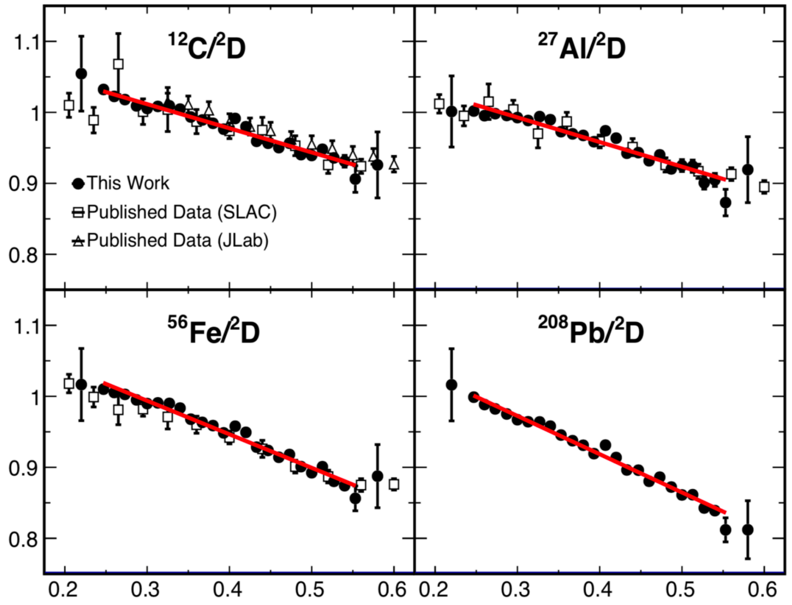
E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Extracting universal behavior in nuclei

$$\frac{F_2^A}{F_2^d} = (Z - N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

Universal function

EMC-DIS Data



$x \in [0.08, 0.95]$ $Q^2 \in [2, 15]$ GeV^2

^{3}He, ^{4}He, ^{9}Be, ^{12}C, ^{27}Al, ^{56}Fe, ^{197}Au, ^{208}Pb

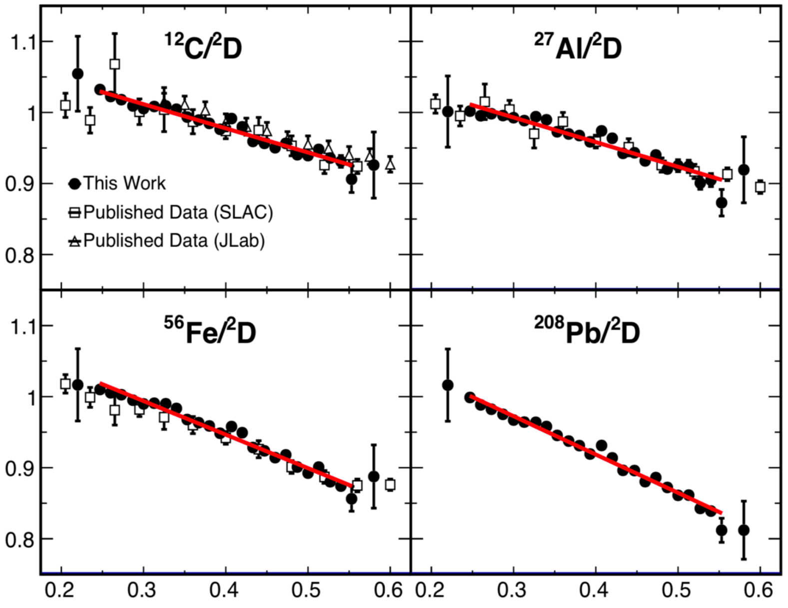
E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Extracting universal behavior in nuclei

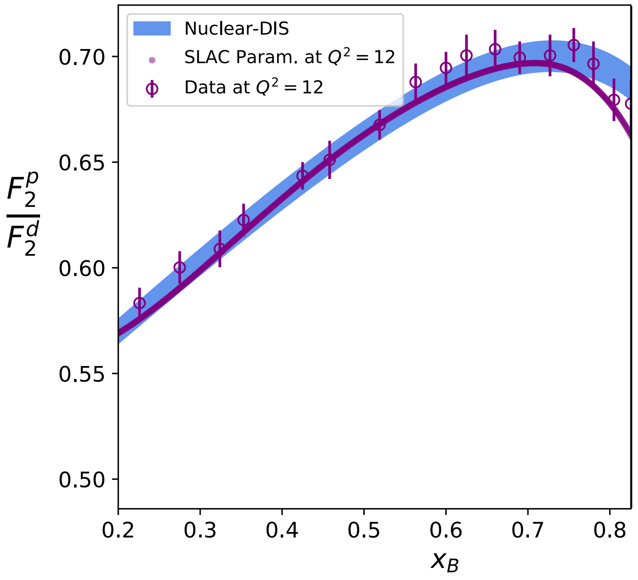
$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

Universal function

EMC-DIS Data



F_2^p/F_2^d Data



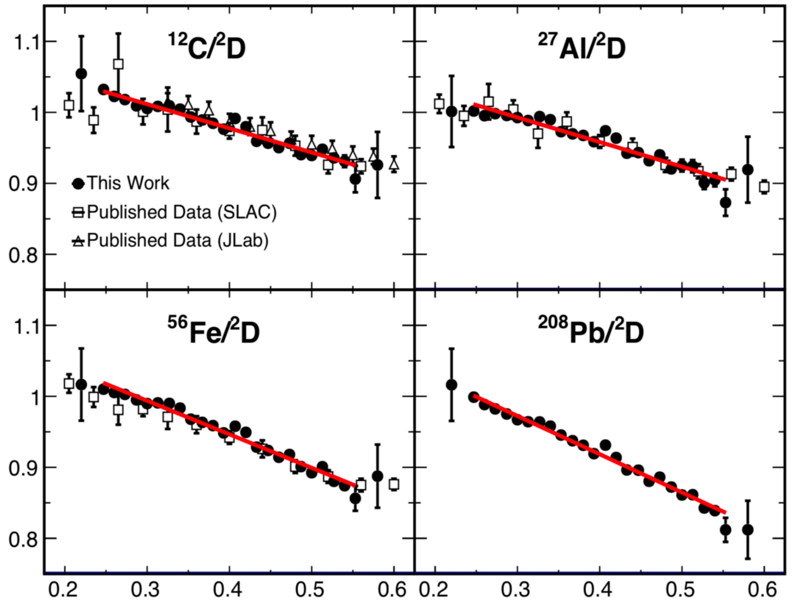
E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Extracting universal behavior in nuclei

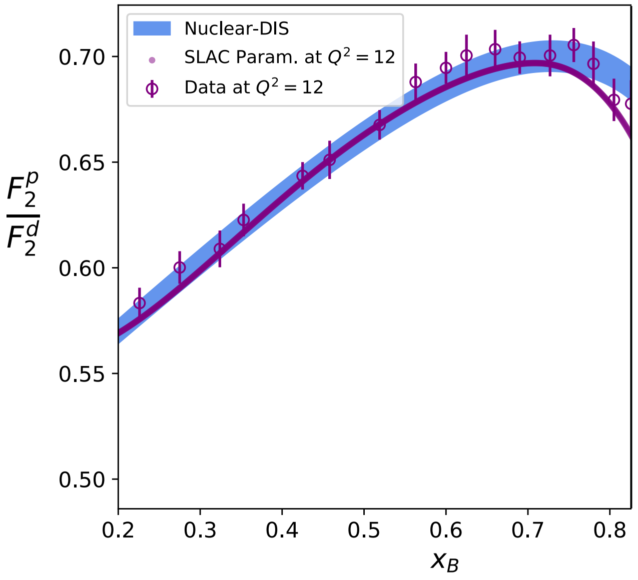
$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

