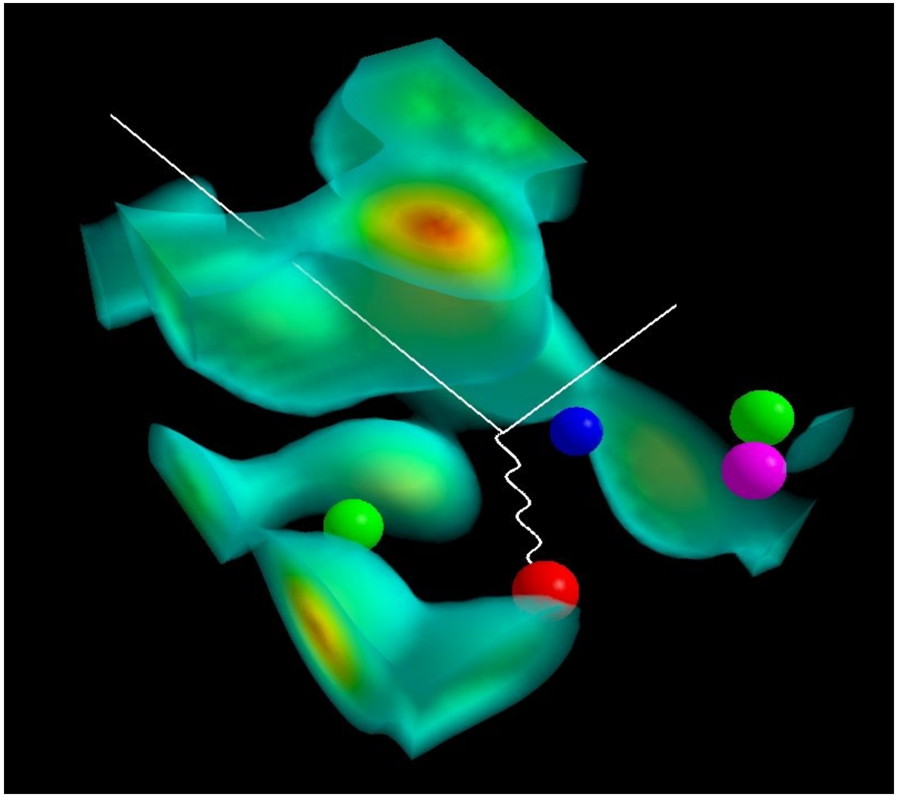
PDFs and GPDs of Light Nuclei



Anthony W. Thomas

GPD Workshop

Trento – 11-30pm November 10th 2022

Outline

I. The EMC Effect – deep-inelastic structure of nuclei is *different*

II. Test the SRC explanation of the EMC effect in the deuteron

III. Structure functions in ^3He and ^3H
– analysis of the Marathon experiment

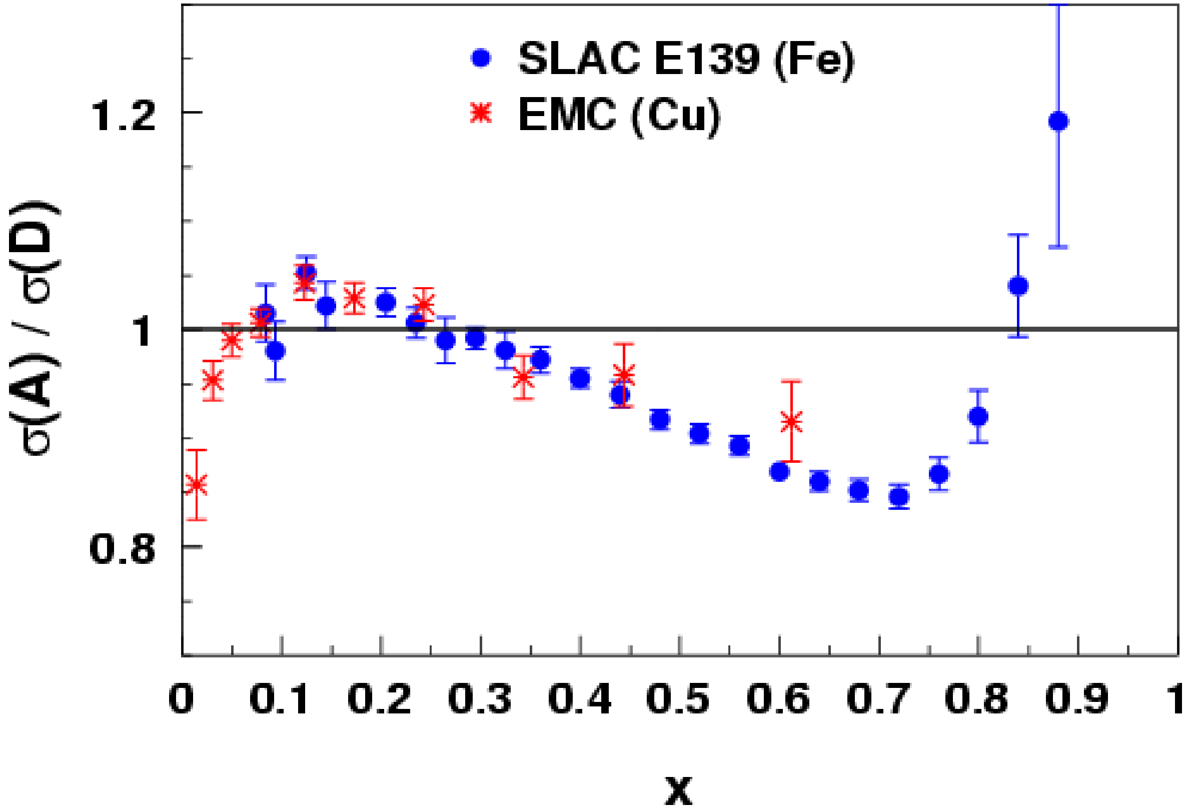
IV. GPDs as a probe of medium modification in ^4He

The EMC Effect

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 39 years ago

- What is it that alters the quark momentum in the nucleus?



J. Ashman *et al*., Z. Phys. C57, 211 (1993)

J. Gomez *et al*., Phys. Rev. D49, 4348 (1994)

See also: Higinbotham *et al*., CERN Courier 2013

Short-range correlations (SRC)

or mean-field modification?

