Test on short-range correlations from the EMC effect in the deuteron

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Outline

- Nuclear EMC effect
- Deuteron structure function
- EMC effect in deuteron and test on SRC hypothesis

Part I: Nuclear EMC effect

- Discovered in early 1980's, the EMC effect refer to that the ratios of structure functions per nucleon of heavier nuclei to that of the deuteron differ from unity in the valence region.
  J.J. Aubert *et al.*, PLB 123 (1983) 275

- This result is unexpected
  binding energy/nucleon (~ 8 MeV) $\ll Q^2$ in DIS

- Confirmed by subsequent experiments:
  BCDMS: A.C. Benvenuti *et al.*, PLB 189 (1987) 483;
  SLAC: S. Dasu *et al.*, PRL 64 (1988) 2591;
  New EMC: J. Ashman *et al.*, PLB 202 (1988) 603

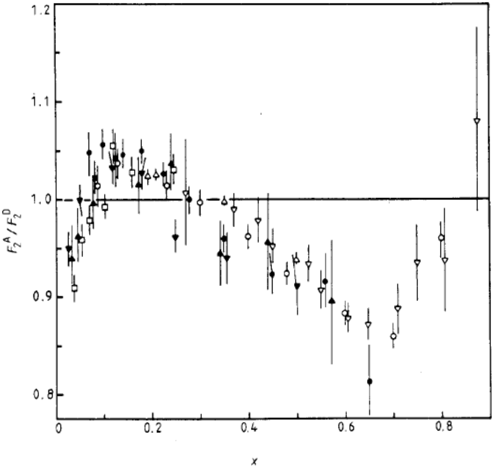


Figure 3. Summary of the most recent and reliable data for the ratio of the Fe (or Cu) and D structure functions. □, SLAC E61; ▽, SLAC E87; ○, SLAC E139; △, SLAC E140; ●, BCDMS; ▲, EMC1: ▼, EMC2.

Figure: This figure is taken from R.P. Bickerstaff and A.W. Thomas, J. Phys. G 15 (1989) 1523.

Origin of the EMC effect

It has now become clear that a quantitative description of the EMC effect requires a change in the internal structure of the bound nucleon.

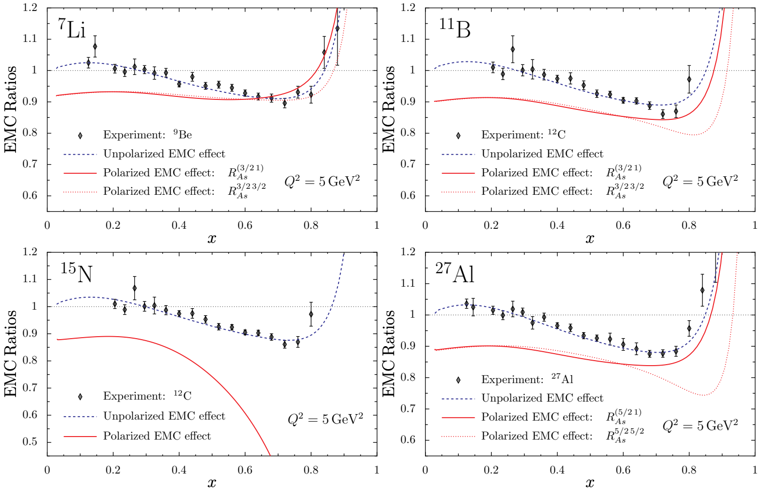
There are two main possibilities that could naturally lead to such modifications:

- Mean-field modifications
- Short-range correlations (SRC)

Mean-field modifications

- A modified NJL model developed by Cloët, Bentz and Thomas provides excellent description of both spin-independent and spin-dependent quark distributions and structure functions
  I.C. Cloët, W. Bentz, A.W. Thomas, PLB 621 (2005) 246

- By incorporating mean-field in nuclear medium modifications, it was successful in reproducing the unpolarized EMC data across the periodic table
  I.C. Cloët, W. Bentz, A.W. Thomas, PLB 642 (2006) 210