Universal function

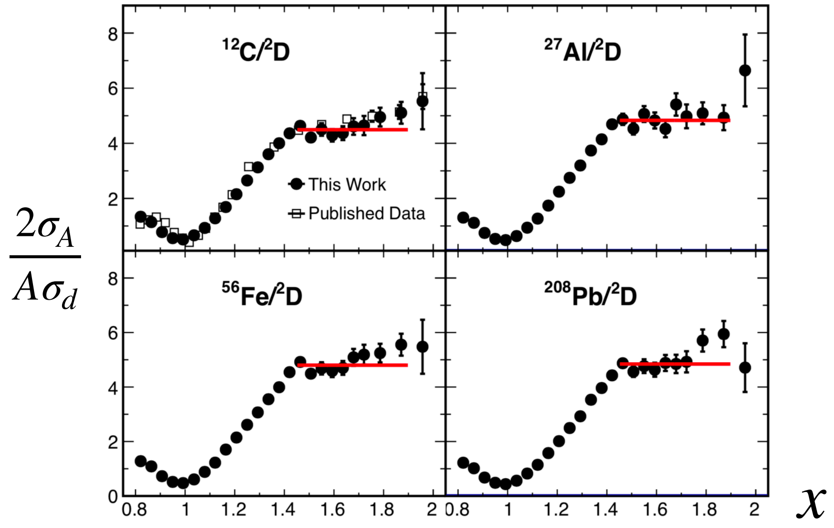
EMC-DIS Data



F_2^p/F_2^d Data



a_2 Pair Abundances

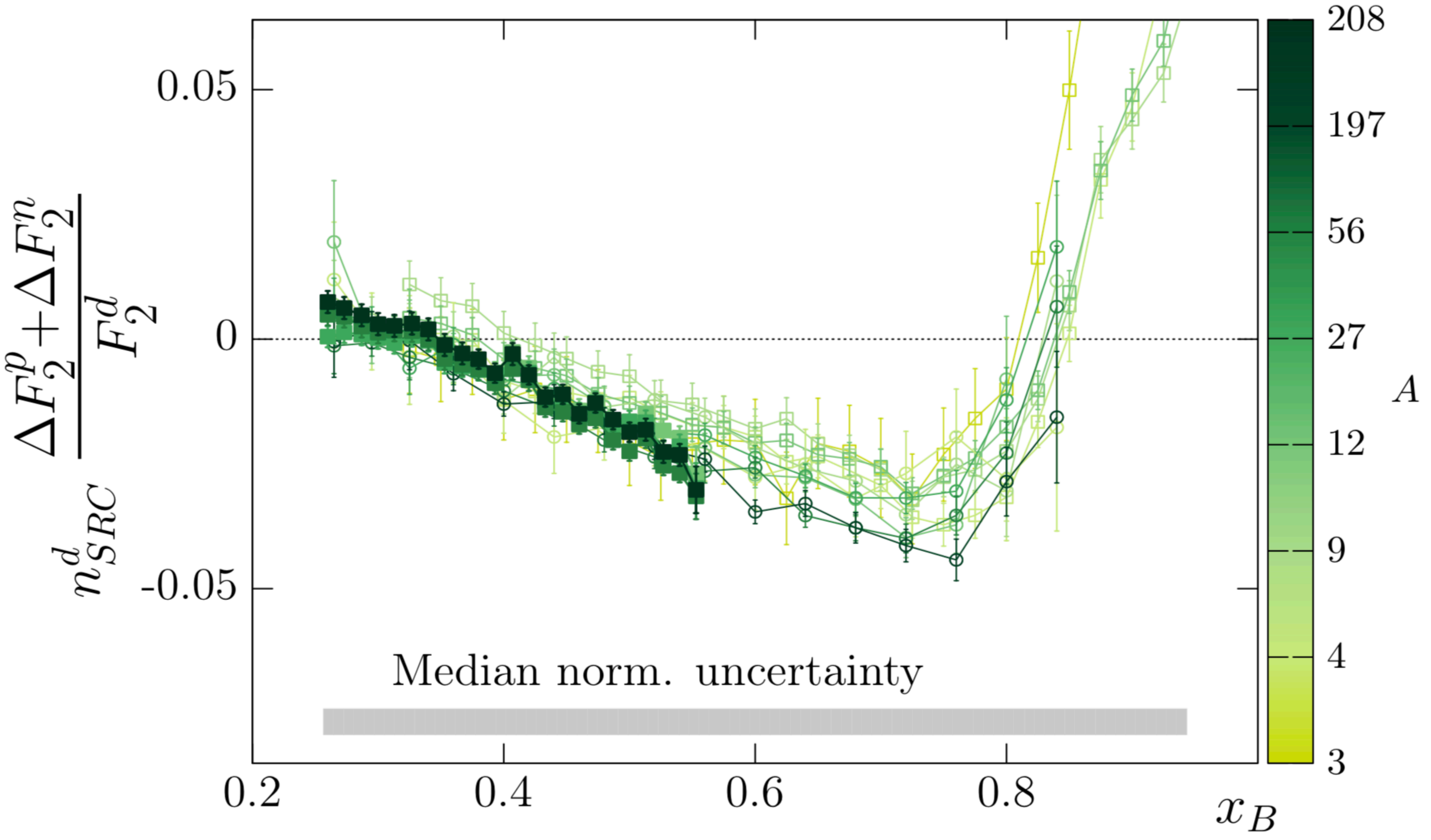


E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Data suggests universal behavior

$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n_{SRC}^A}{n_{SRC}^d} - N\right)\frac{n_{SRC}^d}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

Universal function



Schmookler et al. Nature 566, 354–358 (2019)

Extract universal function using Bayesian inference via Hamiltonian Markov Chain Monte Carlo

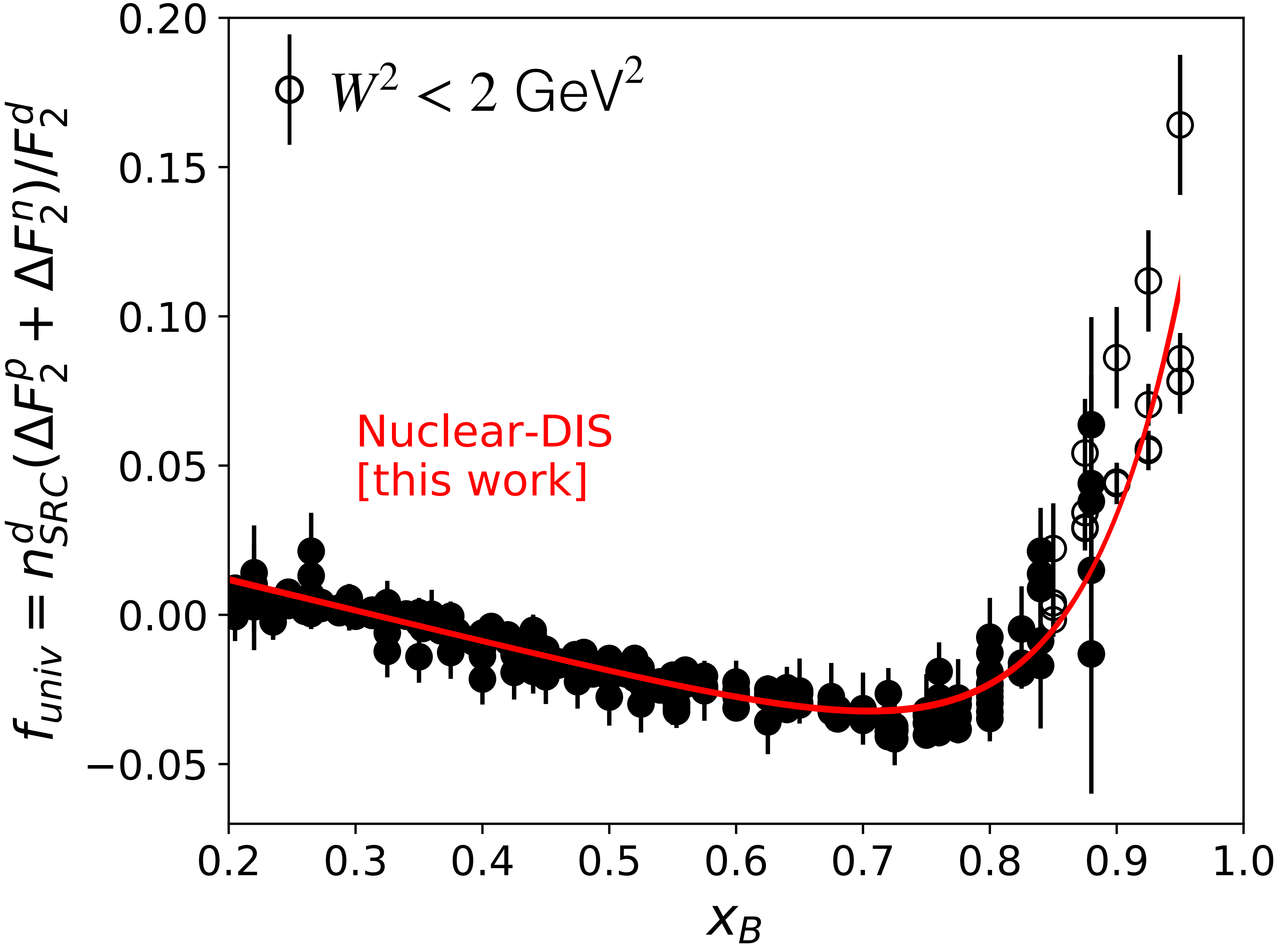
$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n^A_{SRC}}{n^d_{SRC}} - N\right)\frac{n^d_{SRC}}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

Consistent, simultaneous global extraction of model parameters sampled from joint-posterior distribution

$f_{univ}(x)$ $R_{pd}(x)$ $\vec{s}_i$ $\vec{a}_2(A/d)$

E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

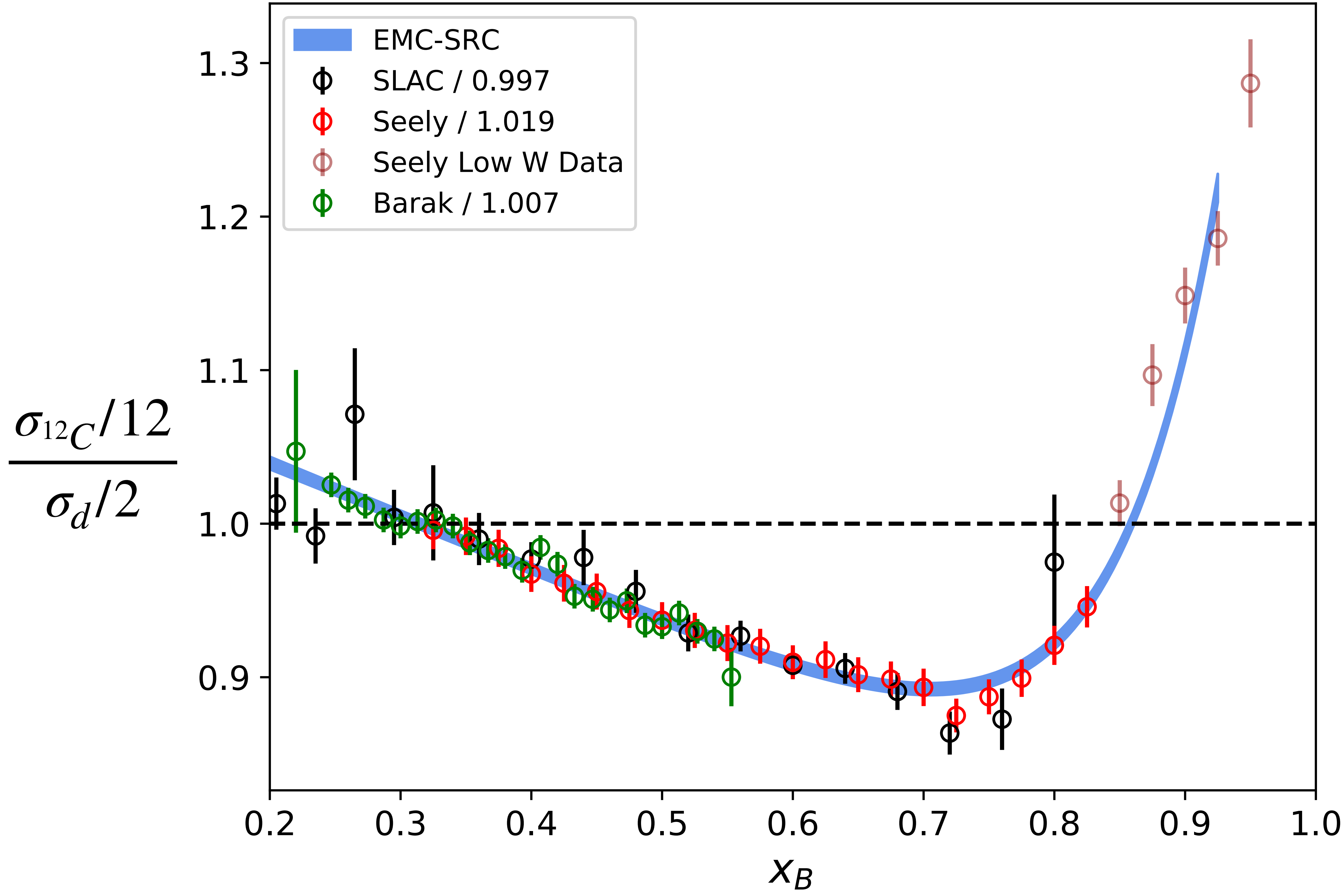
Universal function of nuclei



$$\frac{F_2^A}{F_2^d} = (Z-N)\frac{F_2^p}{F_2^d} + N + \left(\frac{n^A_{SRC}}{n^d_{SRC}} - N\right)\frac{n^d_{SRC}}{F_2^d}\left(\Delta F_2^p + \Delta F_2^n\right)$$