Mean-Field Calculations for Finite Nuclei

(There is also a spin dependent EMC effect - as large as unpolarized)

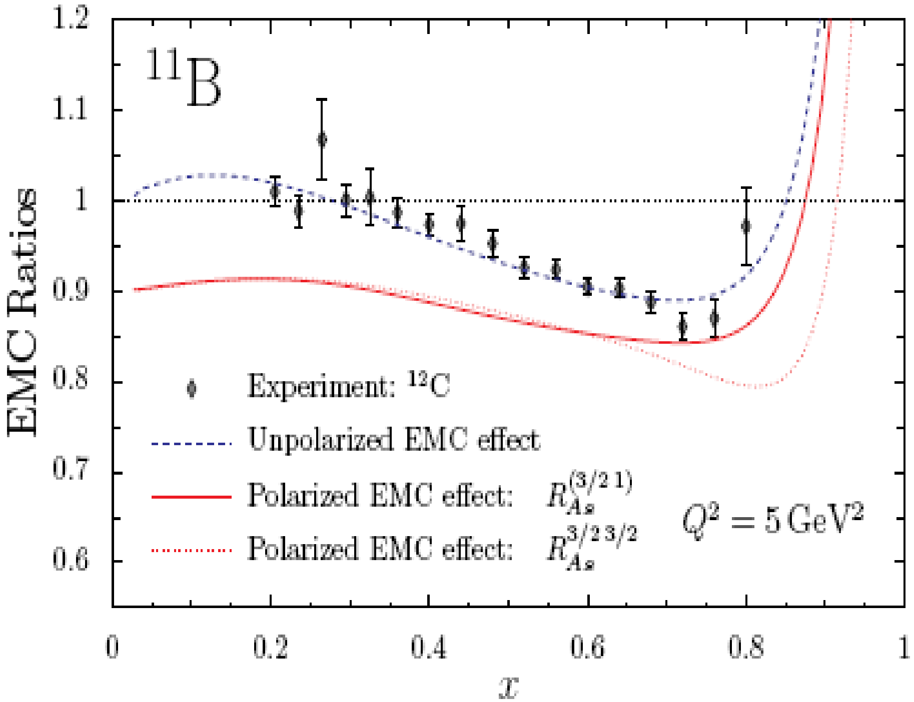


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

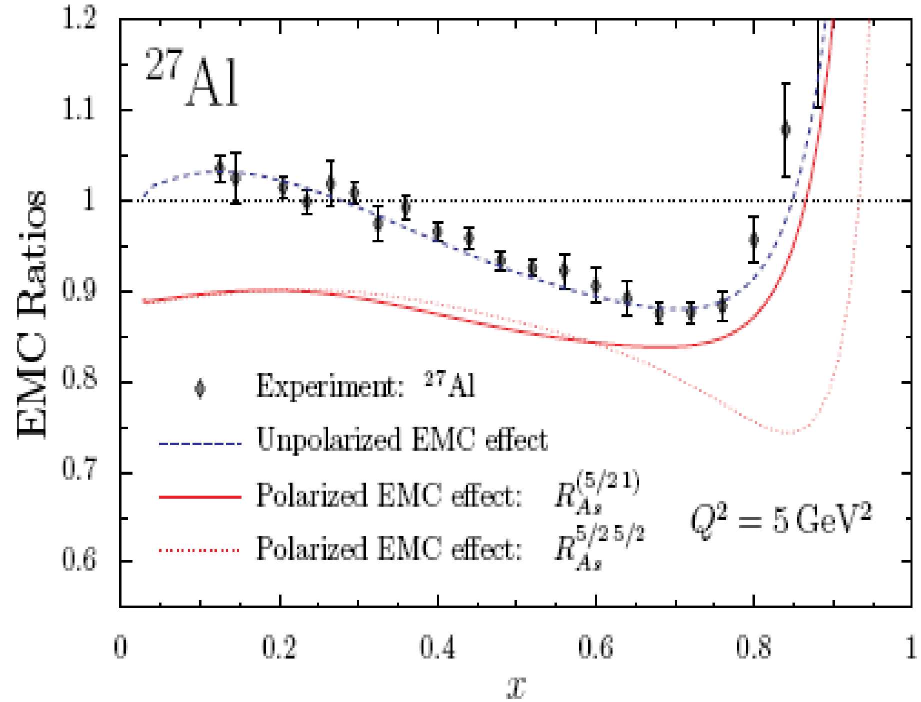


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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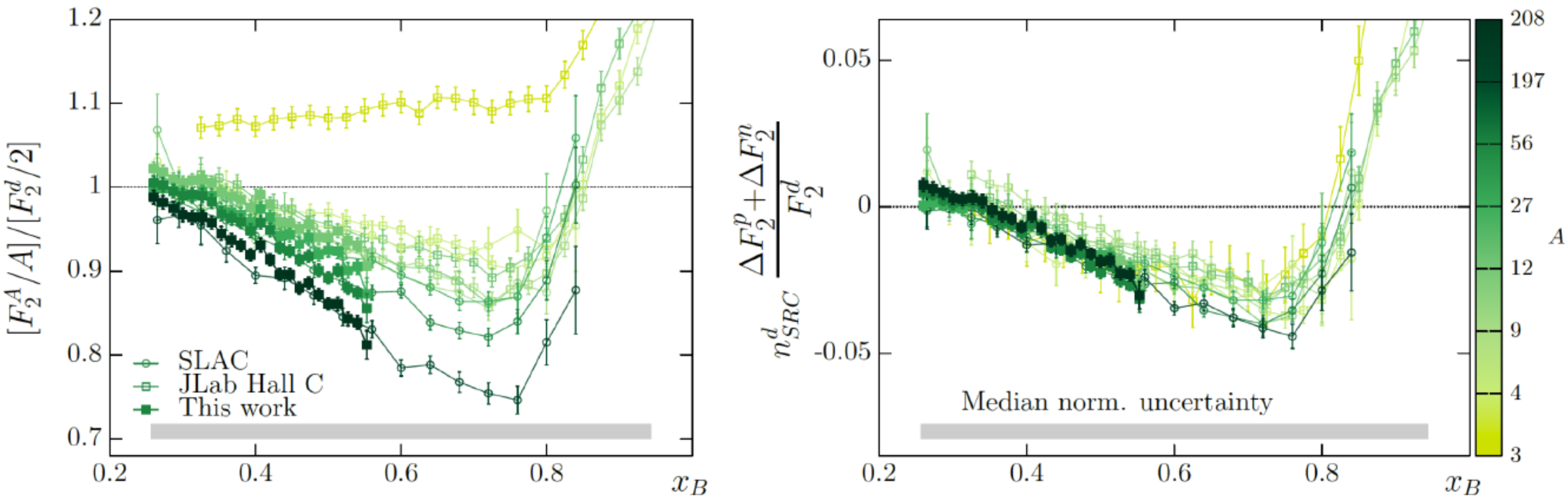
Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210

Linear relation of # in SRC vs Slope of EMC effect
SRC explain the EMC effect

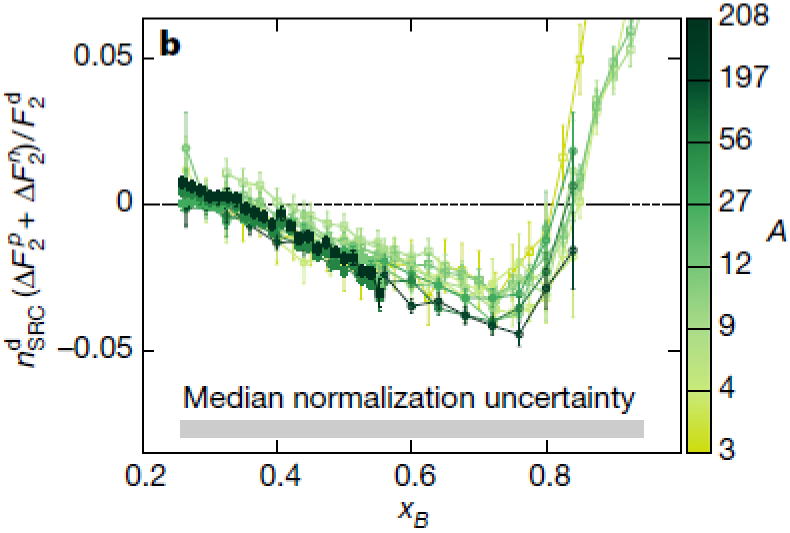
B. Schmookler *et al.*, Nature 566 (2019) 354-358.