7Li
Experiment: 9Be
Unpolarized EMC effect
Polarized EMC effect: $R_{As}^{(3/2\,1)}$
Polarized EMC effect: $R_{As}^{3/2\,3/2}$
$Q^2 = 5\,\mathrm{GeV}^2$
11B
Experiment: 12C
Unpolarized EMC effect
Polarized EMC effect: $R_{As}^{(3/2\,1)}$
Polarized EMC effect: $R_{As}^{3/2\,3/2}$
$Q^2 = 5\,\mathrm{GeV}^2$
15N
Experiment: 12C
Unpolarized EMC effect
Polarized EMC effect
$Q^2 = 5\,\mathrm{GeV}^2$
27Al
Experiment: 27Al
Unpolarized EMC effect
Polarized EMC effect: $R_{As}^{(5/2\,1)}$
Polarized EMC effect: $R_{As}^{5/2\,5/2}$
$Q^2 = 5\,\mathrm{GeV}^2$
EMC Ratios
x

Mean-field modiffications

- The dominant contributions in producing the EMC effect: Effective nucleon and diquark masses: σ (scalar) mean field; Energy shifts: ω (vector) mean field;
- It predicts sizeable "polarized EMC effect';
- All constitute nucleons experience mean-field modifications;

Quark-meson coupling (QMC) model

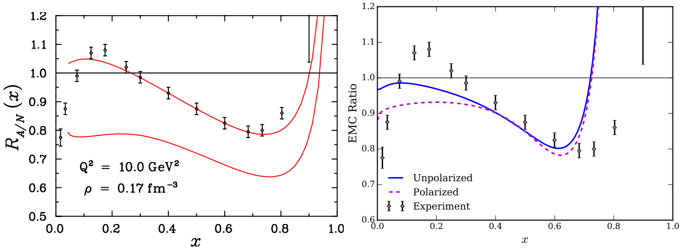


Figure: Spin-independent and spin-dependent EMC ratios of nuclear matter. The experimental data are taken from I. Sick and D. Day, PLB 274 (1992) 16.

- (Left) NJL Model
  I.C. Cloet, W. Bentz, A.W. Thomas, PRL 95 (2005) 052302;
- (Right) QMC Model
  S. Tronchin, H.H. Matevosyan, A.W. Thomas, PLB 783 (2018) 247.

Short-range correlations

- The short-range correlated nucleons refer to two strongly interacting nucleons in close proximity (high momentum);
  O. Hen *et al.*, Rev. Mod. Phys. 89 (2017) 045002
- Well established by experiments at Jefferson Lab
  CLAS Collaboration, PRL 96 (2006) 082501
  CLAS Collaboration, PRL 122 (2019) 172502
- The dominant source driving low-momentum shell model states to high momentum is tensor correlations;
  M. Alvioli, C. Ciofi degli Atti, H. Morita, PRL 100 (2008) 162503
- The SRC nucleons are 'isophobic': mostly in neutron-proton (np) pair

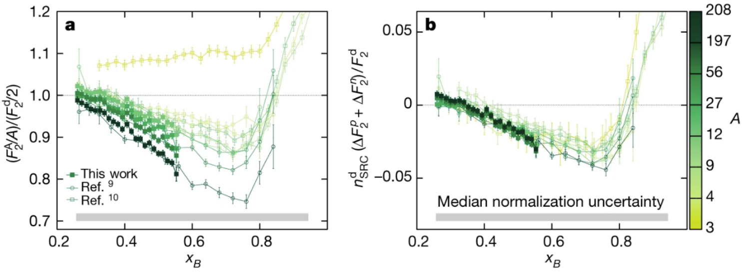
SRC hypothesis

- SRC hypothesis assumes causal connection between SRCs and EMC effect
- In contrast to the mean-field senario, in the Short-range correlation hypothesis, only of those nucleons in an SRC pair will the structure functions be modified,

$$F_2^{p*} = F_2^p + \Delta F_2^p, \quad F_2^{n*} = F_2^n + \Delta F_2^n$$

F_2^{p*} and F_2^{n*} are the nucleon structure functions in an SRC pair.

B. Schmookler *et al.*, Nature 566, 354 (2019)

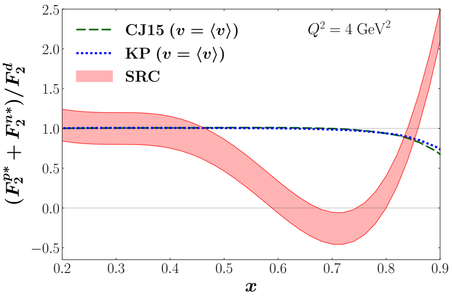


$$
\begin{aligned}
F_2^A &= (Z - n_{\rm SRC}^A)F_2^p + (N - n_{\rm SRC}^A)F_2^n + n_{\rm SRC}^A(F_2^{p*} + F_2^{n*}) \\
&= ZF_2^p + NF_2^n + n_{\rm SRC}^A(\Delta F_2^p + \Delta F_2^n)\,, \qquad (1)
\end{aligned}
$$

where $n_{\rm SRC}^A$ is the number of *np* pairs in the nucleus *A*, and

$$\Delta F_2^p = F_2^{p*} - F_2^p, \qquad \Delta F_2^n = F_2^{n*} - F_2^n \qquad (2)$$