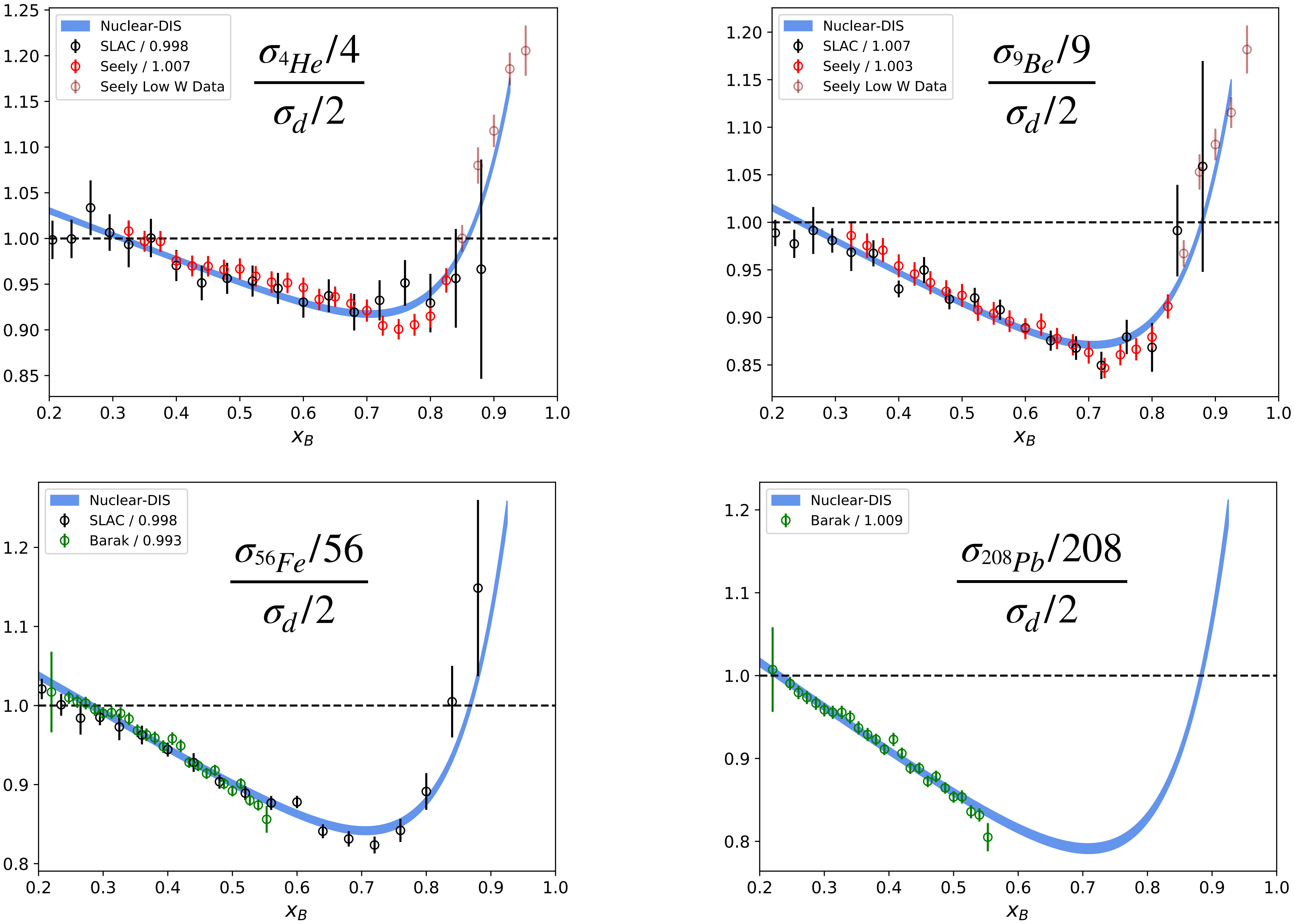
E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Reproduce the data remarkably well



E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Reproduce the data remarkably well



E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

What about neutron structure F_2^n?

Past approaches to get F_2^n

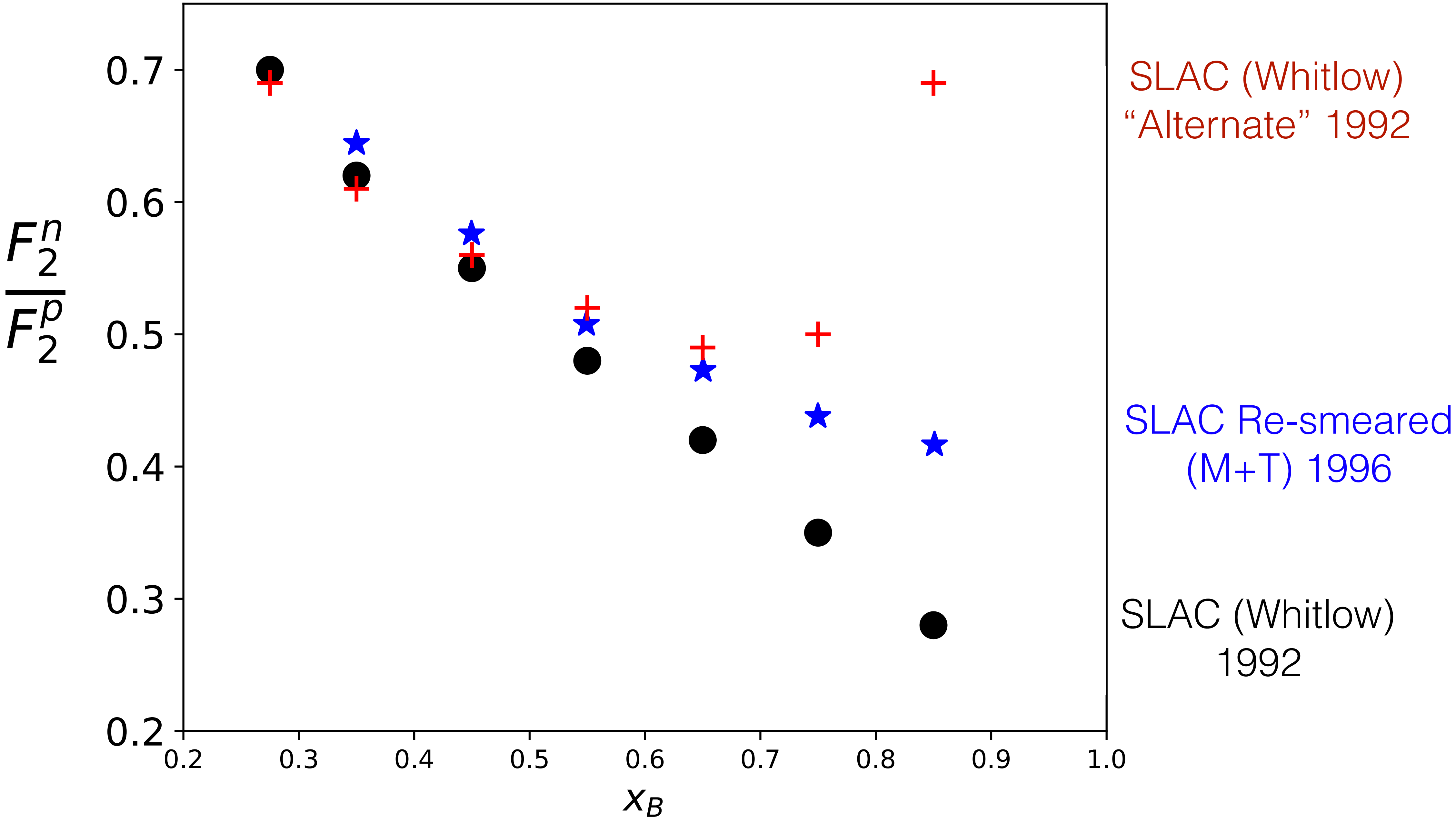
$$F_2^d \approx F_2^p + F_2^n$$

How to treat deuterium to get out neutron?

Smearing, off-shell, etc..