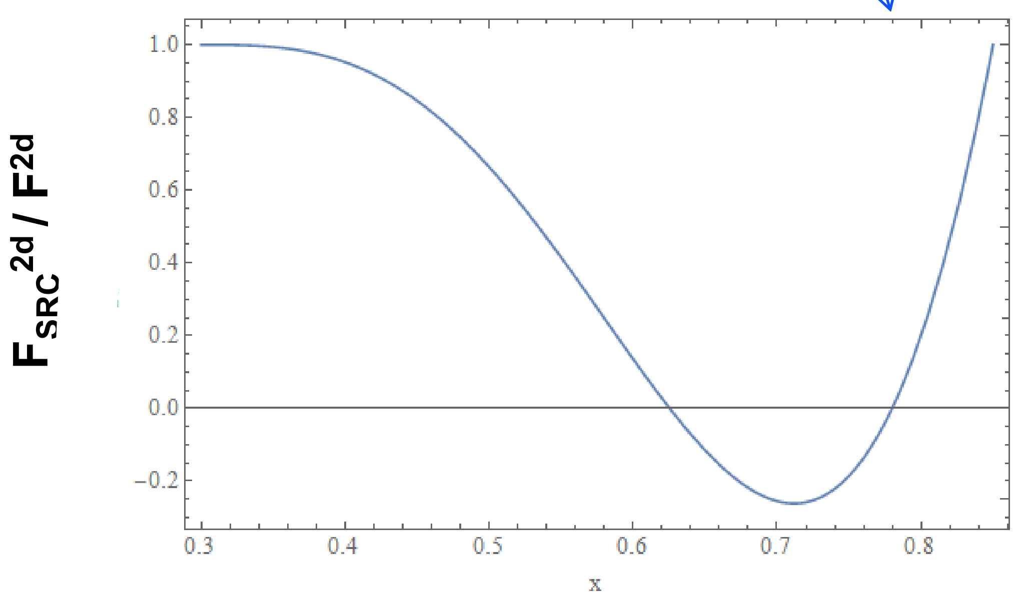
$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + n_{SRC}^A(F_2^{p*} + F_2^{n*})$$
$$= ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n),$$

Entire EMC effect from the change in SF of nucleons in SRC

Further: change in F_2 is dramatic in SRC approach



- Does not look so bad but $n^d{}_{SRC}$ is of order 0.03 (p> 0.3 GeV: only ~80 MeV off-shell))
- Hence suppression of structure of correlated nucleons is greater than or of order 100% in the valence region



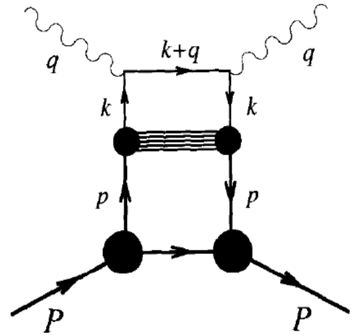
Such a dramatic change does not appear viable

Wang *et al.*, Phys Rev Lett 125 (2000) 262002

The Deuteron

Simple Model calculation of $F_2{}^D$

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



Free nucleon: $q^N(x/y) = 4M\,\chi_0^{\rm on} + 4M^2\,\chi_1^{\rm on} + 4p\cdot q\,\chi_2^{\rm on}$

Deuteron: $q^D(x) = \int_x \frac{dy}{y}\varphi(y)\, q^N(x/y) + \delta^{(\mathcal{A})} q^D(x) + \delta^{(x)} q^D(x)$

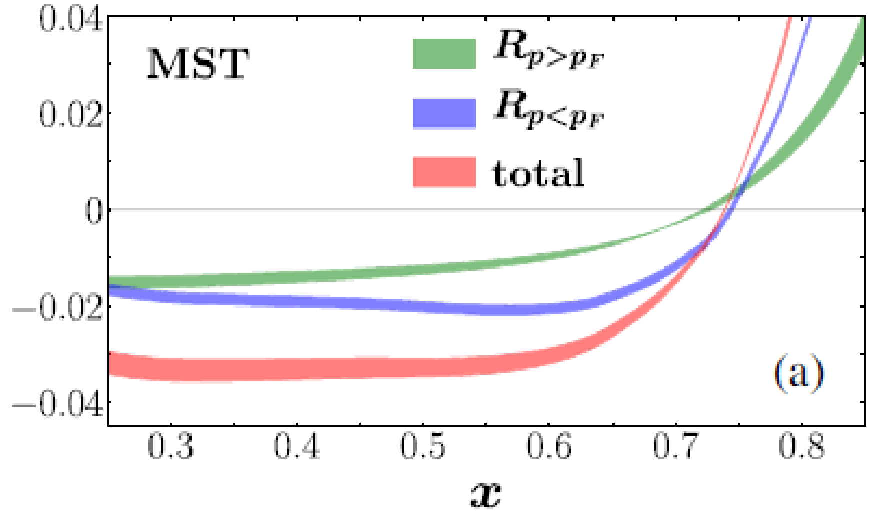
$$\delta^{(x)} q^D(x) = \frac{1}{2\pi^2}\int dy\, dp^2 \left(\mathcal{A}_0\, \chi_0^{\rm off} + \mathcal{A}_1 \cdot p\, \chi_1^{\rm off} + \mathcal{A}_1 \cdot q\, \chi_2^{\rm off}\right)$$

Off-shell effect in PDF

Nuclear correction from wave function

$$\begin{aligned}
&\delta^{(\mathcal{A})} q^D(x) \\
&= \frac{M_D}{2}\int_x^1 dy \int_{-\infty}^{p^2_{\rm max}} dp^2 \Bigg\{ \Bigg[\frac{1}{2}\left(1 - \frac{E_p}{p_0}\right) q^N(x/y) \\
&+ \left(\frac{E_p}{M_D}\chi_1^{\rm on} - \frac{P\cdot q}{M_D^2}\chi_2^{\rm on}\right)(p^2 - M^2)\Bigg]\mathcal{C} \\
&+ \Bigg[-2M\chi_0^{\rm on} + 2p^2\chi_1^{\rm on} \\
&+ \left(1 - y - \frac{E_p}{M_D}\right) P\cdot q\chi_2^{\rm on}\Bigg]\mathcal{P} \\
&+ \Bigg[M\chi_0^{\rm on} + M^2\chi_1^{\rm on} \\
&+ \frac{M^2}{p^2}\left(1 - y - \frac{E_p}{M_D}\right) P\cdot q\chi_2^{\rm on}\Bigg]\mathcal{D}\Bigg\} \qquad (8)
\end{aligned}$$