- negative $F_2^{p*} + F_2^{n*}$?
  XGW, W. Melnitchouk, A.W. Thomas, PRL 125 (2020) 262002



Tested by semi-inclusive DIS on the deuteron, with tagging of high momentum recoil protons and neutrons.

- SRC will depolarize the valence proton, leading to quite small EMC effect on the nuclear spin structure function.
- It can be tested by experiments at Jefferson Lab utilizing CLAS12 with 11 GeV polarized electrons and ^7Li target (a highly polarized proton is embedded in the nuclear medium)

Part II: Deuteron structure function

The nuclear structure functions can be written as a sum of a convolution term involving on-shell nucleon structure functions and an off-shell correction

$$F_2^A(x) = \left(f_{p/A} \otimes F_2^p + f_{n/A} \otimes F_2^n\right)(x) + F_2^{A(\mathrm{off})}(x)\,, \qquad (3)$$

W. Melnitchouk, A.W. Schreiber, A.W. Thomas, PRD 49, 1183 (1994)

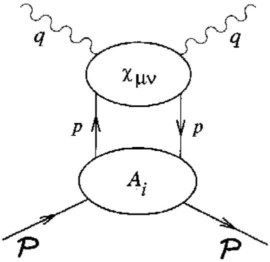


Figure: DIS from an off-shell nucleon in a composite target

$\chi_{\mu\nu}$: (off-shell) nucleon tensor;

A_i: nucleon-nuclei interaction

MST Model

W. Melnitchouk, A.W. Schreiber, A.W. Thomas, PLB 335 (1994) 11

The truncated (off-shell) nucleon structure function

$$\chi(p,q) = \chi_0(p,q) + \not{p}\chi_1(p,q) + \not{q}\chi_2(p,q), \qquad (4)$$

and

$$\mathcal{A}(P,p) = \mathcal{A}_0(P,p) + \gamma^\alpha \mathcal{A}_{1\alpha}(P,p) \qquad (5)$$

The on-shell parts of these functions are defined by setting $p^2 = m^2$.

$\Downarrow$

The spin-averaged quark distribution per nucleon in the deuteron

$$q^D(x) = \frac{1}{2\pi^2}\int dydp^2(\mathcal{A}_0\chi_0 + \mathcal{A}_1 \cdot p\ \chi_1 + \mathcal{A}_1 \cdot q\ \chi_2), \qquad (6)$$

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The DNN vertex relates $\mathcal{A}_0$ and $\mathcal{A}_1$ to the deuteron wave functions,

$$\begin{aligned}
\mathcal{A}_0 &= 2M_D\pi^2 m(\mathcal{C} - 2\mathcal{P} + \mathcal{D}), \\
\mathcal{A}_{1\alpha} &= 2M_D\pi^2\Big\{ \left(p_\alpha - \frac{p^2 - m^2}{M_D^2}P_\alpha\right)\mathcal{C} \\
&\quad + \left(-p_\alpha + \frac{M_D^2 + p^2 - m^2}{2M_D^2}P_\alpha\right)\left(2\mathcal{P} + \frac{m^2}{\boldsymbol{p}^2}\mathcal{D}\right)\Big\}, \qquad (7)
\end{aligned}$$

where

$$\begin{aligned}
\mathcal{C} &= u^2(|\boldsymbol{p}|) + w^2(|\boldsymbol{p}|) + v_t^2(|\boldsymbol{p}|) + v_s^2(|\boldsymbol{p}|) \\
\mathcal{D} &= \frac{2|\boldsymbol{p}|}{\sqrt{3}m}\Big[u(|\boldsymbol{p}|)\left(v_s(|\boldsymbol{p}|) - \sqrt{2}v_t(|\boldsymbol{p}|)\right) \\
&\quad + w(|\boldsymbol{p}|)\left(v_t(|\boldsymbol{p}|) + \sqrt{2}v_s(|\boldsymbol{p}|)\right)\Big] \\
\mathcal{P} &= v_t^2(|\boldsymbol{p}|) + v_s^2(|\boldsymbol{p}|). \qquad (8)
\end{aligned}$$