Past approaches to get F_2^n

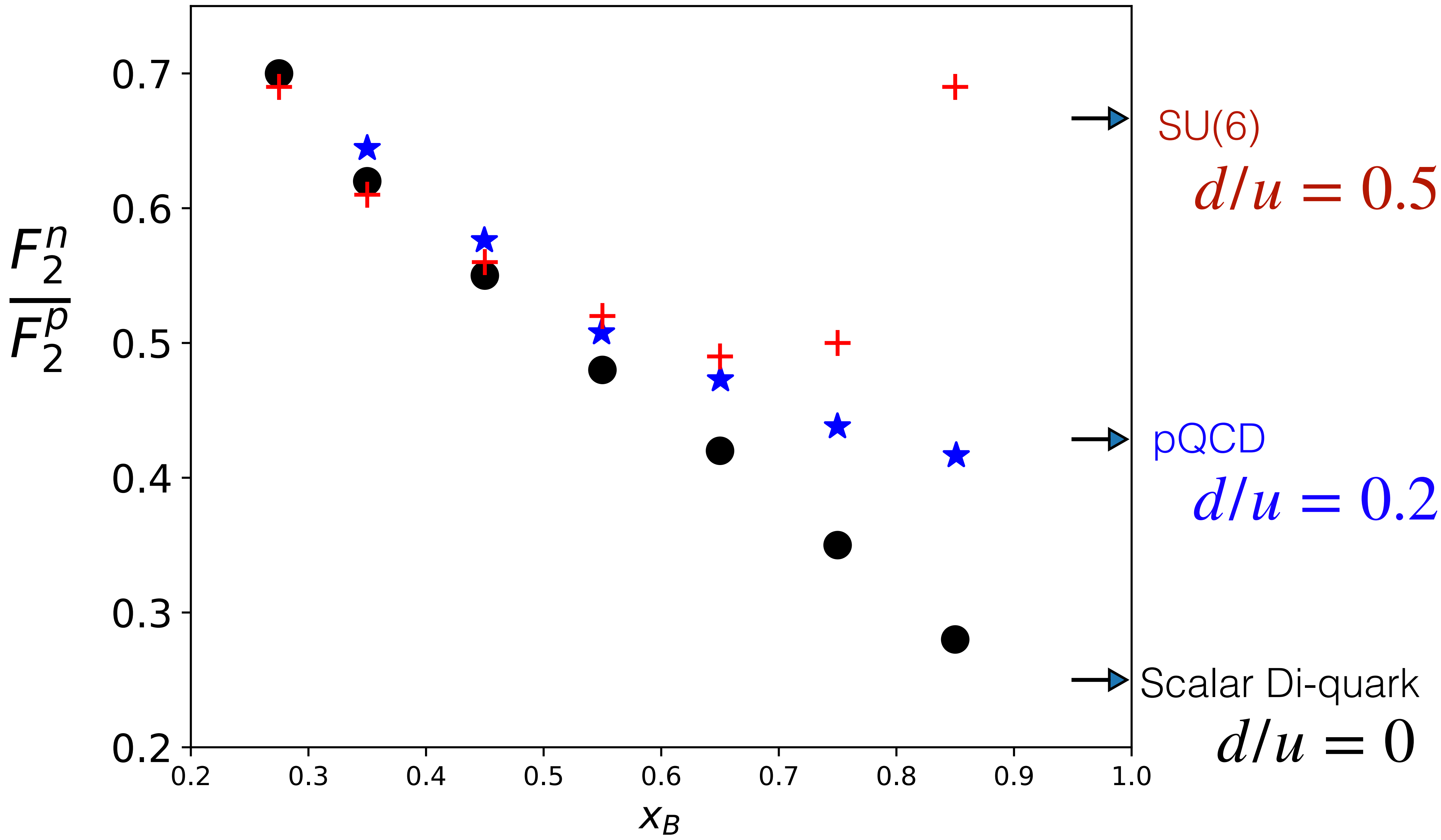
$$F_2^d \approx F_2^p + F_2^n$$



J. Arrington, J.G. Rubin, W. Melnitchouk (2011)

Large-*x* informs fundamental symmetry breaking

$$p\uparrow = \frac{1}{\sqrt{2}} u\uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}} u\uparrow (ud)_{S=1} - \frac{1}{3} u\downarrow (ud)_{S=1} - \frac{1}{3} d\uparrow (uu)_{S=1} - \frac{\sqrt{2}}{3} d\downarrow (uu)_{S=1}$$



J. Arrington, J.G. Rubin, W. Melnitchouk (2011)

EMC-SRC hypothesis proposes universal behavior

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \left(\Delta F_2^p + \Delta F_2^n \right)$$

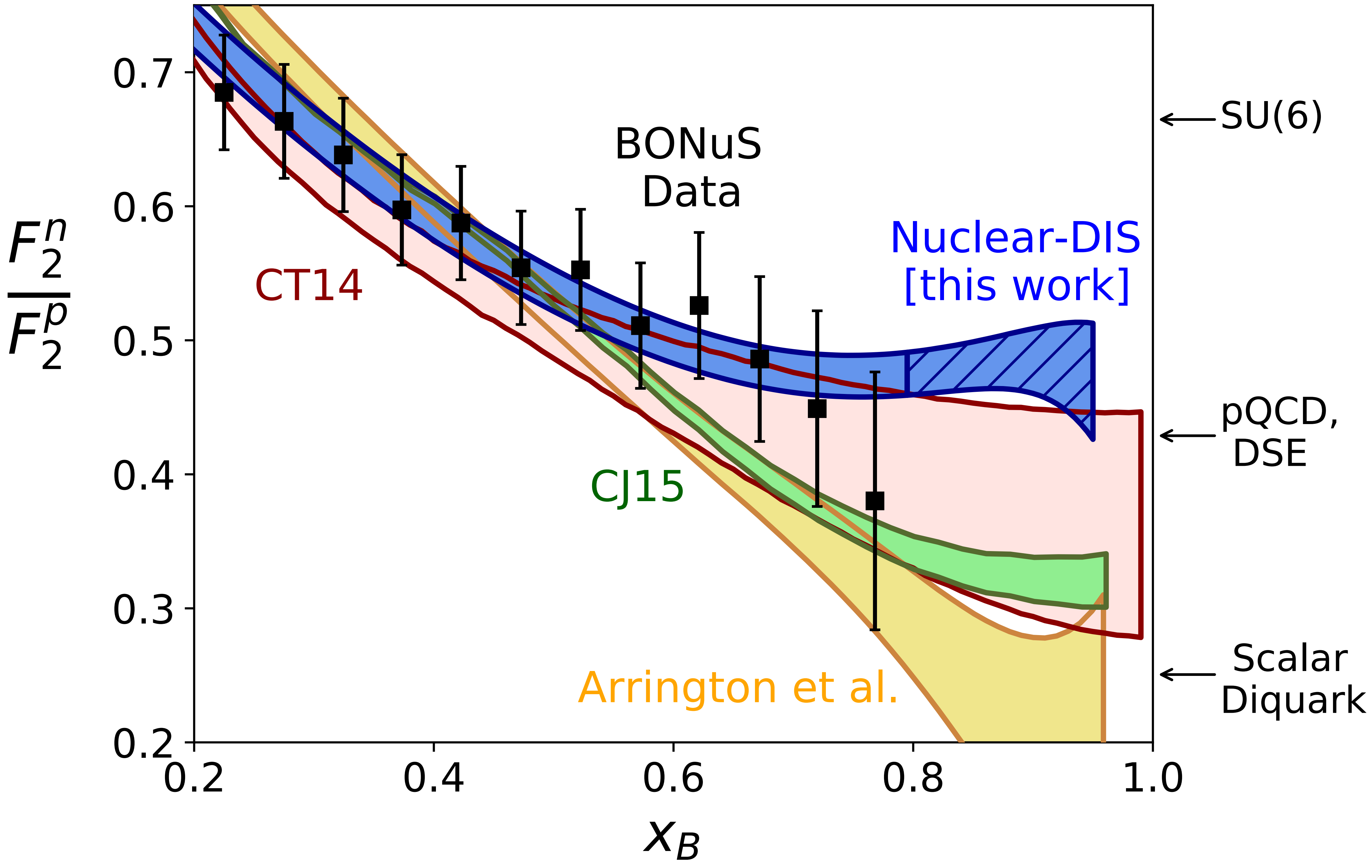
$$F_2^d = F_2^p + F_2^n + n_{SRC}^d \left(\Delta F_2^p + \Delta F_2^n \right)$$

$$F_2^A = (Z - N)\, F_2^p + NF_2^d + \left(n_{SRC}^A - Nn_{SRC}^d \right) \left(\Delta F_2^p + \Delta F_2^n \right)$$

Treat **all** bound nucleon structure **consistently** with **all** nuclear DIS and QE data

Extracting free neutron structure

$$\frac{F_2^n}{F_2^p} = \frac{1 - f_{univ}}{F_2^p / F_2^d} - 1$$



E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Another way to access F_2^n from A=3 nuclei

(MARATHON Experiment, Hall A Jefferson Lab)

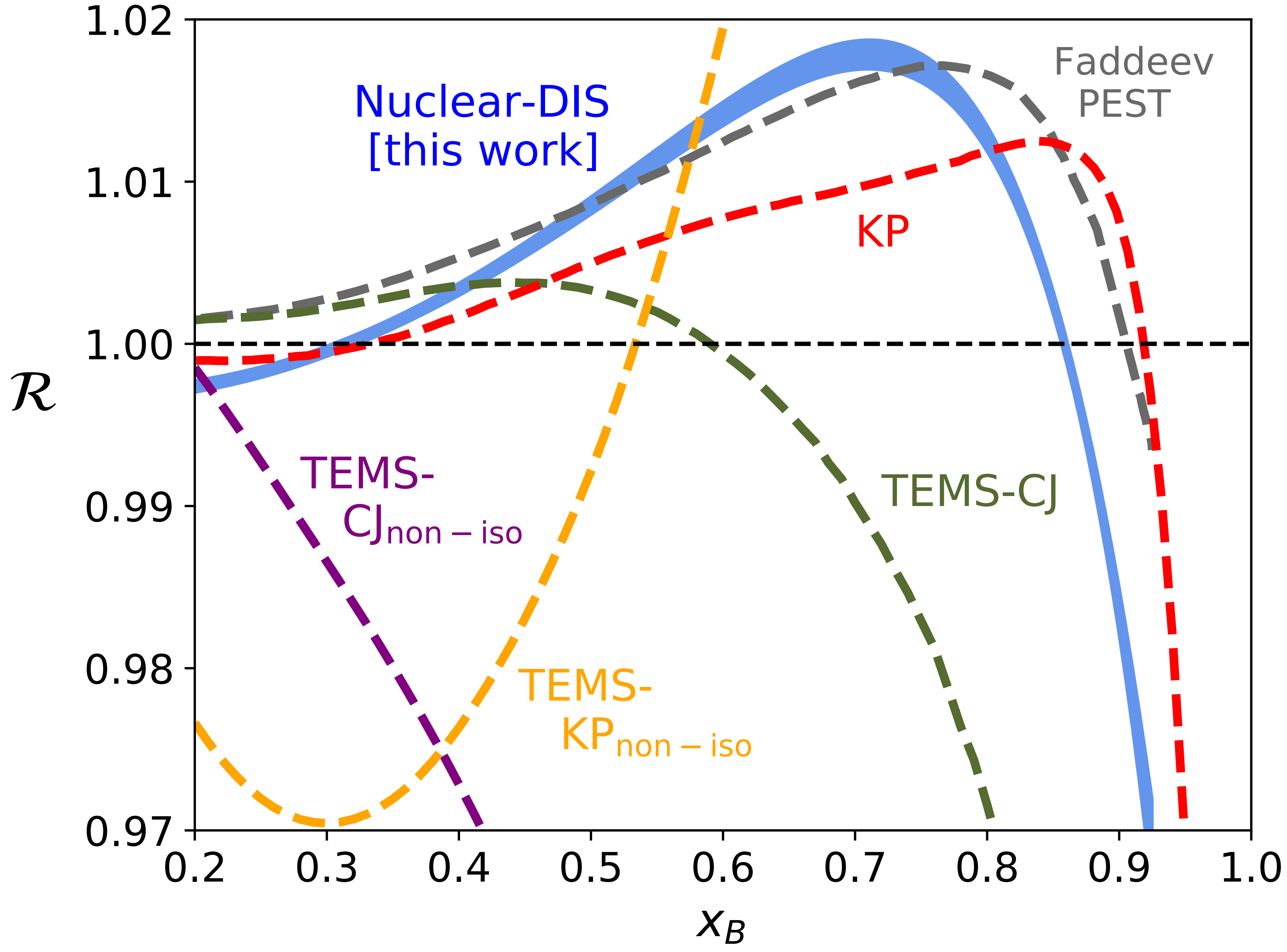
$$\frac{F_2^n}{F_2^p} = \frac{2\mathscr{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathscr{R}}$$