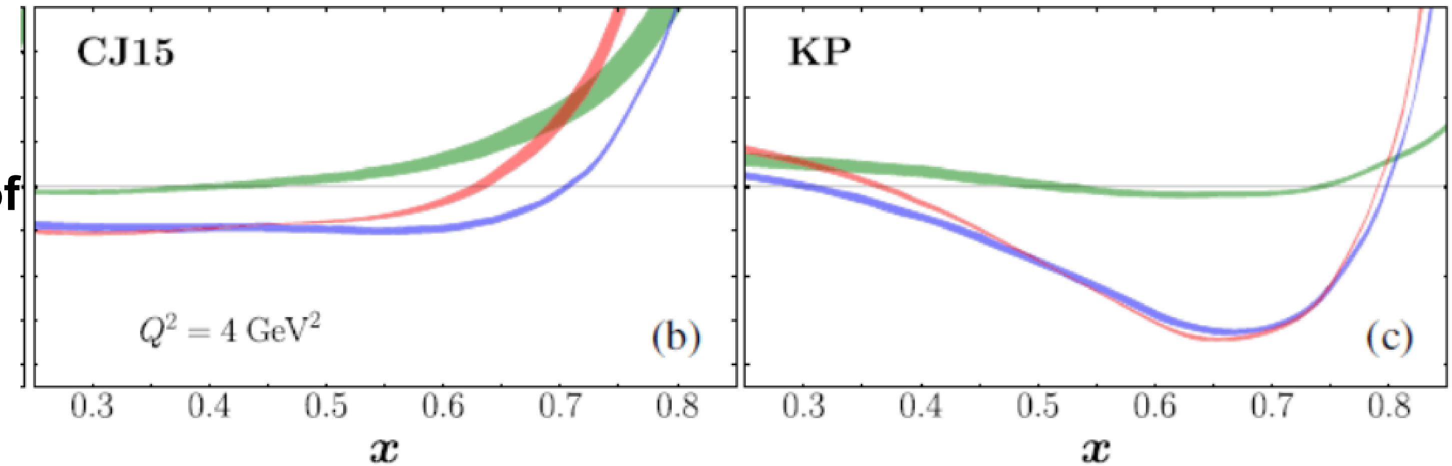
Careful study of the EMC effect in the deuteron



Microscopic model of Melnitchouk *et al*., shows little of valence EMC effect in D arises from nucleons in SRC

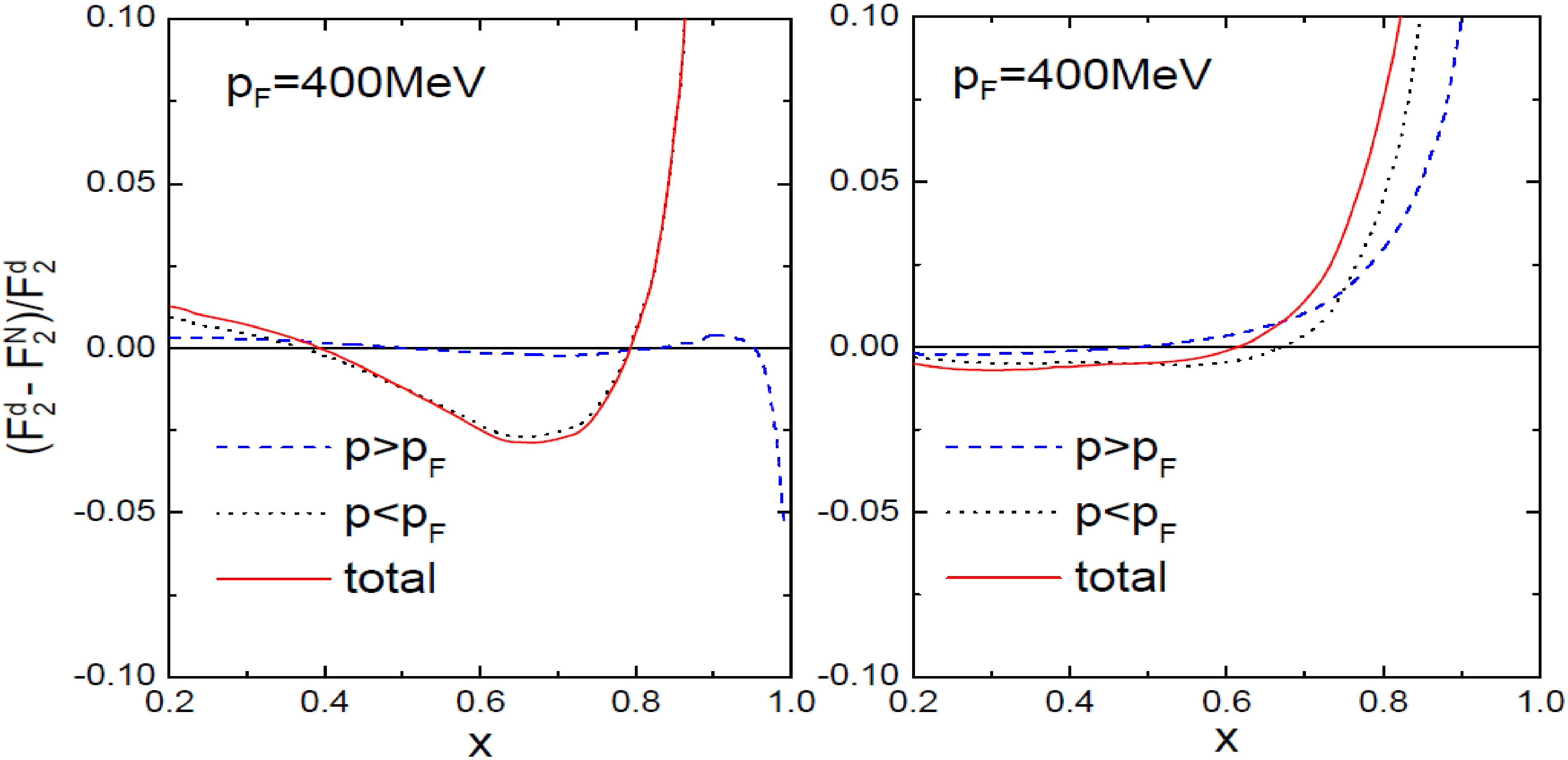
p_F = 300 MeV/c

Even more emphatic in off-shell models of Kulagin-Petti and CTEQ-JLab



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

p_F = 400 MeV/c



(a) Kulagin-Petti (b) CJ15

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Analysis of the Marathon experiment

