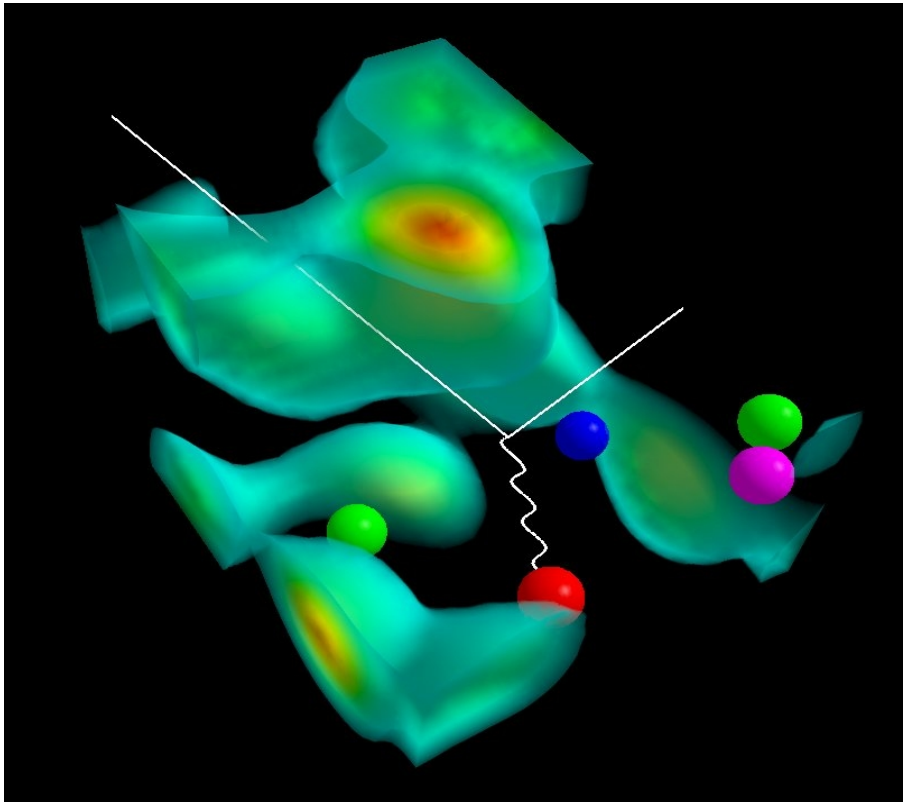
Nuclear Structure and QCD: Origin of the EMC effect



Anthony W. Thomas

Workshop on Lattice Meets Phenomenology
EINN Cyprus : 30th October 2019

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Australian Government
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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

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

II. Recent proposal: Arises from nucleons in short-range correlations

III. Alternate proposal: Nuclei built from Quarks (& Gluons)
- start from a QCD-inspired model of *hadron* structure
- develop a quantitative theory of nuclear structure

IV. Search for observable effects of the change in hadron structure in-medium – notably the EMC effect

V. Mean field versus SRC – can we test it?

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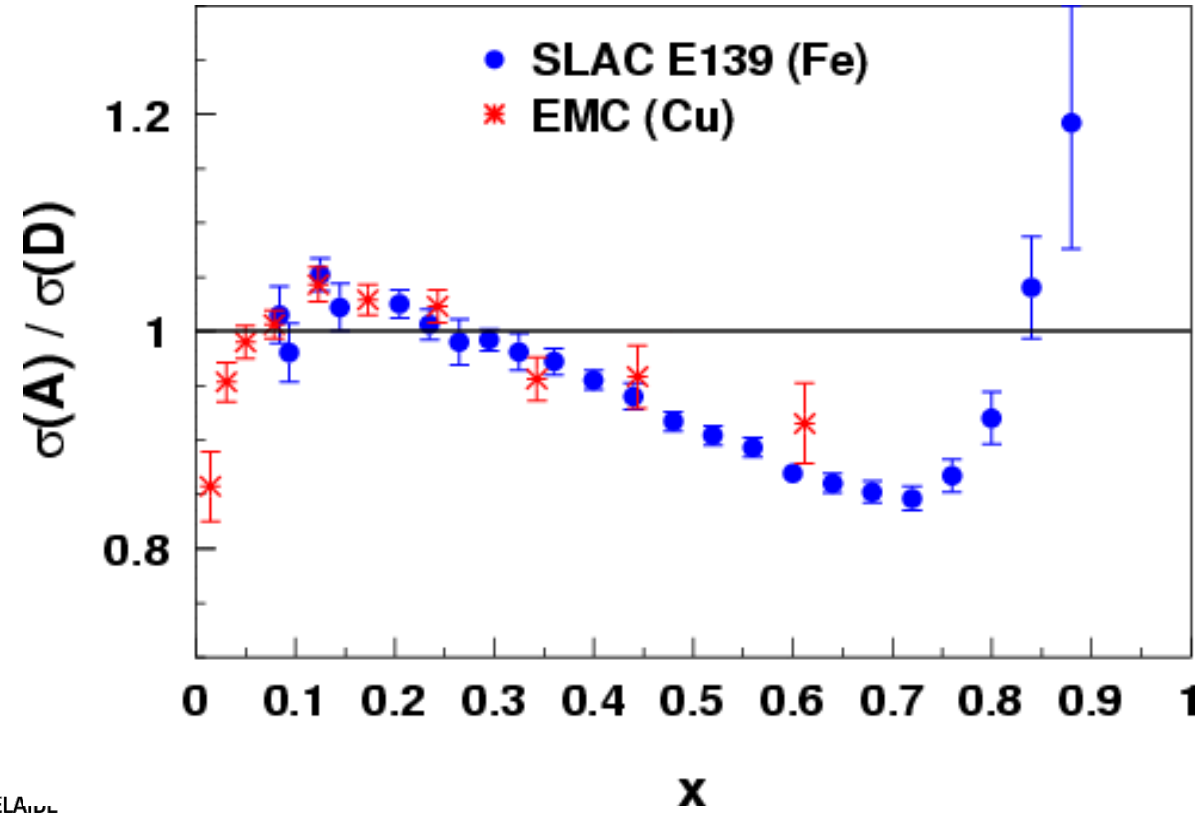
The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 36 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)