Measured

Theoretical input

$$\mathscr{R} = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \cdot \frac{F_2^p + 2F_2^n}{F_2^{^3H}}$$

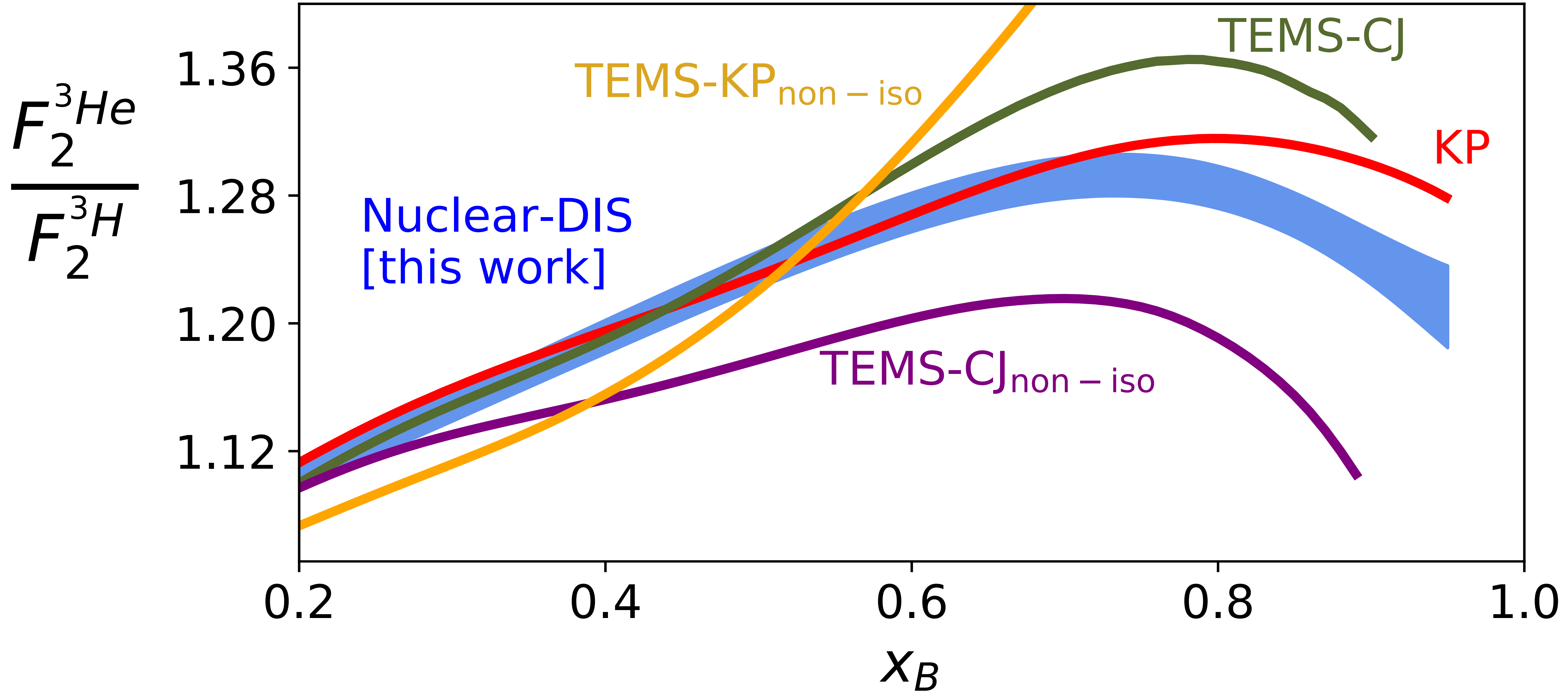
Super-ratio theoretical input



E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

(Model uncertainty for others not shown)

EMC Prediction for A=3



E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

(Model uncertainty for others not shown)

How sensitive is result to theory model?

$$\frac{F_2^n}{F_2^p} = \frac{2\mathscr{R} - F_2^{^3He}/F_2^{^3H}}{2F_2^{^3He}/F_2^{^3H} - \mathscr{R}}$$

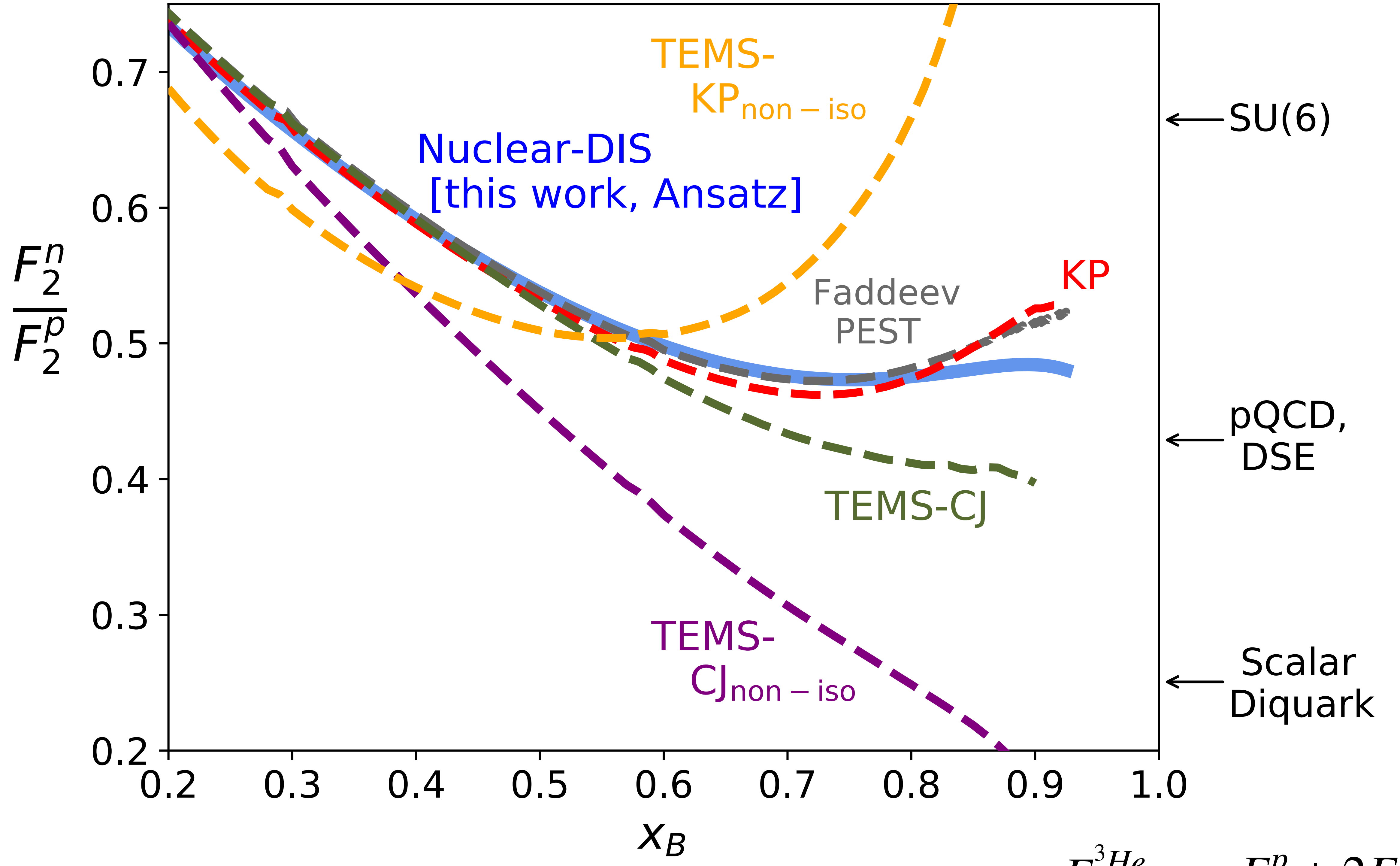
Use our model prediction

Try different theory predictions

$$\mathscr{R} = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \cdot \frac{F_2^p + 2F_2^n}{F_2^{^3H}}$$

E.P. **Segarra** et al. Phys. Rev. Lett. 124, 092002 (2020)

Extraction of F_2^n/F_2^p sensitive to theory at high-x



$$\mathscr{R} = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \cdot \frac{F_2^p + 2F_2^n}{F_2^{^3H}}$$

E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

Another approach to disentangle F_2^n and off-shellness

SRC-EMC hypothesis:

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A \underbrace{\left(\Delta F_2^p + \Delta F_2^n\right)}_{\substack{\text{this includes nucleon} \\ \text{motion and off-shell} \\ \text{modification all in one}}}$$

Another approach to disentangle F_2^n and off-shellness

SRC-EMC hypothesis:

$$F_2^A = ZF_2^p + NF_2^n + n_{SRC}^A\left(\Delta F_2^p + \Delta F_2^n\right)$$

Convolution approach:

$$F_2^A = \int_{x_B}^{A} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} d\nu F_2^p(\tilde{x})\left[Z\rho_p(\alpha,\nu) + N\rho_n(\alpha,\nu)\frac{F_2^n(\tilde{x})}{F_2^p(\tilde{x})}\right] \cdot \underbrace{\left(1 + \nu f^{off}(\tilde{x})\right)}_{\text{off-shell modification}}$$