Isovector EMC Effect from Global QCD Analysis with MARATHON Data

C. Cocuzza,[1] C. E. Keppel,[2] H. Liu,[3] W. Melnitchouk,[2] A. Metz,[1] N. Sato,[2] and A. W. Thomas[4]

PHYSICAL REVIEW LETTERS **127,** 242001 (2021)

- **Remarkable measurement with a tritium target at JLab has given us important data on DIS in ^{3}H**

  Abrams et al., Phys. Rev. Lett. 128 (2022) 13, 132003

- **In combination with earlier data on 3He this provides new insight into potential isovector effects in nuclear DIS**

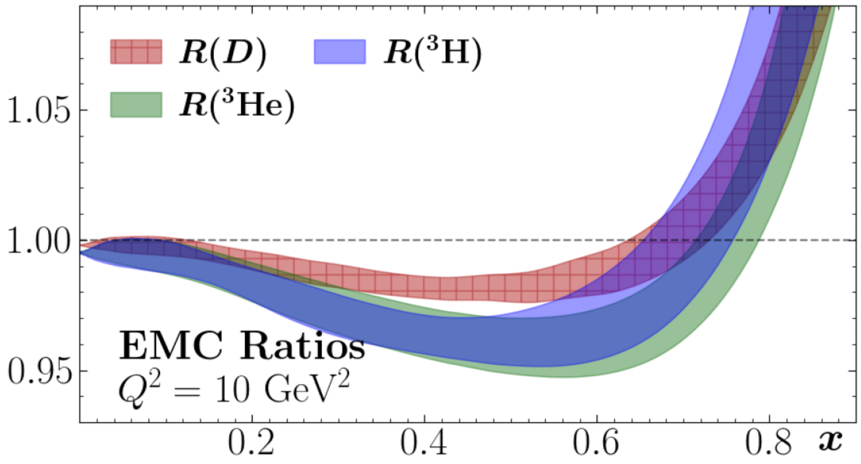
- **In a relativistic mean-field treatment of the EMC effect for nuclei with N>Z this shifts momentum from *all* u quarks to *all* d quarks**

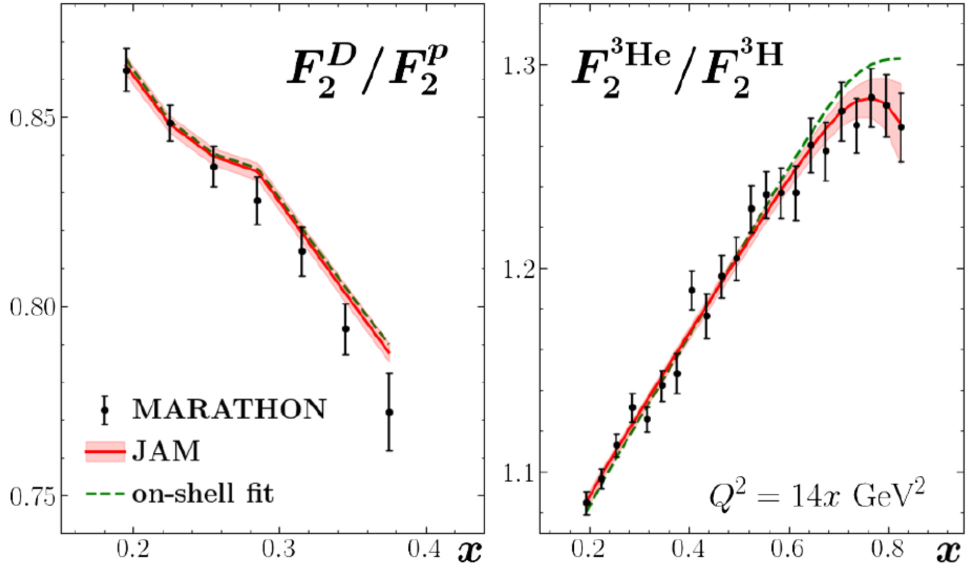
- **Along with CSV this provides a major correction in the context of the NuTeV anomaly**

  I. C. Cloët et al., Phys. Rev. Lett. 102, 252301 (2009)

Results for D and ^{3}He/^{3}H Ratio

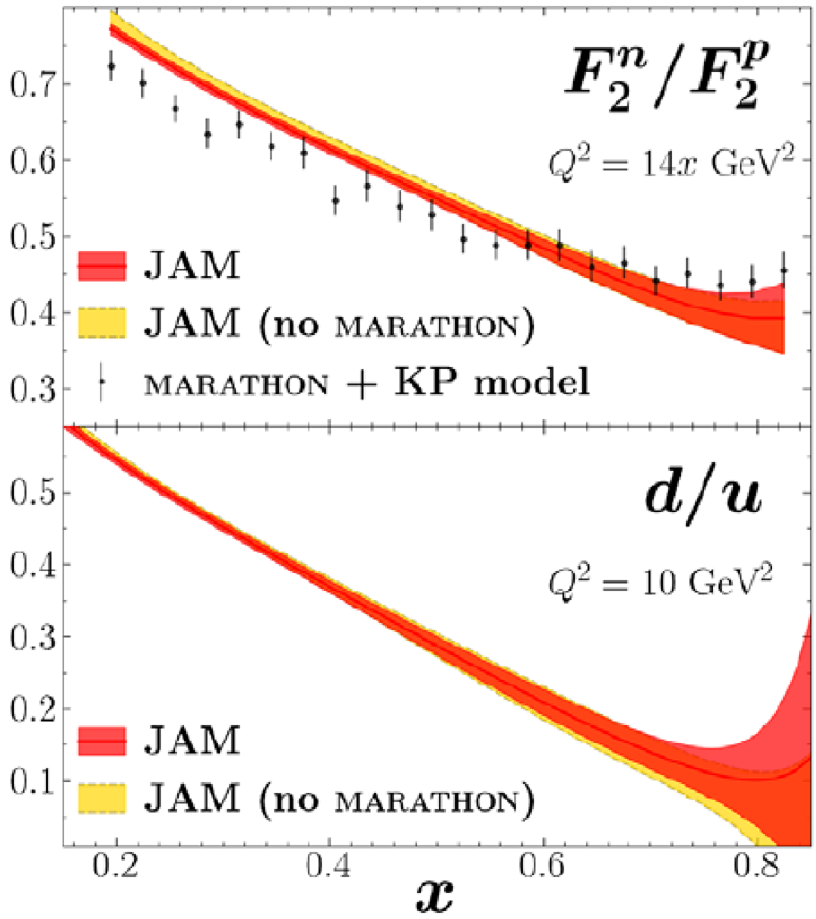
Analysis of Cocuzza et al., including allowance for isovector nuclear corrections





Cocuzza *et al.*, PRL 127 (2021) 242001

d/u ratio extracted from the data



- $W^{\pm}$ **asymmetry data has reduced the capacity of Marathon to uniquely fix d/u**
- **However, it CAN provide unique insight into nuclear effects**