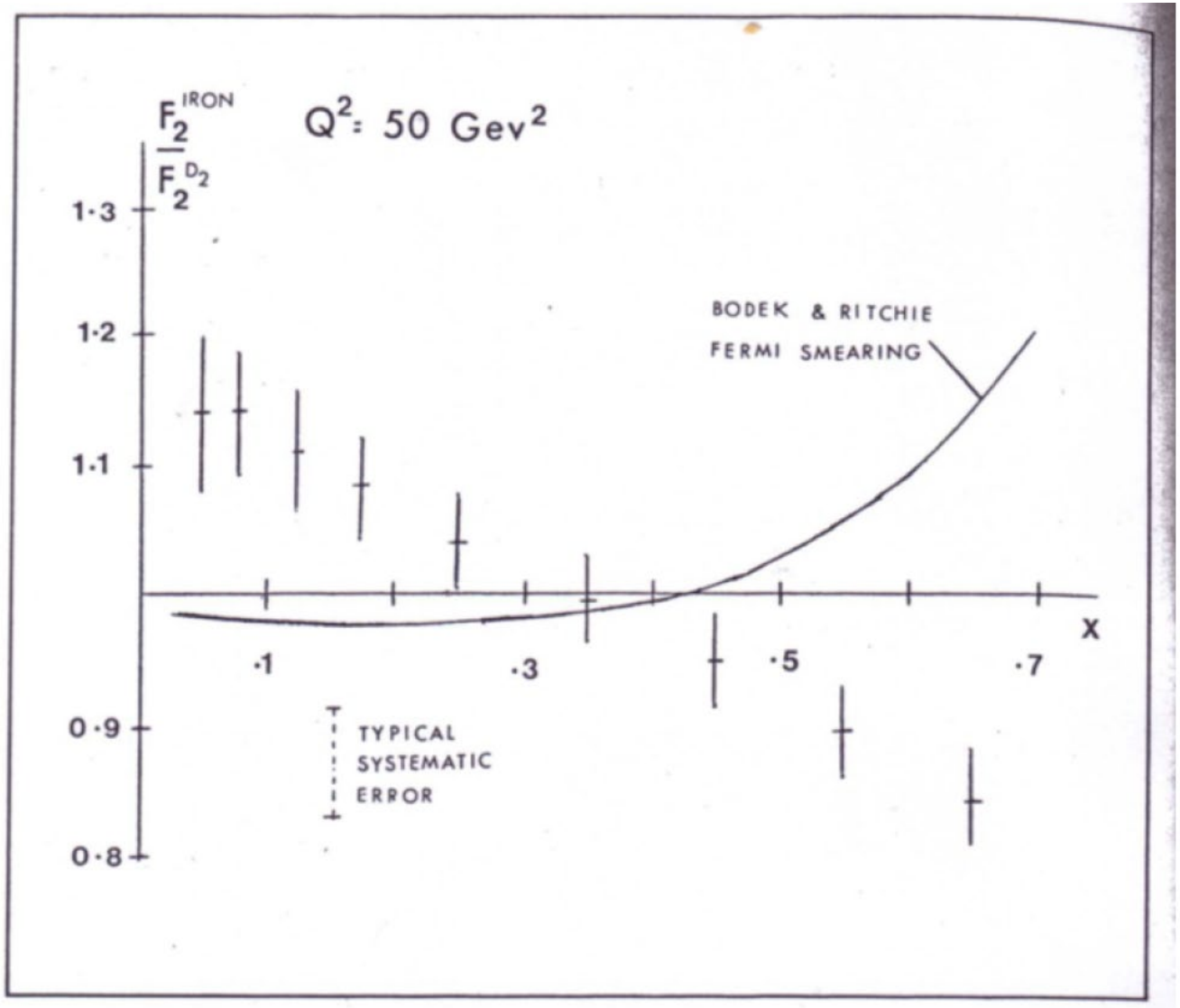
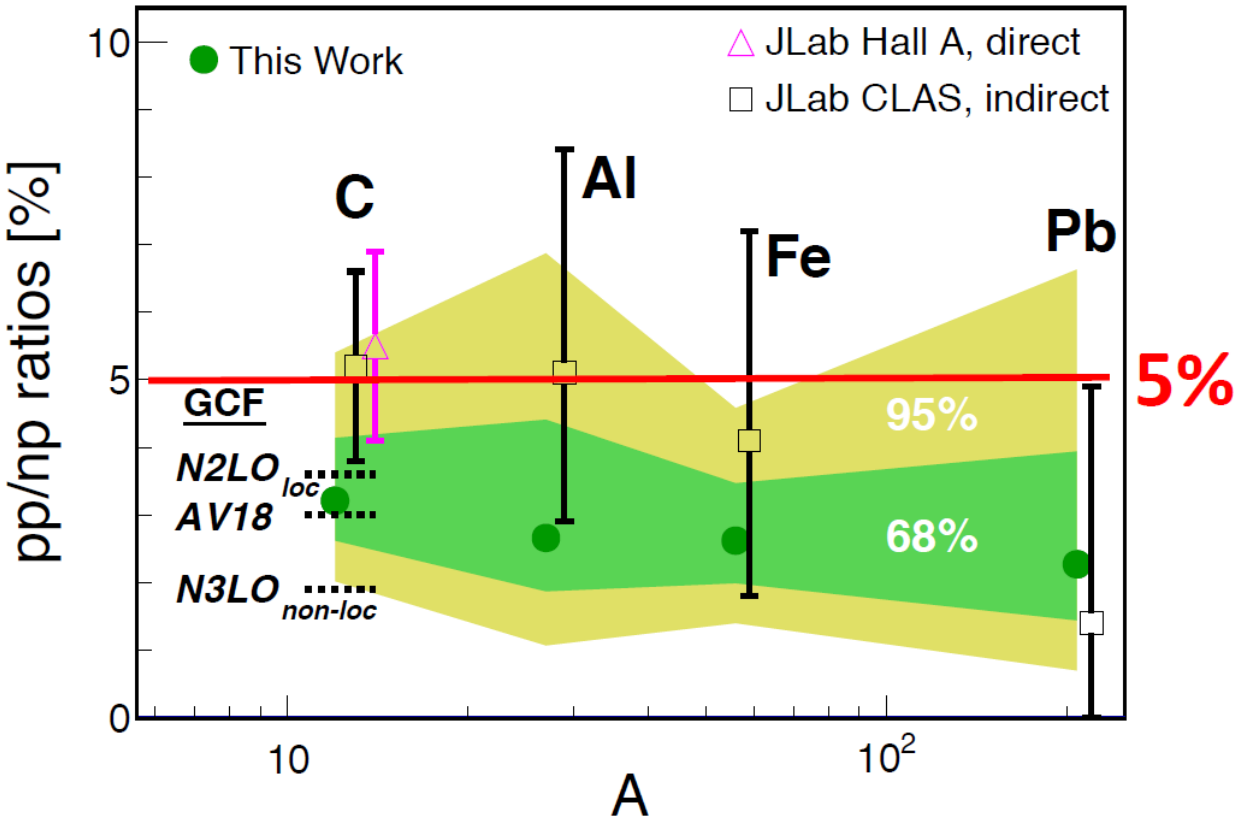


Fig. 1: Image of the EMC data as it appeared in the November 1982 issue of the CERN Courier. This image nearly derailed the highly cited refereed publication (Aubert et al., 1983), as the editor argued that the data had already been published.

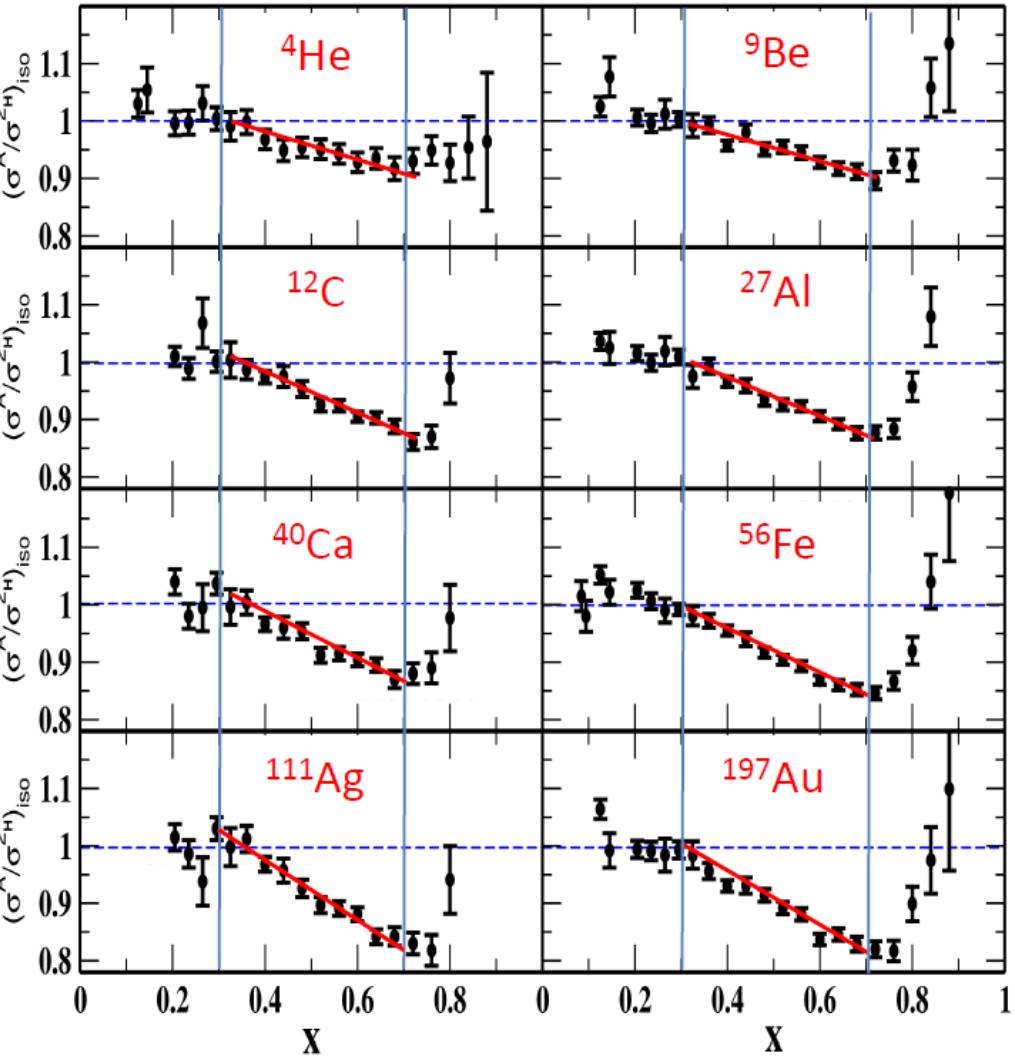
Short-range correlations (SRC)