nucleon motion

With light nuclei, we have calculable $\rho_{p,n}(\alpha, \nu)$

Calculate F_2^A and compare with data to extract F_2^n and f^{off}

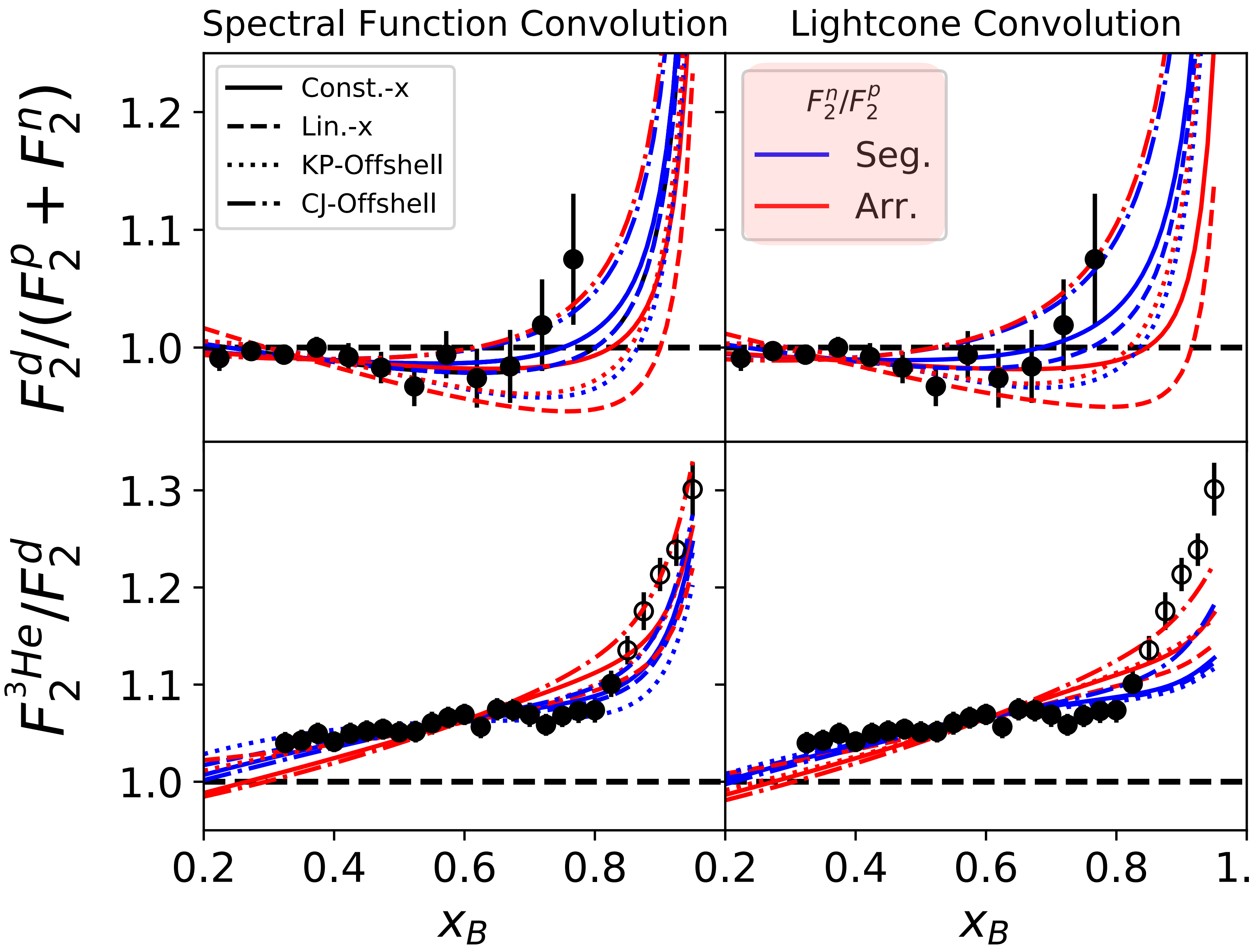
Convolution approach:

$$F_2^A = \int_{x_B}^{A} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} d\nu F_2^p(\tilde{x}) \left[Z\rho_p(\alpha,\nu) + N\rho_n(\alpha,\nu) \frac{F_2^n(\tilde{x})}{F_2^p(\tilde{x})} \right] \cdot \underbrace{\left(1 + \nu f^{off}(\tilde{x})\right)}_{\text{off-shell modification}}$$

free F_2^n structure

Deuterium, He-3 alone not very sensitive to F_2^n

$$F_2^A = \int_{x_B}^{A} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} d\nu F_2^p(\tilde{x}) \Big[Z\rho_p(\alpha,\nu) + N\rho_n(\alpha,\nu) \frac{F_2^n(\tilde{x})}{F_2^p(\tilde{x})} \Big] \cdot \big(1 + \nu f^{off}(\tilde{x})\big)$$



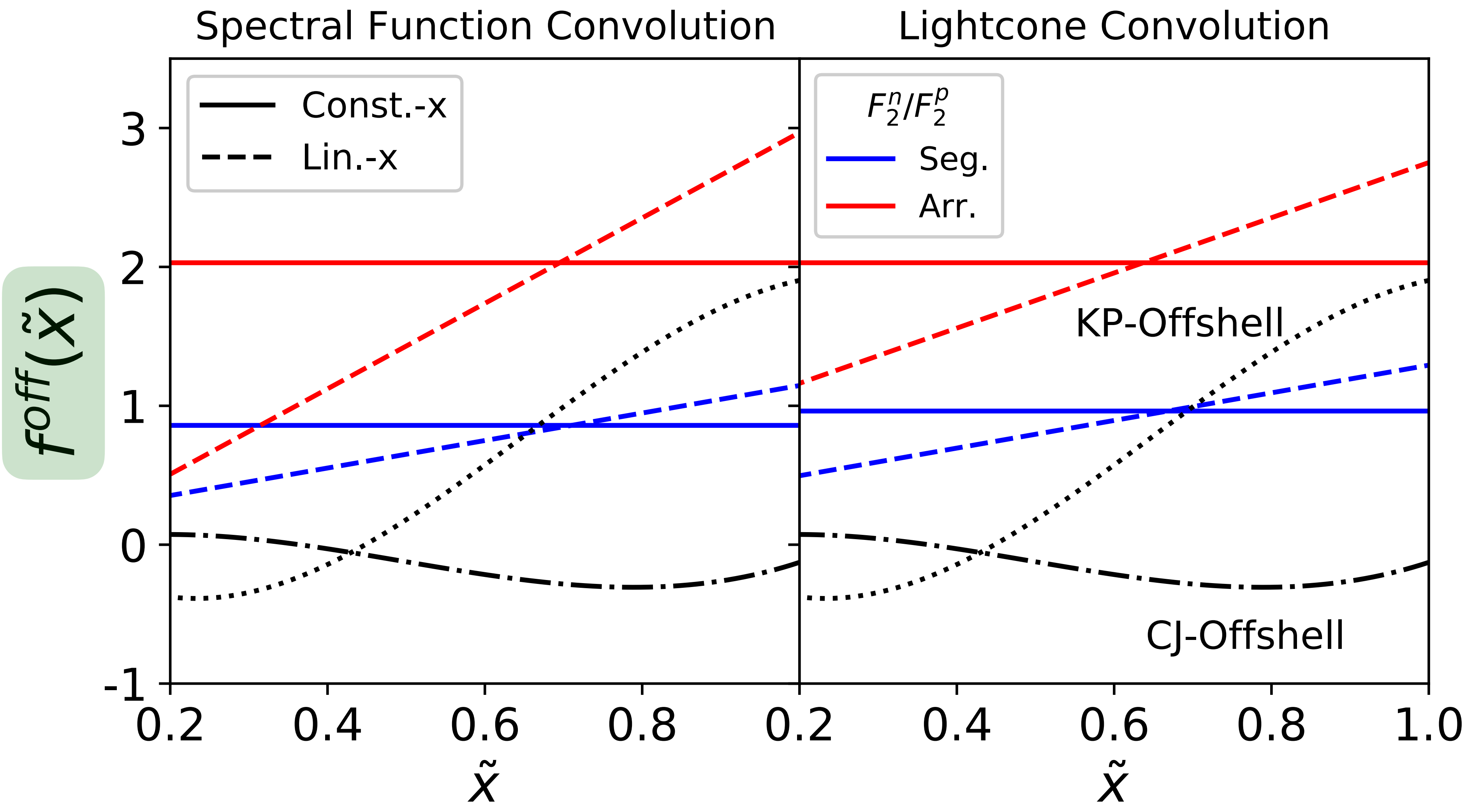
(MARATHON data will help nail this down)

E.P. Segarra et al. arxiv 2006.10249 (submitted)

Wide range of off-shell functions can describe data

$$F_2^A = \int_{x_B}^{A} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} d\nu F_2^p(\tilde{x}) \left[Z\rho_p(\alpha,\nu) + N\rho_n(\alpha,\nu) \frac{F_2^n(\tilde{x})}{F_2^p(\tilde{x})} \right] \cdot \left(1 + \nu f^{off}(\tilde{x})\right)$$

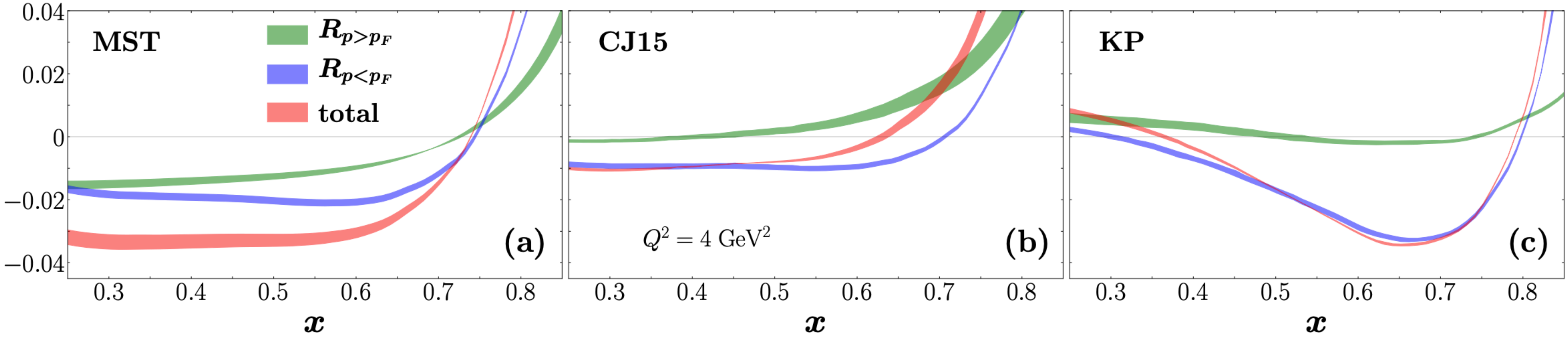
Degeneracy between off-shell and neutron structure



E.P. Segarra et al. arxiv 2006.10249 (submitted)