ARC CENTRE OF EXCELLENCE FOR DARK MATTER PARTICLE PHYSICS

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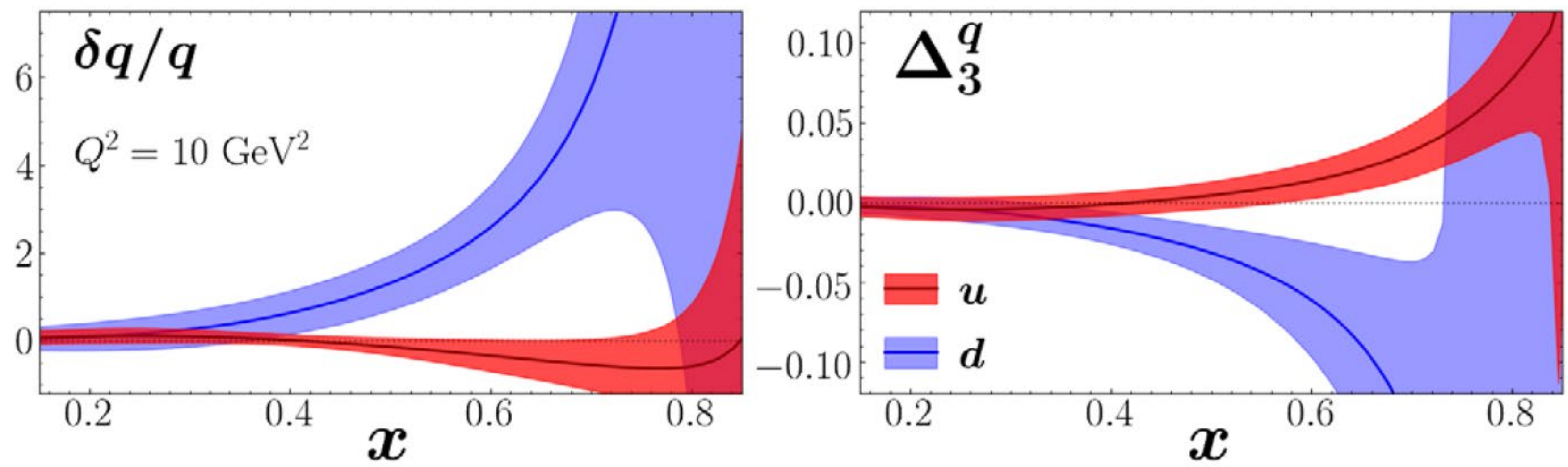
SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Evidence for a Non-zero isovector effect

Parametrize off-shell effects respecting isospin symmetry in terms of q interacting with spectator nucleons

e.g. $\delta u_{p/D} = \delta d_{n/D}$, $\delta d_{p/D} = \delta u_{n/D}$, $\delta u_{p/^3\mathrm{He}} = \delta d_{n/^3\mathrm{H}}$, $\delta d_{p/^3\mathrm{He}} = \delta u_{n/^3\mathrm{H}}$

$\delta u_{p/^3\mathrm{H}} = \delta d_{n/^3\mathrm{He}}$, $\delta d_{p/^3\mathrm{H}} = \delta u_{n/^3\mathrm{He}}$



$$\Delta_3^q \equiv \frac{q_{p/^3\mathrm{H}} - q_{p/^3\mathrm{He}}}{q_{p/^3\mathrm{H}} + q_{p/^3\mathrm{He}}}$$

Would be zero without an isovector effect

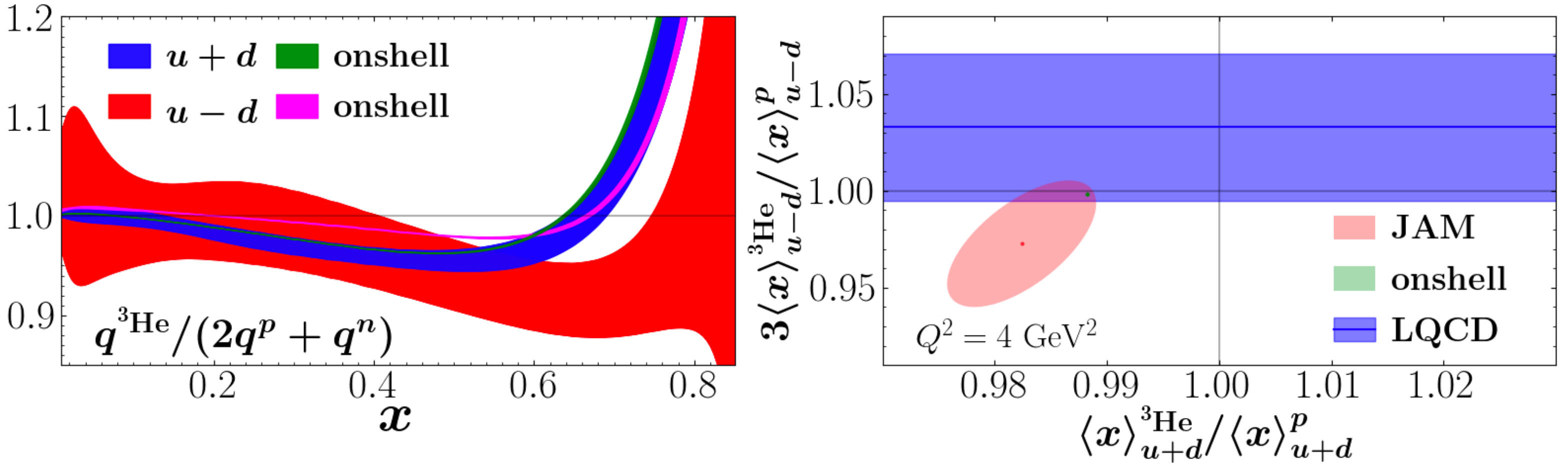
Cocuzza *et al.*, PRL 127 (2021) 242001

Preliminary new result

- **Exciting proposal to use lattice data to constrain/inform PDF analysis, from Detmold et al., PRL 126, 202001 (2021)**

- **Calculated u-d (connected contribution) in ^{3}He at large quark mass (m_π = 800 MeV)**

- **Intriguing comparison with analysis of Coccuzza *et al.*:**



- ***Strongly suggests further lattice calculations!***

GPD of ^4He

Incoherent DVCS on ^{4}He

Physics Letters B 673 (2009) 9–14

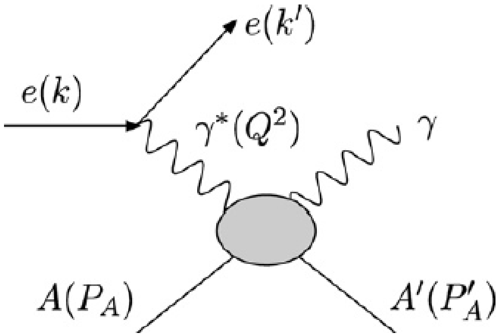
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