Role of Tensor Force in SRC

- **Established in beautiful series of experiments at JLab**
- **Resolves a decades old dispute – with Arima's group as the winner**



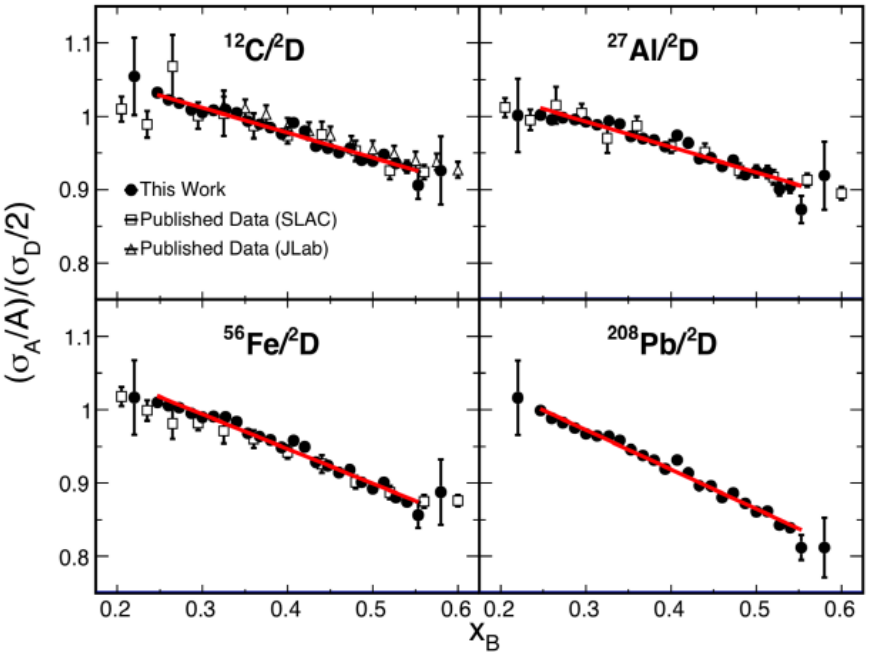
‘Global’ EMC Data



Gomez PRD (1994)

SLAC (1994)

JLab (2018)

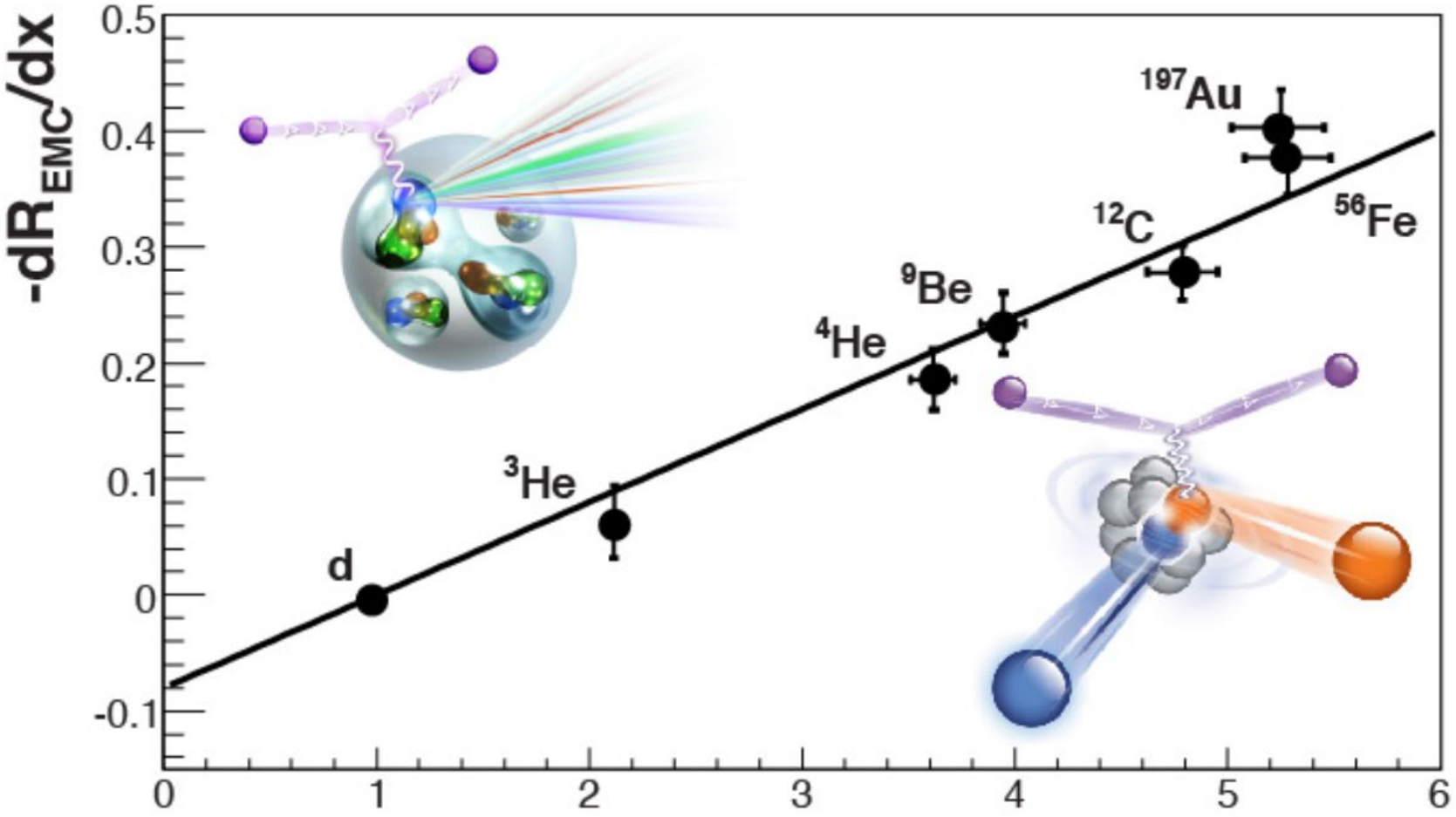


Schmookler, Nature (2019)