- u and w: $S-$ and $D-$state deuteron wave functions;
- v_s and v_t: singlet and triplet P-state wave functions

$$q^D(x) = \frac{1}{2\pi^2}\int dy dp^2 (\mathcal{A}_0\chi_0 + \mathcal{A}_1\cdot p\ \chi_1 + \mathcal{A}_1\cdot q\ \chi_2)$$

$$= \frac{1}{2\pi^2}\int dy dp^2 (\mathcal{A}_0\chi_0^{\rm on} + \mathcal{A}_1\cdot p\ \chi_1^{\rm on} + \mathcal{A}_1\cdot q\ \chi_2^{\rm on}) + \delta^{(\chi)} q^D(x)$$

$$\text{IF}: \quad \mathcal{A}_0^{(\rm on)}/m = \mathcal{A}_1^{(\rm on)}\cdot p/m^2 = \mathcal{A}_1^{(\rm on)}\cdot q/p\cdot q$$

$$= \Big[\int_x^2 \frac{dy}{y} f_{N/d}(y) q^N(x/y) + \underbrace{\delta^{(\mathcal{A})} q^D(x)\Big] + \delta^{(\chi)} q^D(x)}_{F_2^{d(\rm off)}}$$

- The on-shell nucleon structure function:

$$q^N(x/y) = 4m\chi_0^{\rm on} + 4m^2\chi_1^{\rm on} + 4p\cdot q\chi_2^{\rm on} \qquad (9)$$

- The nuclear smearing function:

$$f_{N/d}(y) = \frac{M_d}{8} y \int_{-\infty}^{p^2_{\rm max}} dp^2 \frac{E_p}{p_0}\mathcal{C}(p), \qquad (10)$$

$$
\begin{aligned}
q^D(x) &= \frac{1}{2\pi^2}\int dydp^2(\mathcal{A}_0\chi_0 + \mathcal{A}_1\cdot p\ \chi_1 + \mathcal{A}_1\cdot q\ \chi_2) \\
&= \frac{1}{2\pi^2}\int dydp^2(\mathcal{A}_0\chi_0^{\mathrm{on}} + \mathcal{A}_1\cdot p\ \chi_1^{\mathrm{on}} + \mathcal{A}_1\cdot q\ \chi_2^{\mathrm{on}}) + \delta^{(\chi)}q^D(x)
\end{aligned}
$$

$$
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\end{aligned}
$$

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$$

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$$
q^N(x/y) = 4m\chi_0^{\rm on} + 4m^2\chi_1^{\rm on} + 4p\cdot q\chi_2^{\rm on} \tag{9}
$$

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$$
f_{N/d}(y) = \frac{M_d}{8} y \int_{-\infty}^{p^2_{\rm max}} dp^2 \frac{E_p}{p_0}\mathcal{C}(p), \tag{10}
$$

The off-shell term $F_2^{d(\mathrm{off})}$

- $$\delta^{(\mathcal{A})} q^D(x) = \frac{M_D}{2}\int_x^1 dy \int_{-\infty}^{p^2_{max}} dp^2 \Big\{ \Big[\frac{1}{2}\Big(1-\frac{E_p}{p_0}\Big) q^N(x/y) + \Big(\frac{E_p}{M_D}\chi_1^{\mathrm{on}} - \frac{P\cdot q}{M_D^2}\chi_2^{\mathrm{on}}\Big)(p^2-M^2)\Big]\mathcal{C}$$
$$+ \Big[-2M\chi_0^{\mathrm{on}} + 2\boldsymbol{p}^2\chi_1^{\mathrm{on}} + \Big(1-y-\frac{E_p}{M_D}\Big)P\cdot q\chi_2^{\mathrm{on}}\Big]\mathcal{P}$$
$$+ \Big[M\chi_0^{\mathrm{on}} + M^2\chi_1^{\mathrm{on}} + \frac{M^2}{\boldsymbol{p}^2}\Big(1-y-\frac{E_p}{M_D}\Big)P\cdot q\chi_2^{\mathrm{on}}\Big]\mathcal{D}\Big\}$$

- $$\delta^{(\chi)} q^D(x) = \frac{1}{2\pi^2}\int dy dp^2 \Big(\mathcal{A}_0\chi_0^{\mathrm{off}} + \mathcal{A}_1\cdot p\chi_1^{\mathrm{off}} + \mathcal{A}_2\cdot q\chi_2^{\mathrm{off}}\Big),$$

  where $\chi_i^{\mathrm{off}} = \chi_i - \chi_i^{\mathrm{on}}$.