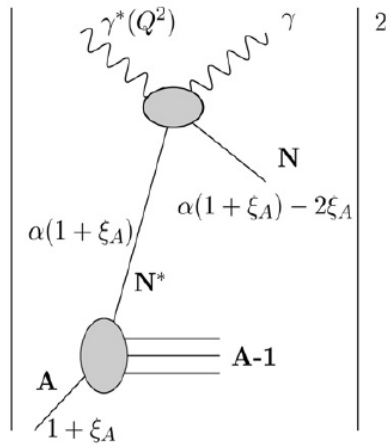
Medium modifications of the bound nucleon GPDs and incoherent DVCS on nuclear targets

V. Guzey [a,*], A.W. Thomas [a,b], K. Tsushima [c]

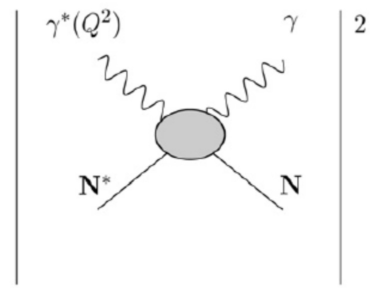


DVCS on a bound nucleon

- **Calculate incoherent DVCS in terms of DVCS from a bound nucleon:**



$$=\int \frac{d\alpha}{\alpha}\rho_A^N(\alpha,\lambda)\,\Sigma_\lambda$$



- **Assume:**

$$H^{q/p^*}(x,\xi,t,Q^2)=\frac{F_1^{p^*}(t)}{F_1^p(t)}H^q(x,\xi,t,Q^2),$$

$$E^{q/p^*}(x,\xi,t,Q^2)=\frac{F_2^{p^*}(t)}{F_2^p(t)}E^q(x,\xi,t,Q^2),$$

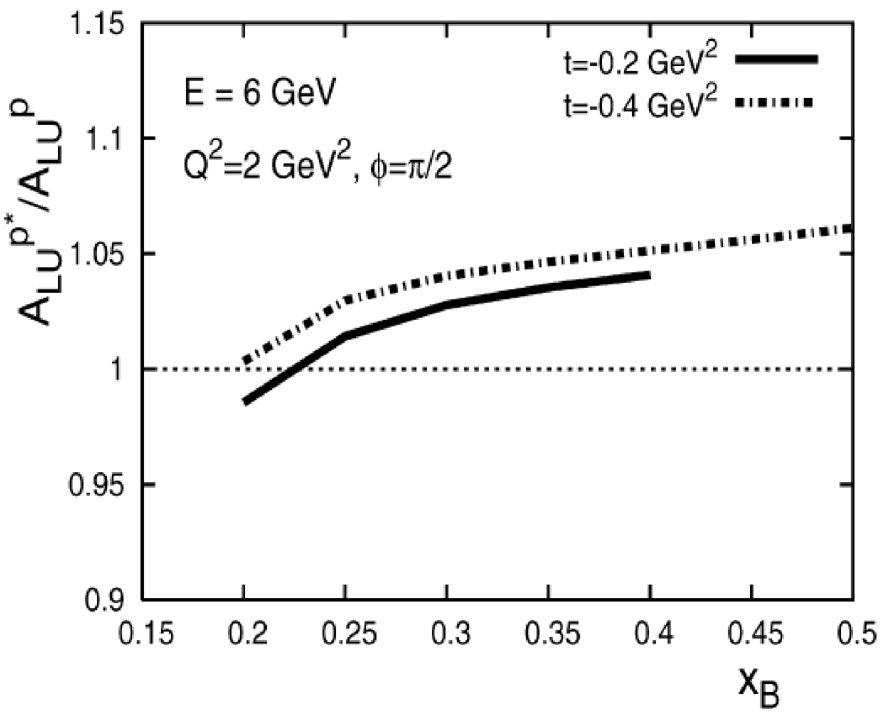
$$\tilde{H}^{q/p^*}(x,\xi,t,Q^2)=\frac{G_1^*(t)}{G_1(t)}\tilde{H}^q(x,\xi,t,Q^2),$$

with modification of bound nucleon form factors calculated in the QMC model

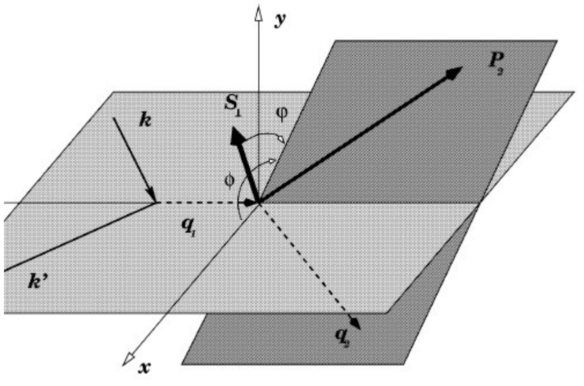
(e.g. Lu *et al*., Phys Lett B417 (1998) 217)

New opportunity to probe medium modifications

$$A_{LU}(\phi) \propto \mathrm{Im}\Big(F_1^{p^*}\mathcal{H}^{p^*} + \frac{x_B}{2-x_B}(F_1^{p^*}+F_2^{p^*})\tilde{\mathcal{H}}^{p^*} - \frac{t}{4m_N^2}F_2^{p^*}\mathcal{E}^{p^*}\Big)\Big/ f\left(F_1^{p^*}, F_2^{p^*}\right)\sin\phi,$$

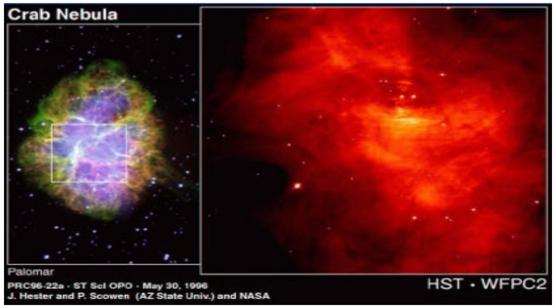


A.V. Belitsky et al. / Nuclear Physics B 629 (2002) 323–392



Guzey *et al.*, Phys Lett B673 (2009) 9

Summary



- The EMC effect contains fundamental information about the structure of atomic nuclei
- Analysis of the deuteron suggests SRC do not play a dominant role
- Study of recent data for ^{3}H and ^{3}He suggests there is an isovector contribution to the nuclear corrections of PDFs
- Comparison with recent lattice QCD study suggests urgent need for further work
- Studies of GPDs in nuclei may provide insight into changes of structure of bound nucleons

Nuclear DIS Structure Functions : The EMC Effect

The QMC approach is ideal as one MUST start with a theory that quantitatively describes nuclear structure and allows calculation of structure functions

– there are no other examples.....