From O. Hen

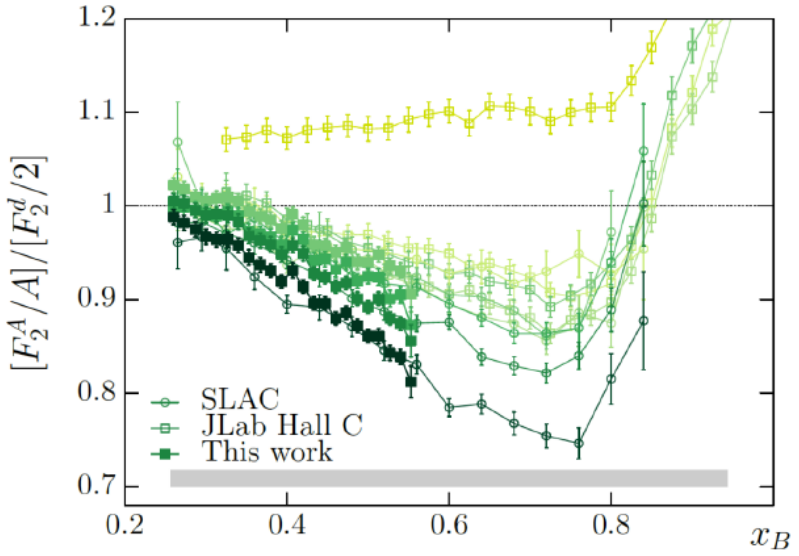
x>1 Ratios and EMC Slope Correlation

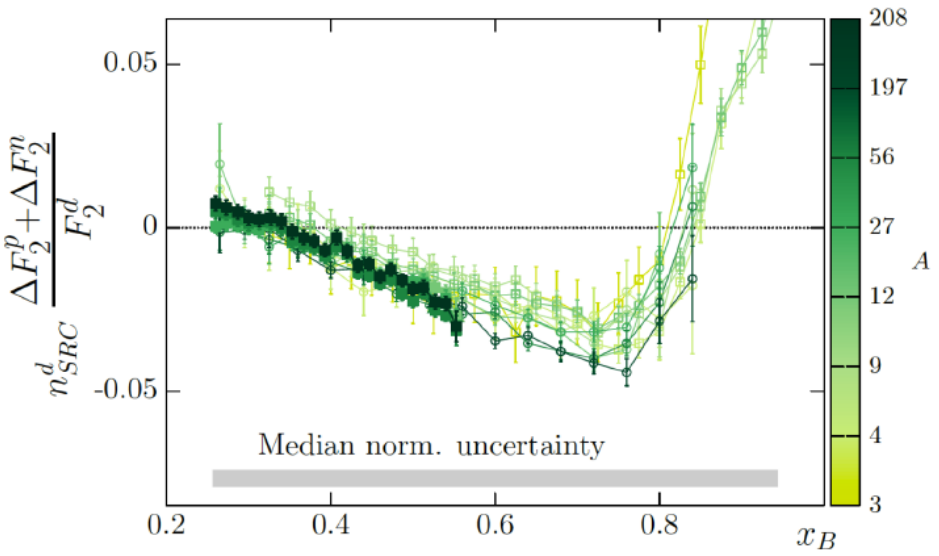
L. Weinstein *et al.*, Phys. Rev. Lett. **106** (2011) 052301.



Linear relation proposed as evidence that 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

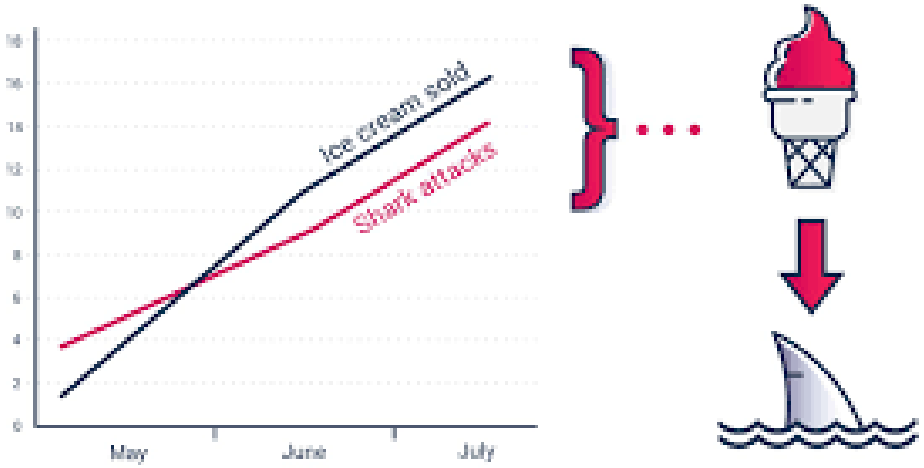
From talk of D. Higinbotham

"Cum hoc ergo propter hoc" is false!

- **Phrase taken from Wikipedia –**
  rough translation of the conclusion:

  "A correlation tells you absolutely nothing about cause"

  e.g.

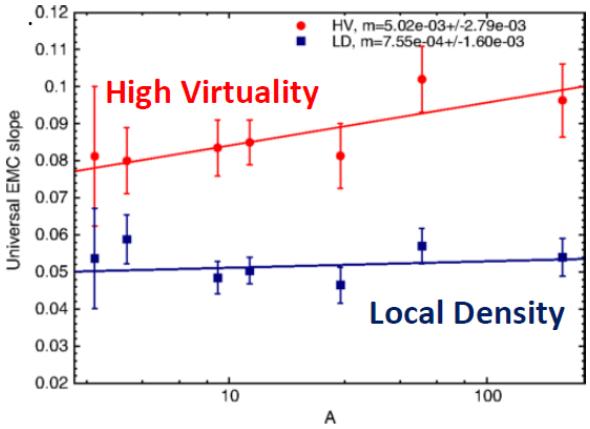


- **Yet the correlation between EMC slope and number of nucleons in short-range correlations is widely represented as proving SRC are the origin of the EMC effect**
  – THIS IS WITHOUT LOGICAL FOUNDATION

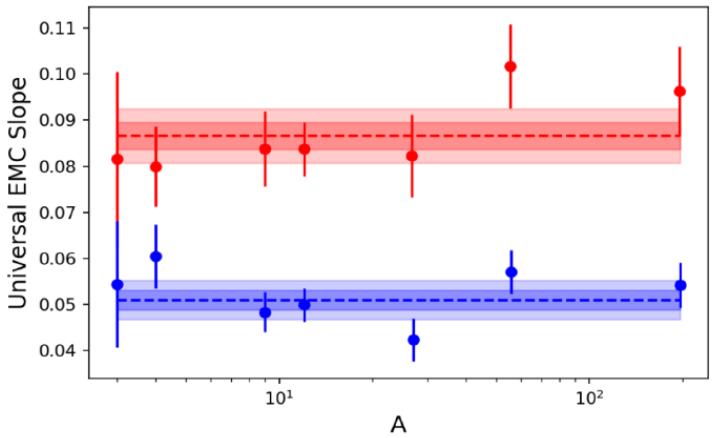
The same correlation applies to Local Density

High Virtuallity vs. Local Density

J. Arrington and N. Fomin, Phys. Rev. Lett. 123 (2019) 042501



O. Hen et al., arXiv:1905.02172.



The plots on the left and right side are exactly the same data.

The simpler model (i.e. a constant) is consistent with both universal functions.

One should define there criterion for adding parameters to a regression.
(see Higinbotham *et al.*, Phys. Rev. C. 93 (2015) 055207 for examples)

NOTE: When handled consistently, HV and LD give exactly the same 'a2' values.
https://arxiv.org/abs/1907.03658

From O. Hen

Alternate explanation based upon the effect of local scalar and vector mean-fields (~ local density) on confined quarks

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 46, NUMBER 6 DECEMBER 1992

Towards a microscopic understanding of nuclear structure functions

K. Saito
Physics Division, Tohoku College of Pharmacy, Sendai 981, Japan

A. Michels
Department of Theoretical Physics, Oxford University, 1 Keble Road, Oxford, United Kingdom

A. W. Thomas
Department of Physics and Mathematical Physics, University of Adelaide, P. O. Box 498, Adelaide, South Australia 5001, Australia
(Received 10 February 1992)

To understand this approach we need:

Insights into nuclear structure

– what is the atomic nucleus?

There are two very different extremes….

Quark Structure matters/doesn't matter

- **Nuclear femtography: the science of mapping the quark and gluon structure of *atomic nuclei* is just beginning**

- **"Considering quarks is in contrast to our modern understanding of nuclear physics… the basic degrees of freedom of QCD (quarks and gluons) have to be considered only at higher energies. The *energies relevant for nuclear physics are only a few* MeV"**

What do we know?

- Since 1970s: Dispersion relations → intermediate range NN attraction is a strong Lorentz scalar

- In relativistic treatments (RHF, RBHF, QHD…) this leads to mean scalar field on a nucleon ~300 to 500 MeV!!