Phenomenological Model for $F_2^{d(\mathrm{off})}$

The off-shell term, $F_2^{d(\mathrm{off})}$, is more model dependent,

$$F_2^{d(\mathrm{off})} = (f_{N/d}^{(\mathrm{off})} \otimes [F_2^N \cdot \delta f])(x) \quad (11)$$

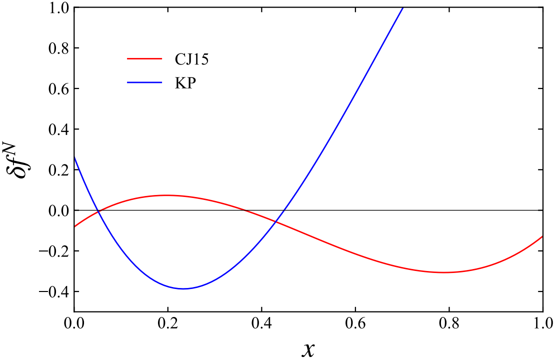
where

$$f_{N/d}^{(\mathrm{off})} = \frac{M_d}{8} y \int_{-\infty}^{p^2_{\mathrm{max}}} dp^2 v(p^2) \frac{E_p}{p_0} C(p) \quad (12)$$

with $v(p^2) = (p^2 - M^2)/M^2$ the nucleon virtuality, and

$$\delta f^N = C(x - x_0)(x - x_1)(1 + x_0 - x) \quad (13)$$

- CJ15: A. Accardi, PRD 93 (2016) 114017
- KP: S. A. Kulagin and R. Petti, PRC 82 (2010) 054614


CJ15
KP
δf^N
x
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
0.0
0.2
0.4
0.6
0.8
1.0

Part III: EMC effect in the deuteron

XGW, A.W. Thomas, W. Melnitchouk, PRL 125 (2020) 262002

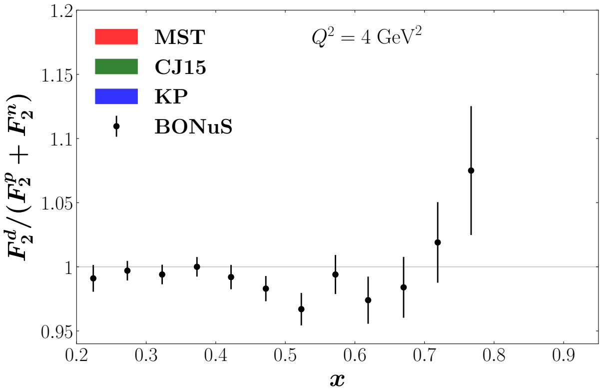


Figure: BoNuS data are taken from K.A. Griffioen *et al.*, PRC 92 (2015) 015211.

The convolution formalism makes it possible to separate the contributions to the deuteron structure function from the low- and high-momentum regions,

$$F_2^d = F_2^d\Big|_{|\vec{p}|<p_F} + F_2^d\Big|_{|\vec{p}|>p_F}, \tag{14}$$

where p_F is a critical momentum distinguishing low-momentum nucleons and those in SRCs, typically $p_F = 300\ \mathrm{MeV}$

$$R = \frac{F_2^d - (F_2^p + F_2^n)}{F_2^d} = R_{p>p_F} + R_{p<p_F}\,, \qquad (15)$$

where

$$R_{p>p_F} = \frac{F_2^d\big|_{p>p_F} - n^d_{\mathrm{SRC}}(F_2^p + F_2^n)}{F_2^d}, \qquad (16a)$$

$$R_{p<p_F} = \frac{F_2^d\big|_{p<p_F} - (1 - n^d_{\mathrm{SRC}})(F_2^p + F_2^n)}{F_2^d}\,. \qquad (16b)$$

SRC hypothesis $\Leftrightarrow$ $R_{p>p_F}$ plays leading role in R

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SRC hypothesis $\Leftrightarrow$ $R_{p>p_F}$ plays leading role in R

The probability of finding nucleons in an SRC pair in the deuteron can be evaluated by integrating the deuteron wave function over large relative momenta,

$$n^d_{\mathrm{SRC}} = \int_{p_F}^{\infty} d|\boldsymbol{p}|\, \boldsymbol{p}^2 \left|\psi_d(p)\right|^2. \tag{17}$$

With $p_F = 300\ \mathrm{MeV}$:

- $n^d_{\mathrm{SRC}} = 3.4\%$ for Paris deuteron wave functions
  M. Lacombe *et al.*, PLB 101 (1981) 139.
- $n^d_{\mathrm{SRC}} = 3.8\%$ for WJC-2 wave functions
  F. Gross and A. Stadler, PRC 78 (2008) 014005.