EMC Effect for Finite Nuclei

(There is also a spin dependent EMC effect - as large as unpolarized)

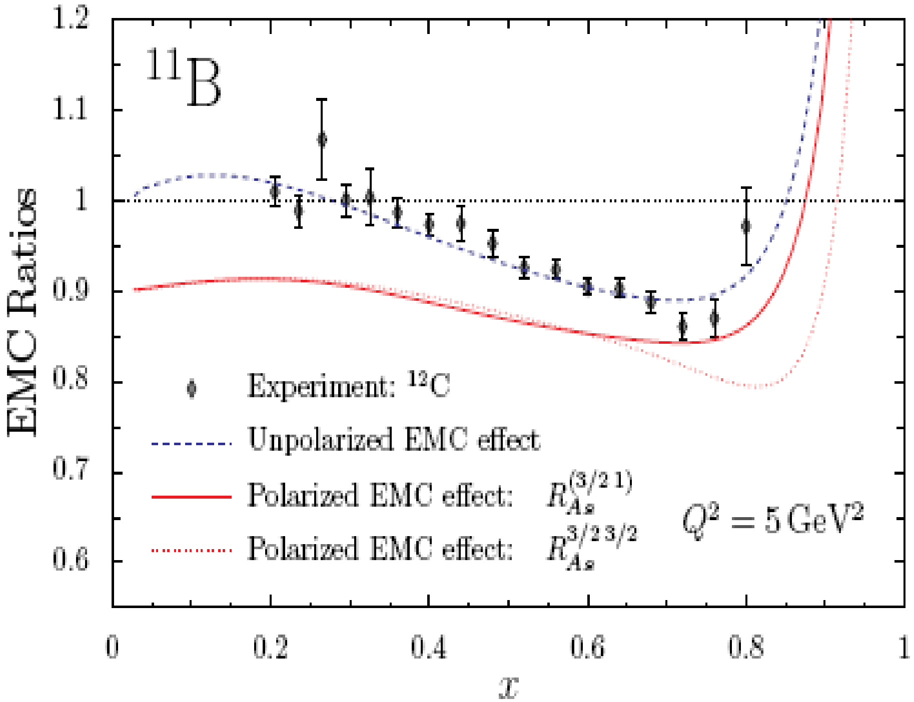


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

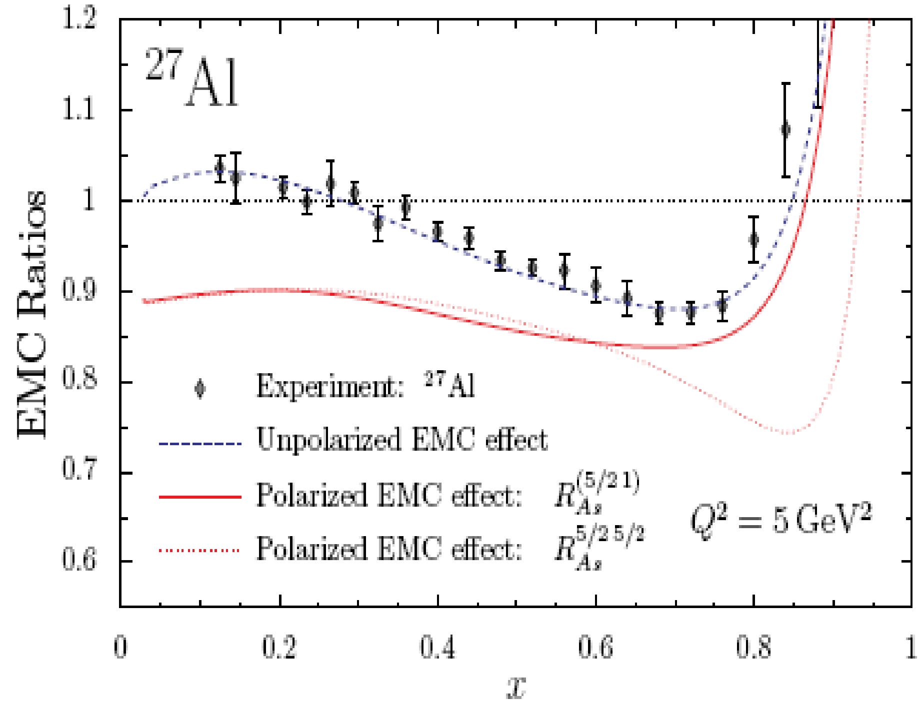


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210 (nucl-th/0605061)

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Spin-EMC Effect is a crucial test

- Tensor correlations leading to high momentum components in nuclear wave function have been proposed as an alternate explanation of the EMC effect

- The tensor force scatters $^3S_1$ pairs almost entirely into $^3D_1$ at high momentum (~84% at p > 400 MeV/c)

- Nucleons in SRC are depolarized – simple Clebsch-Gordan coefficients - and cannot contribute to spin-EMC effect

- That is, SRC idea gives essentially NO spin-EMC effect

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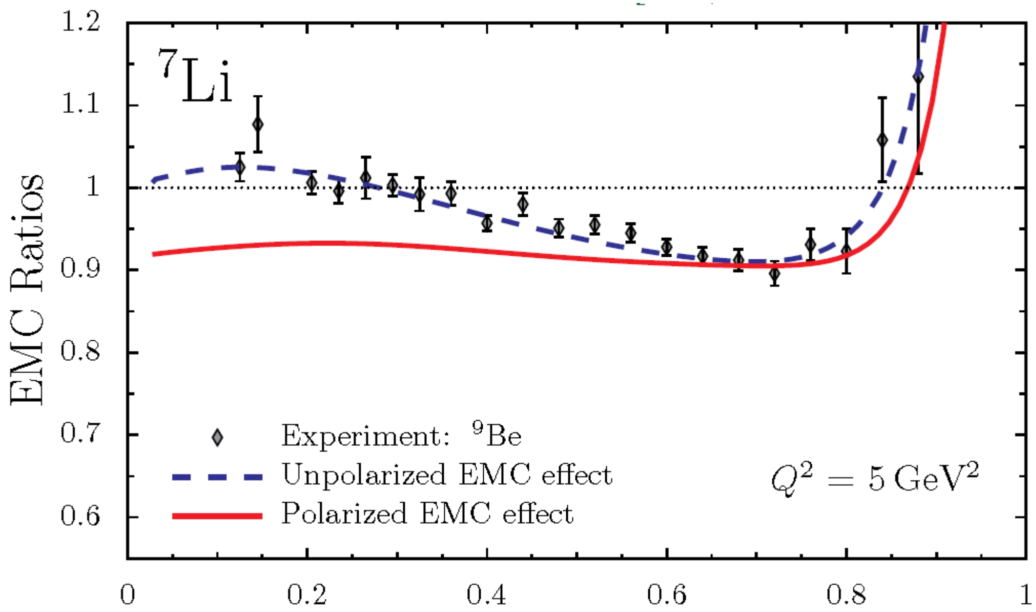
AWT - Int J Mod Phys 27 (2018) 1840001 (Ernest Henley Memorial)

Approved JLab Experiment

- Effect in ^{7}Li is slightly suppressed because it is a light nucleus and proton does not carry all the spin (simple WF: $P_p = 13/15$ & $P_n = 2/15$)
- Experiment now approved at JLab [E12-14-001] to measure spin structure functions of ^{7}Li (GFMC: $P_p = 0.86$ & $P_n = 0.04$)
- *Everyone with their favourite explanation for the EMC effect should make a prediction for the polarized EMC effect in ^{7}Li*



Other tests (e.g. Isovector EMC effect)