- *This is not small* – up to half the nucleon mass
  - death of "wrong energy scale" arguments

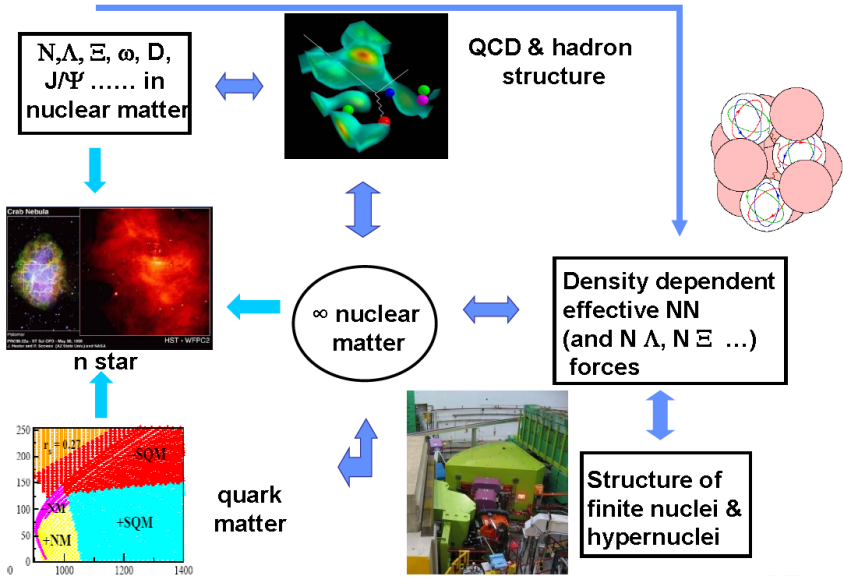
- Largely cancelled by large vector mean field BUT these have totally different dynamics: ω^0 just shifts energies, σ seriously modifies internal hadron dynamics

- Latter cannot be accurately captured by EFT with N and π

Suggests a different approach : QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- Start with quark model (MIT bag/NJL...) for all hadrons
- Introduce a relativistic Lagrangian with σ, ω and ρ mesons coupling to non-strange quarks
- Hence only 3 parameters (if σ mass fixed)
  - determine by fitting to:
    ρ_0 , E/A and symmetry energy
  - same in dense matter & finite nuclei
- Must solve self-consistently for the internal structure of baryons in-medium



Quark-Meson Coupling Model (QMC):
Role of the Scalar Polarizability of the Nucleon

The response of the nucleon internal structure to the scalar field is of great interest… and importance

$$M^*(\mathbf{r}) = M - g_\sigma \sigma(\mathbf{r}) + \frac{d}{2}\left(g_\sigma \sigma(\mathbf{r})\right)^2$$

Non-linear dependence through the scalar polarizability

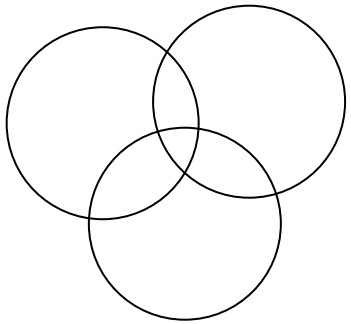
d ~ 0.22 R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level (e.g. QMC), this is the ONLY place the response of the internal structure of the nucleon enters.

Summary : Scalar Polarizability

- Can always rewrite non-linear coupling as linear coupling plus non-linear scalar self-coupling – likely physical origin of some non-linear versions of QHD

- Consequence of polarizability in atomic physics is many-body forces:



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

– same is true in nuclear physics

Application to nuclear structure

and Neutron Stars – not discussed here….

QMC model predicted heavy neutron stars with hyperons before their discovery

Derivation of Density Dependent Effective Force

Physical origin of density dependent forces of Skyrme type within the quark meson coupling model

P.A.M. Guichon [a,*], H.H. Matevosyan [b,c], N. Sandulescu [a,d,e], A.W. Thomas [b]

Nuclear Physics A 772 (2006) 1–19

- **Start with classical theory of MIT-bag nucleons with structure modified in medium to give M_{eff} (σ).**
- **Quantise nucleon motion (non-relativistic), expand in powers of derivatives**
- **Derive equivalent, local energy functional:**

$$\langle H(\vec{r}) \rangle = \rho M + \frac{\tau}{2M} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\text{eff}} + \mathcal{H}_{\text{fin}} + \mathcal{H}_{\text{so}}$$

Derivation of effective Force (cont.)

$$\mathcal{H}_0+\mathcal{H}_3=\rho^2\left[\frac{-3G_\rho}{32}+\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}-\frac{G_\sigma}{2(1+d\rho G_\sigma)}+\frac{3G_\omega}{8}\right]$$
$$+(\rho_n-\rho_p)^2\left[\frac{5G_\rho}{32}+\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}-\frac{G_\omega}{8}\right],$$

$$\mathcal{H}_{\rm eff}=\left[\left(\frac{G_\rho}{8{m_\rho}^2}-\frac{G_\sigma}{2{m_\sigma}^2}+\frac{G_\omega}{2{m_\omega}^2}+\frac{G_\sigma}{4{M_N}^2}\right)\rho_n+\left(\frac{G_\rho}{4m_\rho^2}+\frac{G_\sigma}{2M_N^2}\right)\rho_p\right]\tau_n$$
$$+p\leftrightarrow n,$$

$$\mathcal{H}_{\rm fin}=\left[\left(\frac{3G_\rho}{32{m_\rho}^2}-\frac{3G_\sigma}{8{m_\sigma}^2}+\frac{3G_\omega}{8{m_\omega}^2}-\frac{G_\sigma}{8{M_N}^2}\right)\rho_n\right.$$
$$\left.+\left(\frac{-3G_\rho}{16{m_\rho}^2}-\frac{G_\sigma}{2{m_\sigma}^2}+\frac{G_\omega}{2{m_\omega}^2}-\frac{G_\sigma}{4{M_N}^2}\right)\rho_p\right]\nabla^2(\rho_n)+p\leftrightarrow n,$$

$$\mathcal{H}_{\rm so}=\nabla\cdot J_n\left[\left(\frac{-3G_\sigma}{8{M_N}^2}-\frac{3G_\omega(-1+2\mu_s)}{8{M_N}^2}-\frac{3G_\rho(-1+2\mu_v)}{32{M_N}^2}\right)\rho_n\right.$$
$$\left.+\left(\frac{-G_\sigma}{4{M_N}^2}+\frac{G_\omega(1-2\mu_s)}{4{M_N}^2}\right)\rho_p\right]+p\leftrightarrow n.$$

Spin-orbit force predicted!

Note the totally new, subtle density dependence

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Overview: 4 parameters vs 10

data	rms error %	
	QMC	SV-min
fit nuclei: ~ 70 nuclei across the periodic table		
binding energies	0.36	0.24
diffraction radii	1.62	0.91
surface thickness	10.9	2.9
rms radii	0.71	0.52
pairing gap (n)	57.6	17.6
pairing gap (p)	25.3	15.5
ls splitting: proton	15.8	18.5
ls splitting: neutron	20.3	16.3
superheavy nuclei:	0.1	0.3
N=Z nuclei	1.17	0.75
mirror nuclei	1.50	1.00
other	0.35	0.26