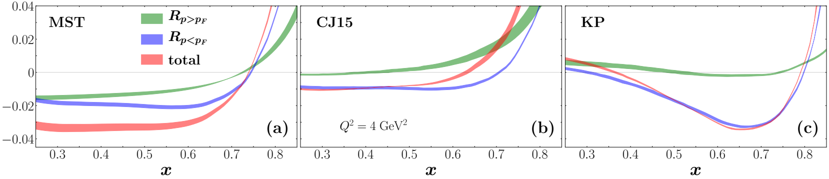
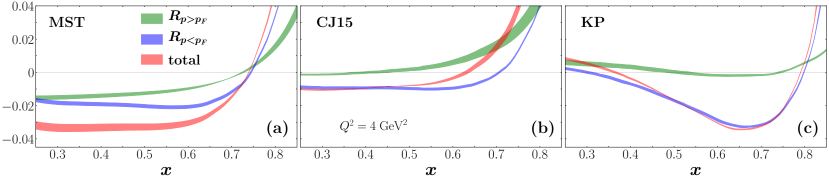


Figure: The bands envelop the results obtained using the nonrelativistic Paris and the relativistic WJC-2 deuteron wave functions.

- The high momentum contributions play less important role, or even have wrong sign, in producing the EMC ratio;
- Neglecting the Fermi motion is not a good approximation;
- Do not support the SRC hypothesis as the only source;
- For $p_F = 400\ \mathrm{MeV}$, the $R_{p>p_F}$ will be even smaller



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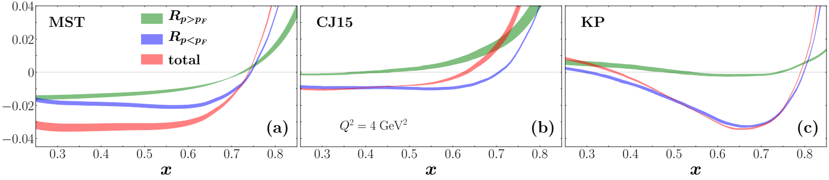

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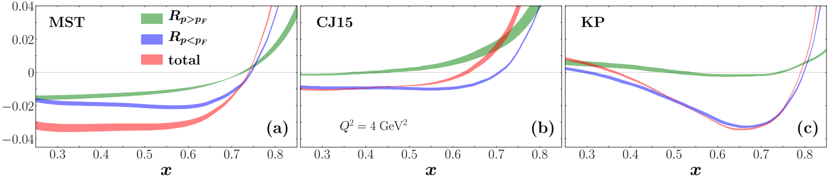

Figure: The bands envelop the results obtained using the nonrelativistic Paris and the relativistic WJC-2 deuteron wave functions.

- The high momentum contributions play less important role, or even have wrong sign, in producing the EMC ratio;
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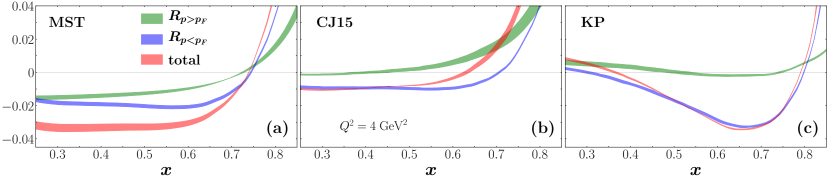

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Summary

- We investigate the deuteron structure function by taking into account binding, Fermi motion, and off-shell effect.
- In a convolution formalism, we separate the high momentum and low momentum contributions to the deuteron EMC ratio.
- From three theoretical and phenomenological models, we find that, in no cases do the SRCs give the dominant contribution to the valence EMC effect.
- Upcoming experiments at JLab and Electron-Ion Collider (EIC) could provide vital information on revealing the origin of the EMC effect.

Thanks!