As Wang et al. mentioned, MF dominates full F_2^d

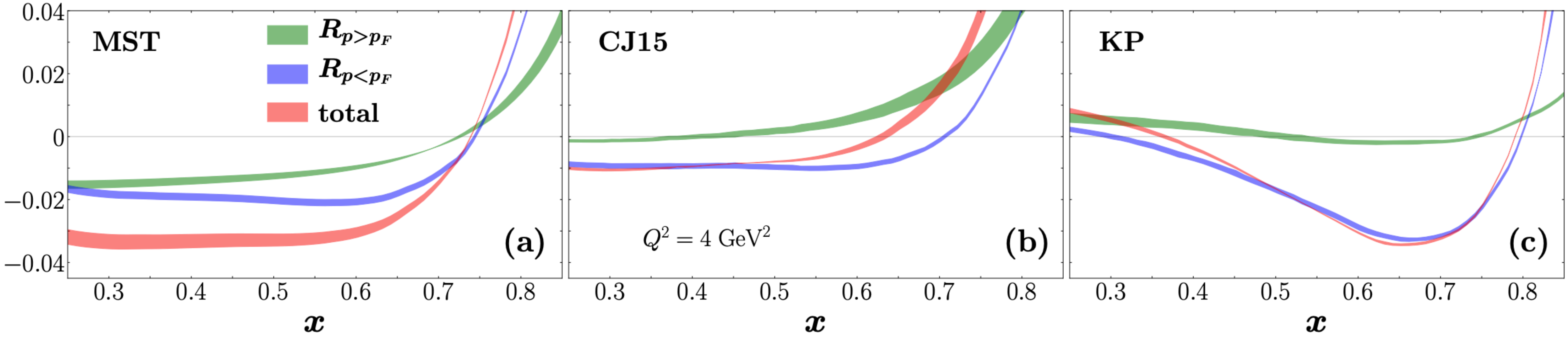
$$R = \frac{F_2^d - (F_2^p + F_2^n)}{F_2^d}$$



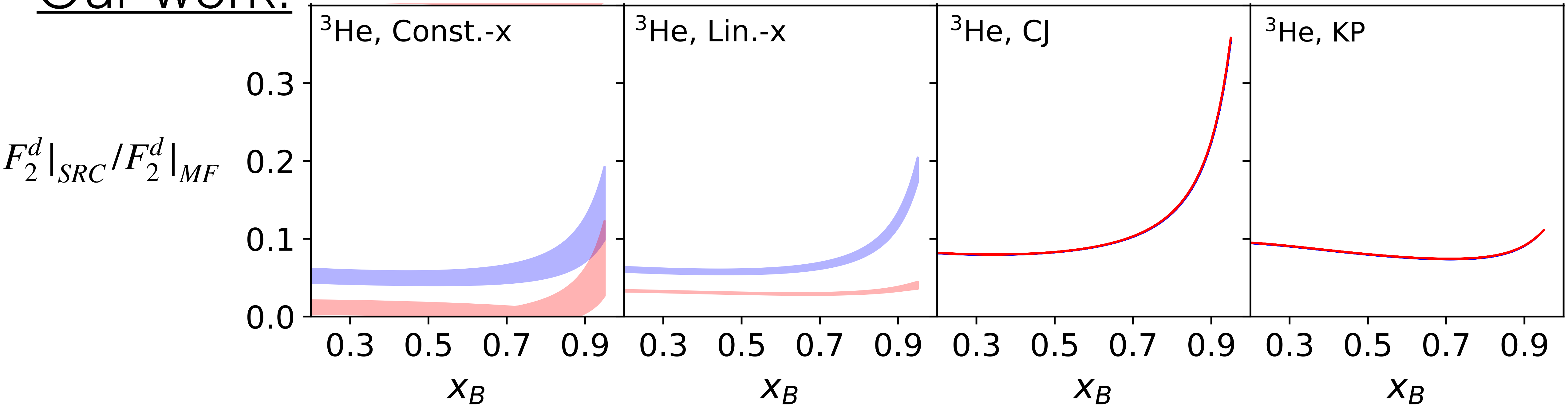
X.G. Wang et al., Phys. Rev. Lett. **125**, 262002 (2020)

As Wang et al. mentioned, MF dominates full F_2^d

$$R = \frac{F_2^d - (F_2^p + F_2^n)}{F_2^d}$$



Our work:



E.P. Segarra et al. arxiv 2006.10249 (submitted)

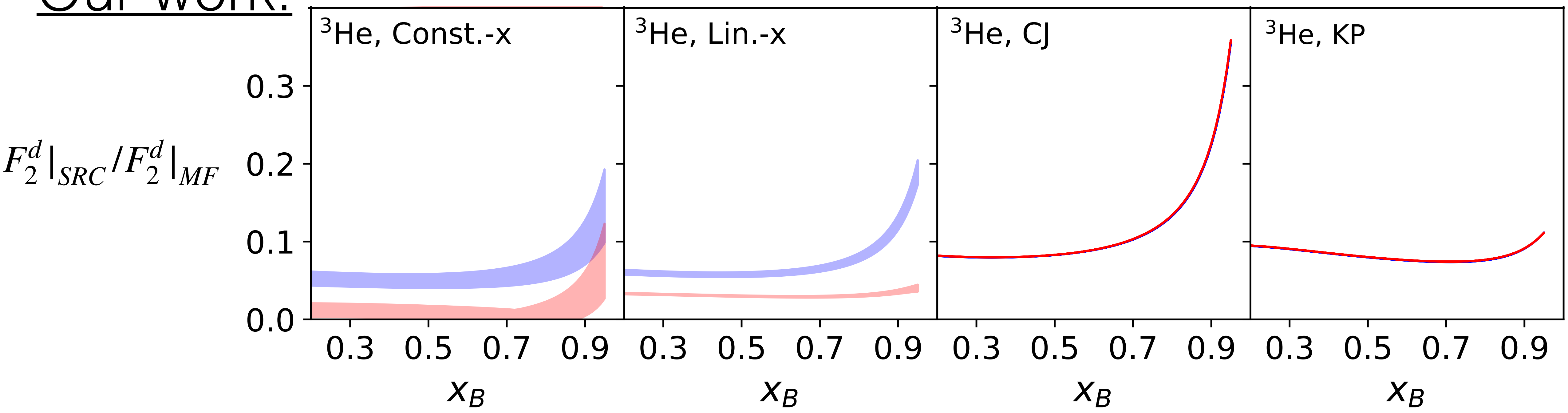
X.G. Wang et al., Phys. Rev. Lett. **125**, 262002 (2020)

As Wang et al. mentioned, MF dominates full F_2^d

This **combines** motion (big) and off-shell (small)

Low-momenta states dominate motion but **not** off-shell effect

Our work:



E.P. Segarra et al. arxiv 2006.10249 (submitted)

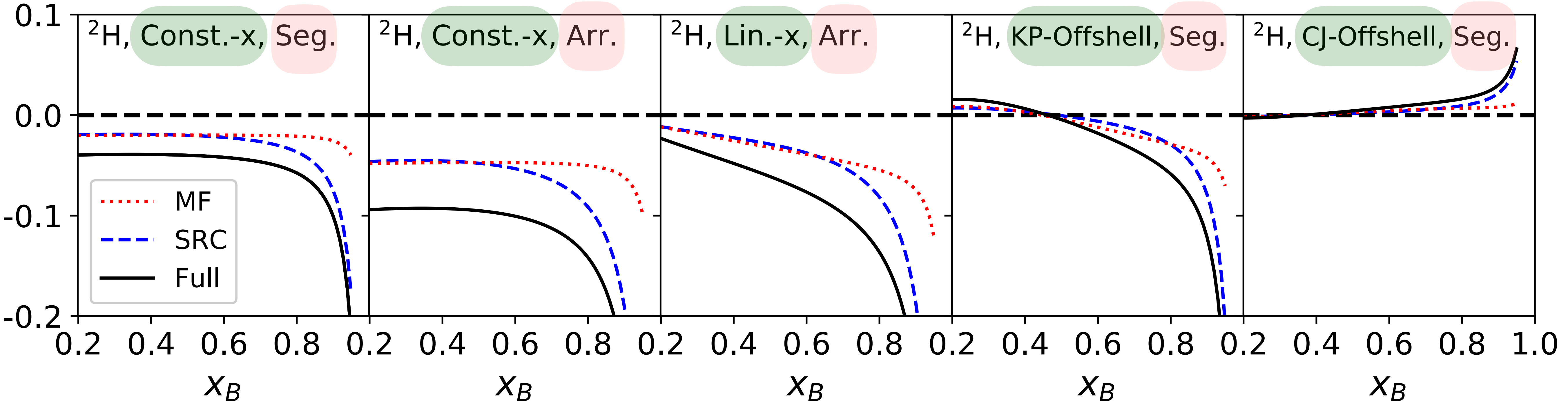
X.G. Wang et al., Phys. Rev. Lett. **125**, 262002 (2020)

But universal off-shell features exist

$$F_2^A = \int_{x_B}^{A} \frac{d\alpha}{\alpha} \int_{-\infty}^{0} d\nu F_2^p(\tilde{x}) \left[Z\rho_p(\alpha,\nu) + N\rho_n(\alpha,\nu) \frac{F_2^n(\tilde{x})}{F_2^p(\tilde{x})} \right] \cdot \left(1 + \nu f^{off}(\tilde{x})\right)$$

High momentum nucleons are <u>significant</u> component to off-shell contribution — more pronounced for He-3

Offshell contribution to F_2^d $\left(F_2^d|_{full} - F_2^d|_{no-mod}\right)$

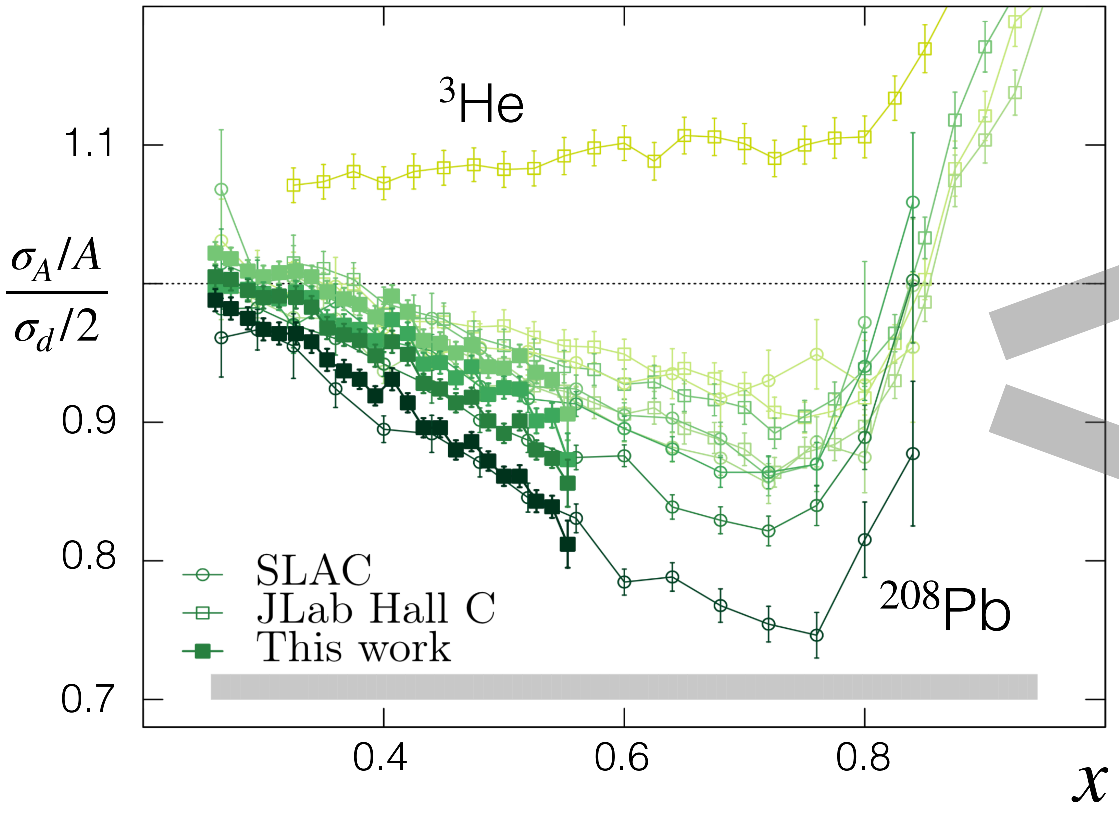


E.P. Segarra et al. arxiv 2006.10249 (submitted)