Stone et al., PRL 116 (2016) 092501

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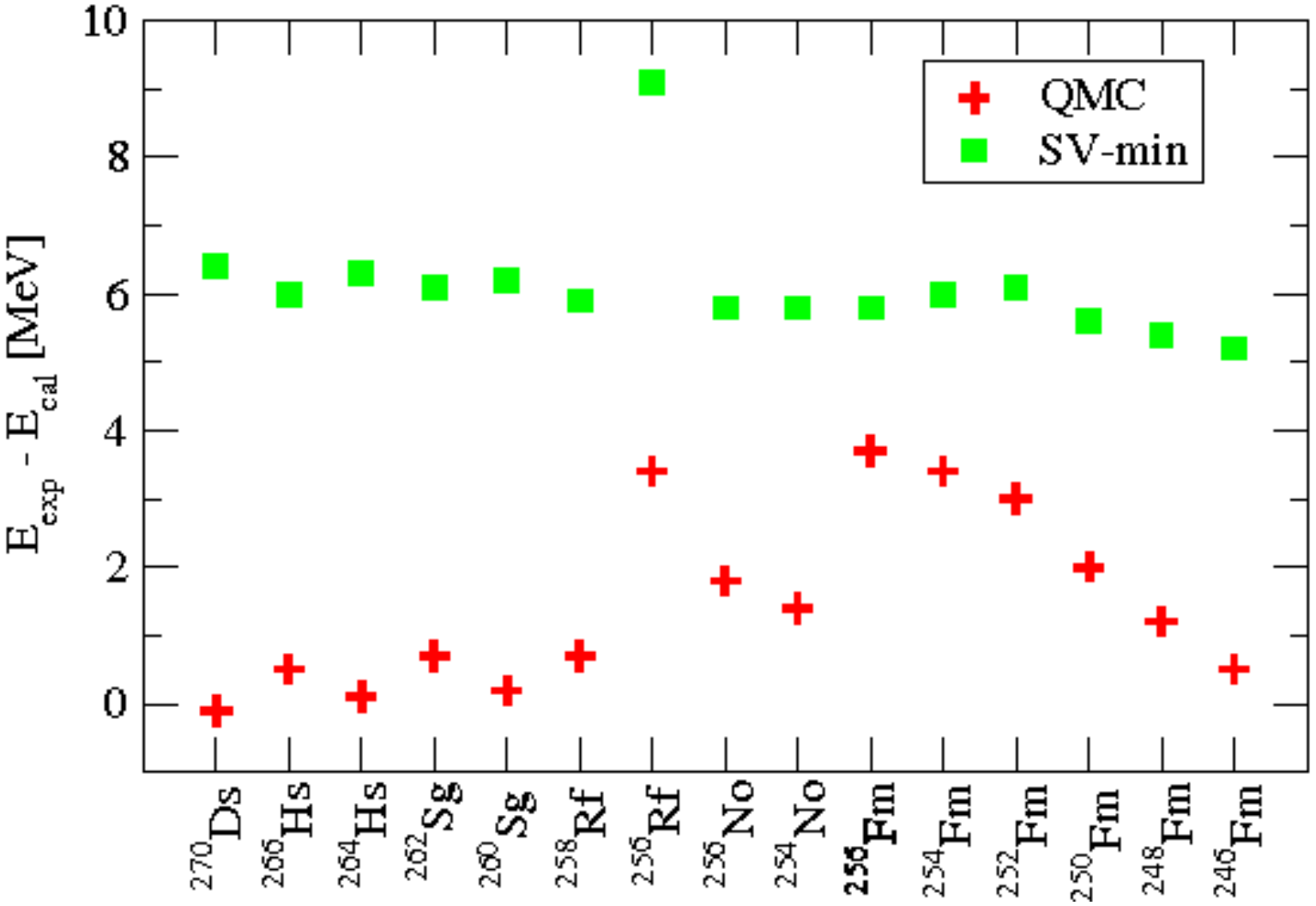
Superheavies (not fit) : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

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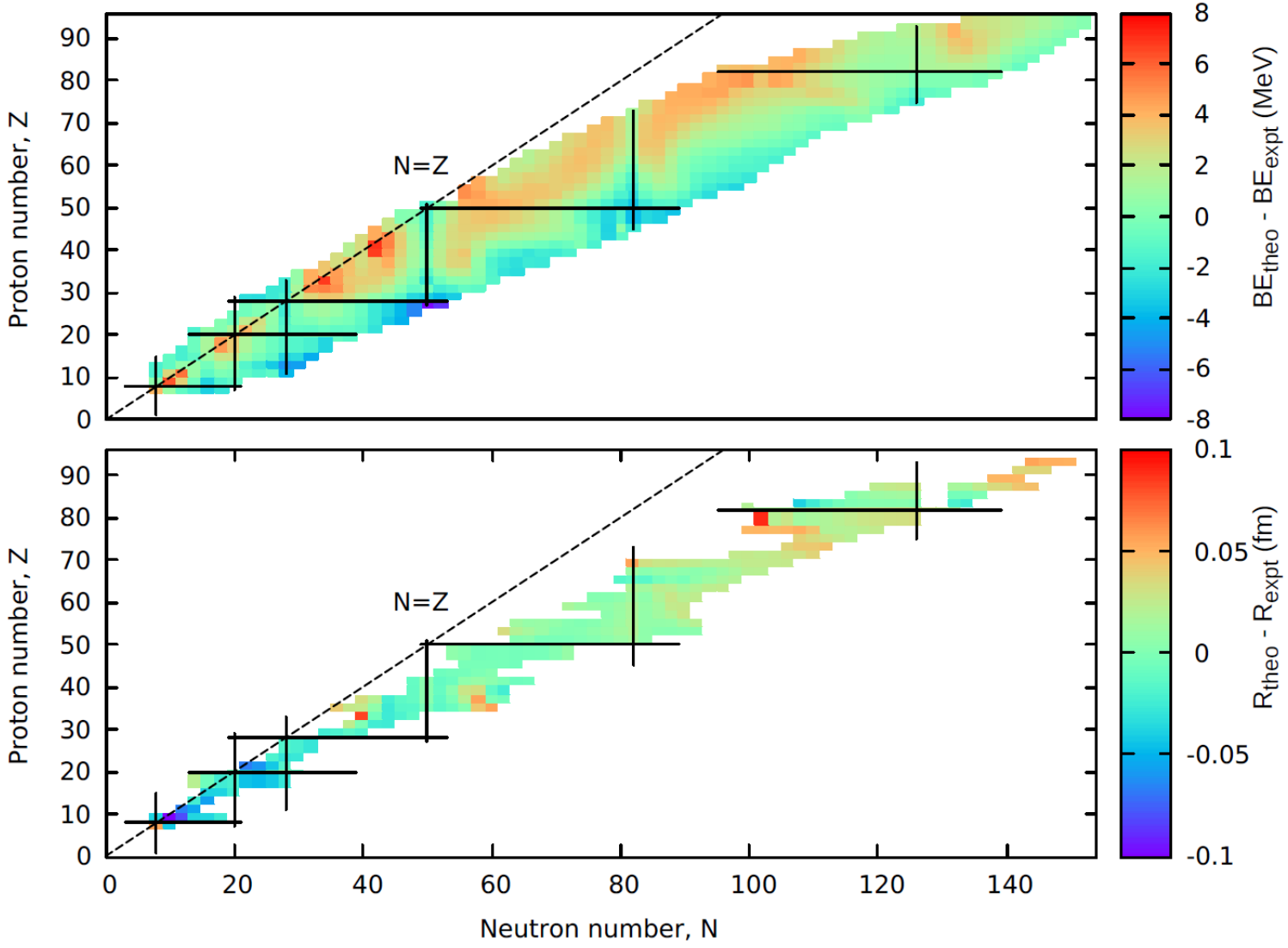
Overview of 739 even-even nuclei



Martinez *et al.*, arXiv:1811.06628 – Phys Rev C 2019

Summary: Finite Nuclei

- **The effective force was *derived* at the quark level *based upon changing structure of bound nucleon***
- **Has many less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces**
- **Can be used in same codes that use Skyrme forces**
- **BUT underlying theory also predicts modified internal structure and hence modified**
  - **DIS structure functions**
  - **elastic form factors.....**

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)

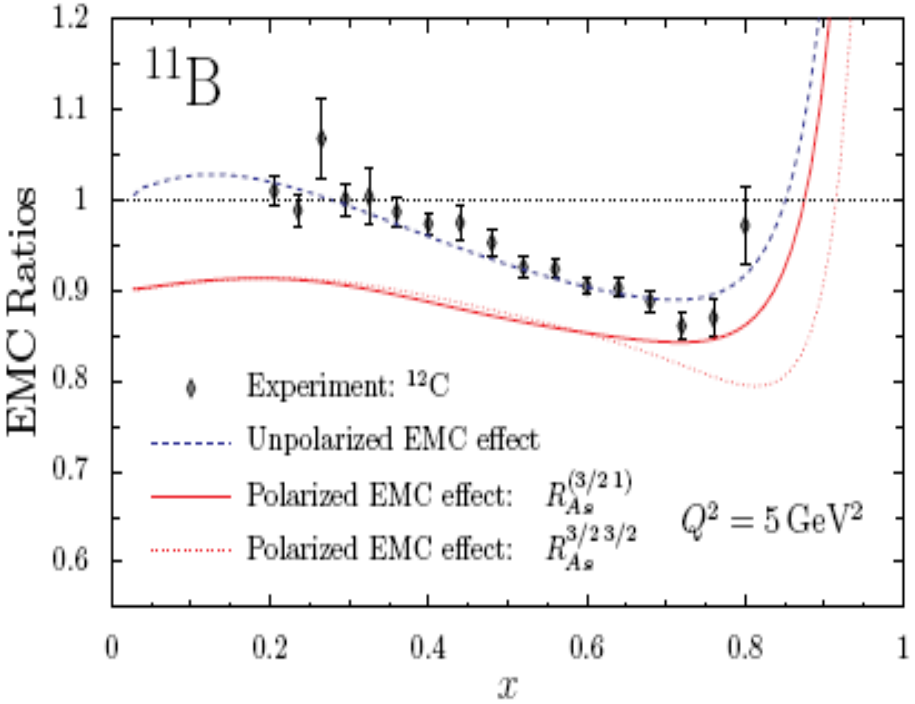


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

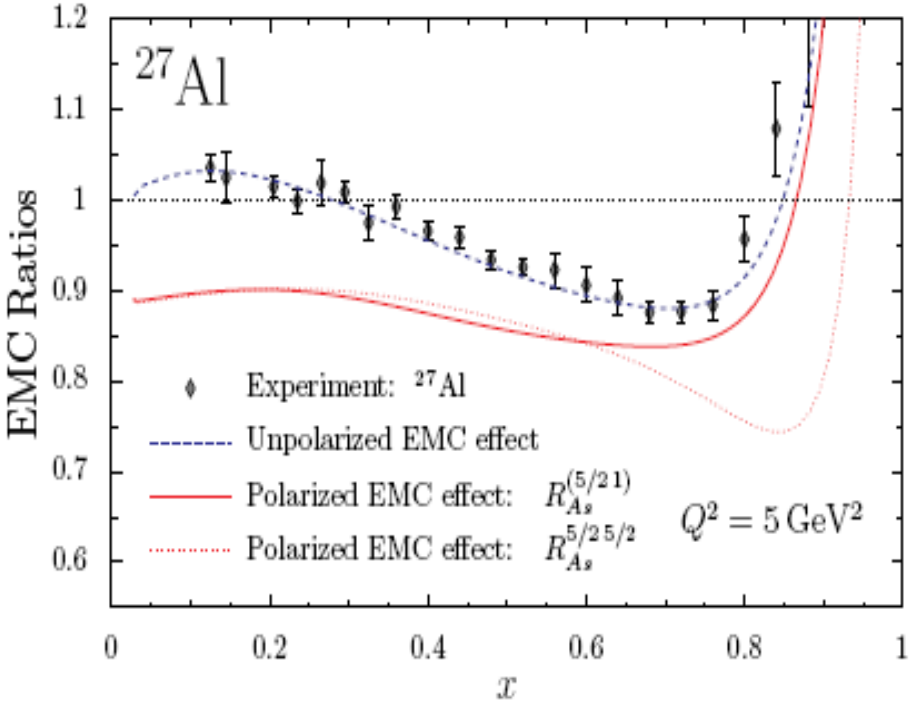
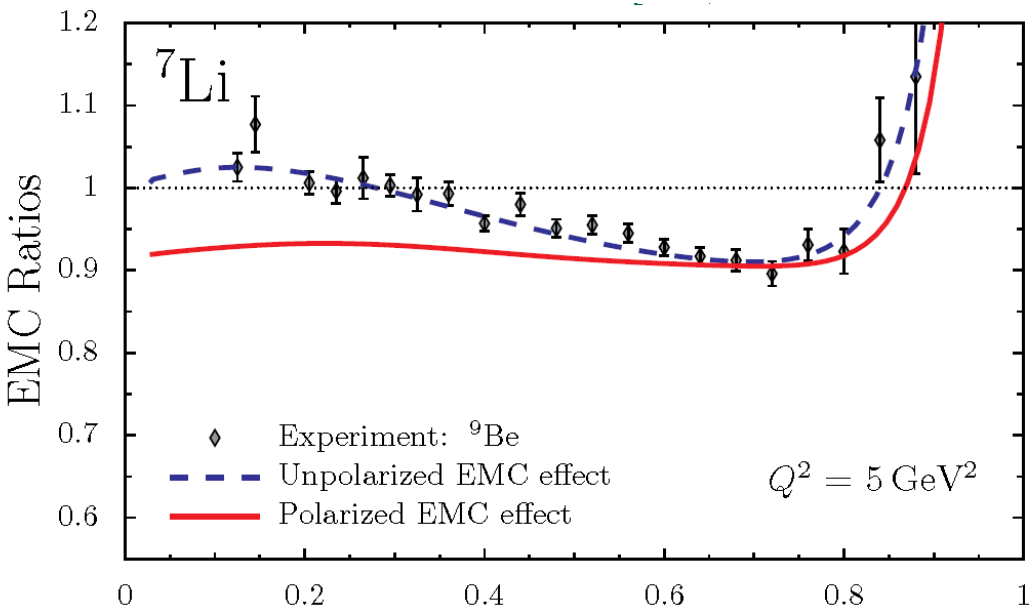


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

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)

SRC versus QMC - tests

Spin-EMC Effect is a crucial test

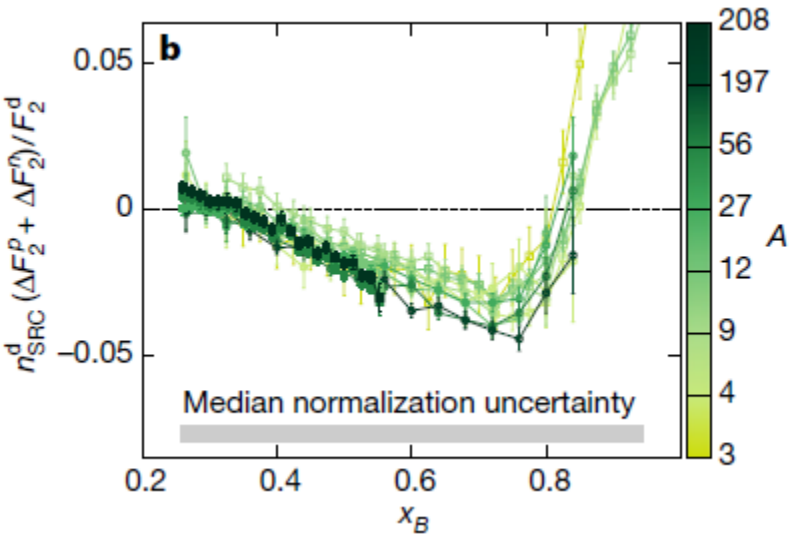
- **Tensor correlations leading to high momentum components in nuclear wave function have been proposed as an alternate explanation of the EMC effect**

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

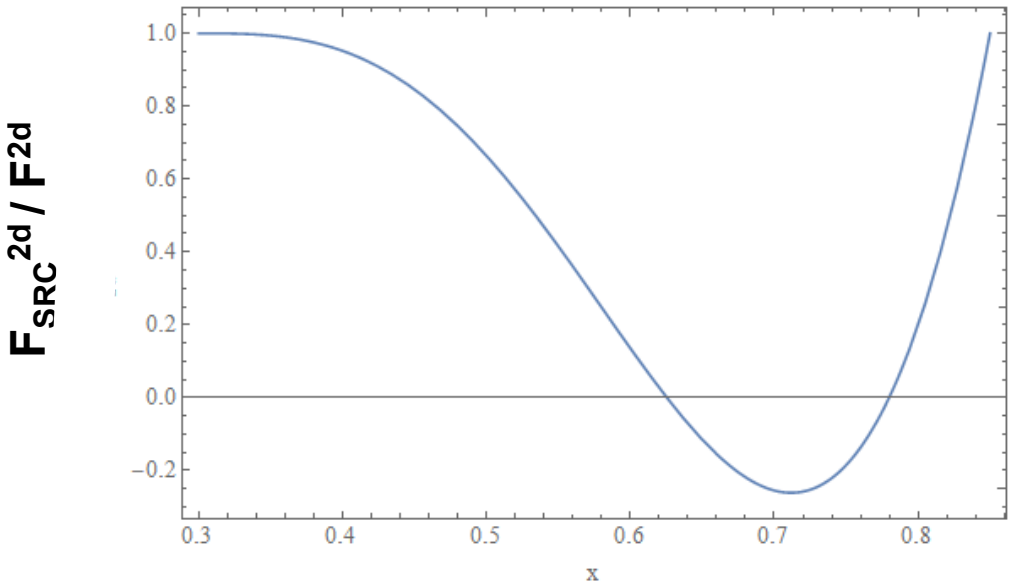
- **Nucleons in SRC are depolarized – simple Clebsch-Gordan coefficients - and cannot contribute to spin-EMC effect**