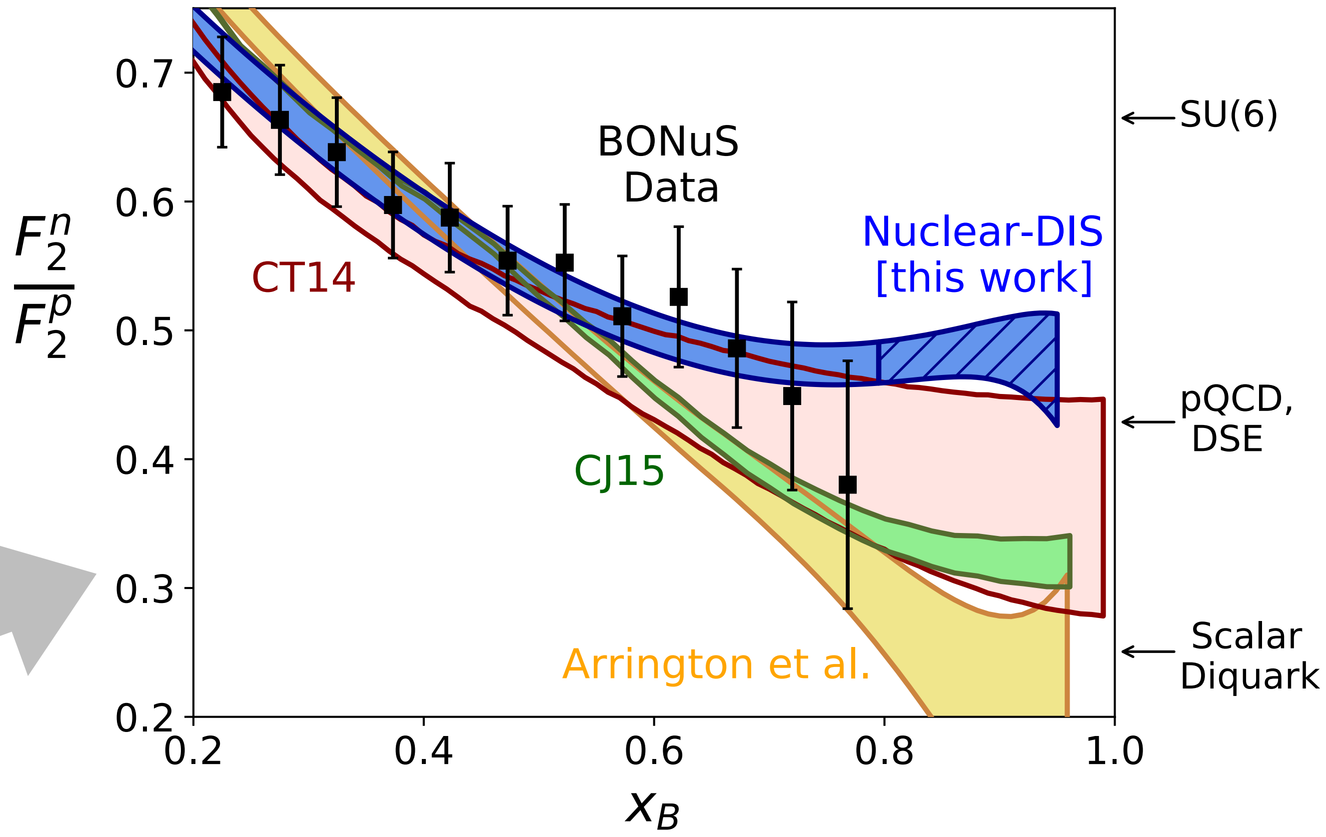
Upcoming MARATHON and BAND data will close the loop

(BAND - See talk by Tyler Kutz)

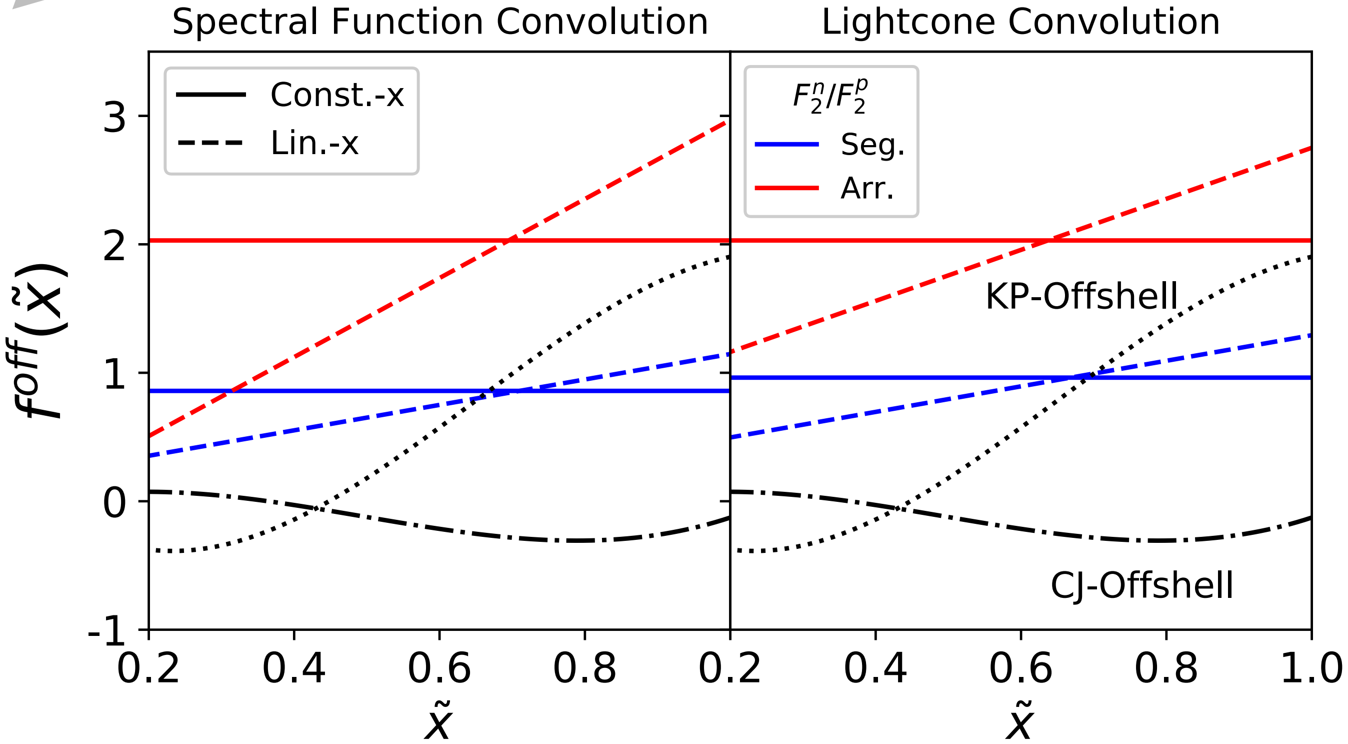
Nuclear EMC



Free neutron structure



Off-shell modification



Schmookler et al. Nature 566, 354–358 (2019)

E.P. Segarra et al. Phys. Rev. Lett. 124, 092002 (2020)

E.P. Segarra et al. arxiv 2006.10249 (submitted)

Thank you!

Hen Lab

Laboratory for Nuclear Science @

LNS

Laboratory for Nuclear Science

SU(6) proton wave-function

$$p \uparrow = \frac{1}{\sqrt{2}} u \uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}} u \uparrow (ud)_{S=1} - \frac{1}{3} u \downarrow (ud)_{S=1}$$

$$- \frac{1}{3} d \uparrow (uu)_{S=1} - \frac{\sqrt{2}}{3} d \downarrow (uu)_{S=1}$$

SU(6) as $x \to 1$: $d/u = 0.5$ (But $m_\Delta \neq m_N$)

Scalar di-quark dominance

(Mass splitting of spectator di-quark spin states)

$$(qq)_{S=0} \gg (qq)_{S=1}$$

$$p \uparrow = \frac{1}{\sqrt{2}} u \uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}} u \uparrow (ud)_{S=1} - \frac{1}{3} u \downarrow (ud)_{S=1}$$

$$-\frac{1}{3} d \uparrow (uu)_{S=1} - \frac{\sqrt{2}}{3} d \downarrow (uu)_{S=1}$$

SU(6) as $x \to 1$: $d/u = 0.5$ (But $m_\Delta \neq m_N$)

Scalar di-quark as $x \to 1$: $d/u = 0$

pQCD

(exchange of longitudinal gluons vs transverse gluons)

$$(qq)_{S_z=0} \gg (qq)_{S_z=1}$$

$$p \uparrow = \frac{1}{\sqrt{2}} u \uparrow (ud)_{S=0} + \frac{1}{\sqrt{18}} u \uparrow (ud)_{S=1} - \frac{1}{3} u \downarrow (ud)_{S=1}$$

$$- \frac{1}{3} d \uparrow (uu)_{S=1} - \frac{\sqrt{2}}{3} d \downarrow (uu)_{S=1}$$

SU(6) as $x \to 1$: $d/u = 0.5$ (But $m_\Delta \neq m_N$)

Scalar di-quark as $x \to 1$: $d/u = 0$

pQCD as $x \to 1$: $d/u = 0.2$