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

Further – change in F_2 dramatic



- Does not look so dramatic 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 more than 100% in the valence region



AWT to be published

Such a dramatic change is not viable

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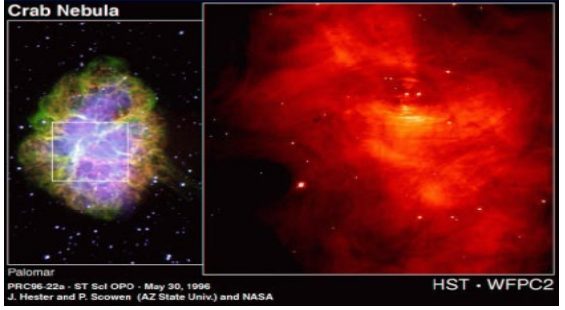
I. Summary



- The EMC effect contains fundamental information about the structure of atomic nuclei

- The QMC approach is based upon the change in nucleon structure because of STRONG Lorentz scalar mean field

- This modifies the intrinsic structure of the bound nucleon
  - profound change in shell model :
    what occupies shell model states are NOT free nucleons

- Scalar polarizability is a natural source of three-body forces (NNN, HNN, HHN…)
  - clear physical interpretation

- Naturally generates effective HN and HNN forces with no new parameters and predicts heavy neutron stars

II. Summary

- Initial systematic study of finite nuclei very promising
  - Binding energies typically within 0.3% across periodic table with super-heavies (Z > 100) especially good

- Model describes the EMC effect very well, and in addition:
  - Predicts isovector EMC effect (>1σ of the NuTeV anomaly)
  - Predicts significant spin-EMC effect

- SRC explanation implies a HUGE/unphysical suppression of F_2 for correlated nucleons
  - This needs serious study!
  - SRC proposal also predicts NO spin-EMC effect

- Latter (spin-EMC) is a vital test

Special Mentions……

Guichon

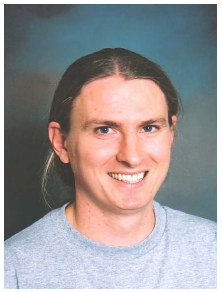
Tsushima

Saito

Stone

Krein

Matevosyan



Cloët

Whittenbury

Simenel

Bentz

Martinez

Motta

Antic

Kalaitzis

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Key papers on QMC

- **Two major, recent papers:**

  1. Guichon, Matevosyan, Sandulescu, Thomas, Nucl. Phys. A772 (2006) 1.
  2. Guichon and Thomas, Phys. Rev. Lett. 93 (2004) 132502

- **Built on earlier work on QMC: e.g.**

  3. Guichon, Phys. Lett. B200 (1988) 235
  4. Guichon, Saito, Rodionov, Thomas, Nucl. Phys. A601 (1996) 349

- **Major review of applications of QMC to many nuclear systems:**

  5. Saito, Tsushima, Thomas, Prog. Part. Nucl. Phys. 58 (2007) 1-167 (hep-ph/0506314)

References to: Covariant Version of QMC

- Basic Model: (Covariant, chiral, confining version of NJL)

•Bentz & Thomas, Nucl. Phys. A696 (2001) 138

• Bentz, Horikawa, Ishii, Thomas, Nucl. Phys. A720 (2003) 95

- Applications to DIS:

• Cloet, Bentz, Thomas, Phys. Rev. Lett. 95 (2005) 052302

• Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210

- Applications to neutron stars – including SQM:

• Lawley, Bentz, Thomas, Phys. Lett. B632 (2006) 495

• Lawley, Bentz, Thomas, J. Phys. G32 (2006) 667

Effect of scalar field on quark spinor

- **MIT bag model: quark spinor modified in bound nucleon**

$$\psi = \frac{\mathcal{N}}{4\pi}\begin{pmatrix} j_0(xu'/R_B) \\ i\beta_q \vec{\sigma}\cdot\hat{u}' j_1(xu'/R_B) \end{pmatrix}\chi_m$$

- **Lower component enhanced by attractive scalar field**

$$\beta_q = \sqrt{\frac{\Omega_0 - m_q^* R_B}{\Omega_0 + m_q^* R_B}}$$

- **This leads to a *very small* (~1% at ρ_0) *increase in bag radius***

- **It also *suppresses the scalar coupling to the nucleon as the scalar field increases***

$$\frac{\Omega_0/2 + m_q^* R_B(\Omega_0 - 1)}{\Omega_0(\Omega_0 - 1) + m_q^* R_B/2} = \int \bar{\psi}\,\psi \; dV$$

- **This is the "scalar polarizability": a new saturation mechanism for nuclear matter**

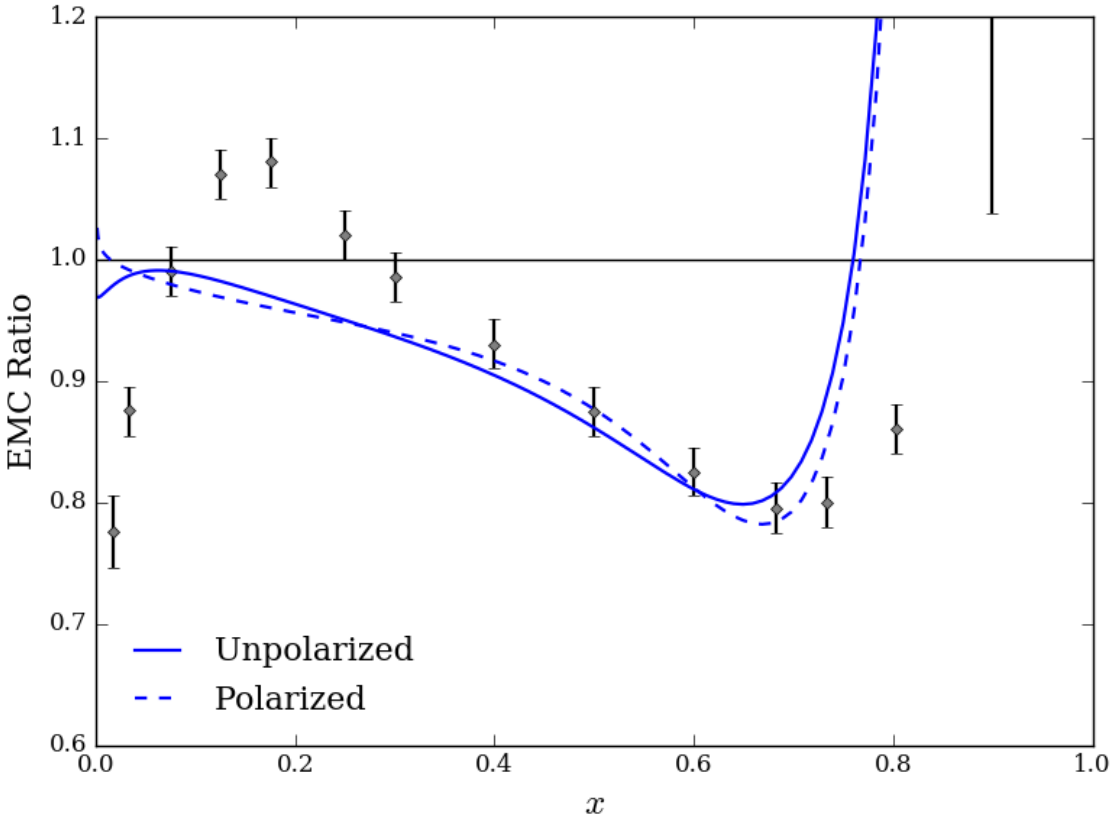
Theoretical Understanding

- Still numerous proposals but few consistent theories
- Initial studies used MIT bag[1] to estimate effect of self-consistent change of structure in-medium – but better to use a covariant theory
- For that Bentz and Thomas[2] re-derived change of nucleon structure in-medium in the NJL model
- This set the framework for sophisticated studies by Cloët and collaborators over the last decade

[1] Thomas, Michels, Schreiber and Guichon, Phys. Lett. B233 (1989) 43
[2] Bentz and Thomas, Nucl. Phys. A696 (2001) 138

Model dependence of spin-EMC effect

Went back to QMC, with defects of bag model (especially too small at large-x). Simply examine, without details of nuclear structure, at ρ_0 , how the polarized EMC effect compares with the unpolarized effect.



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