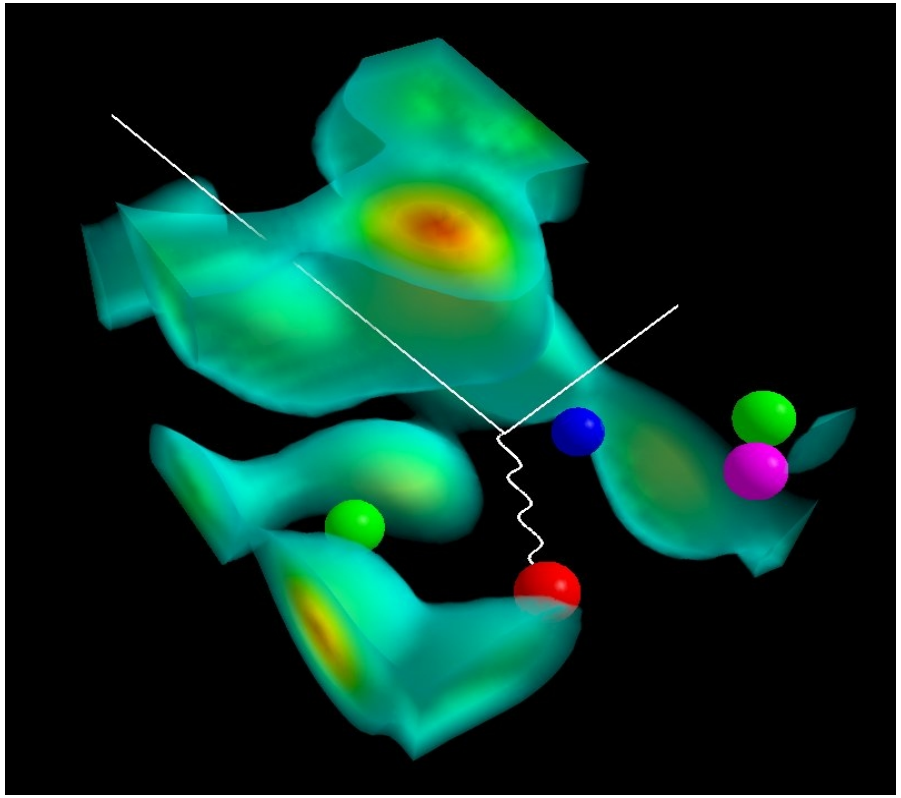
Nuclear Structure, QCD and the EMC Effect



Anthony W. Thomas

EMC SRC Workshop
Jefferson Lab – 4am March 25th 2021

ADELAIDE UNIVERSITY AUSTRALIA

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

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

II. Proposal: arises *entirely* from nucleons in short-range correlations

III. Alternate: It matters that nuclei are built from Quarks & Gluons
- start from a QCD-inspired model of *hadron* structure
- develop a quantitative theory of nuclear structure

IV. Test the SRC explanation of the EMC effect

— using D as an example

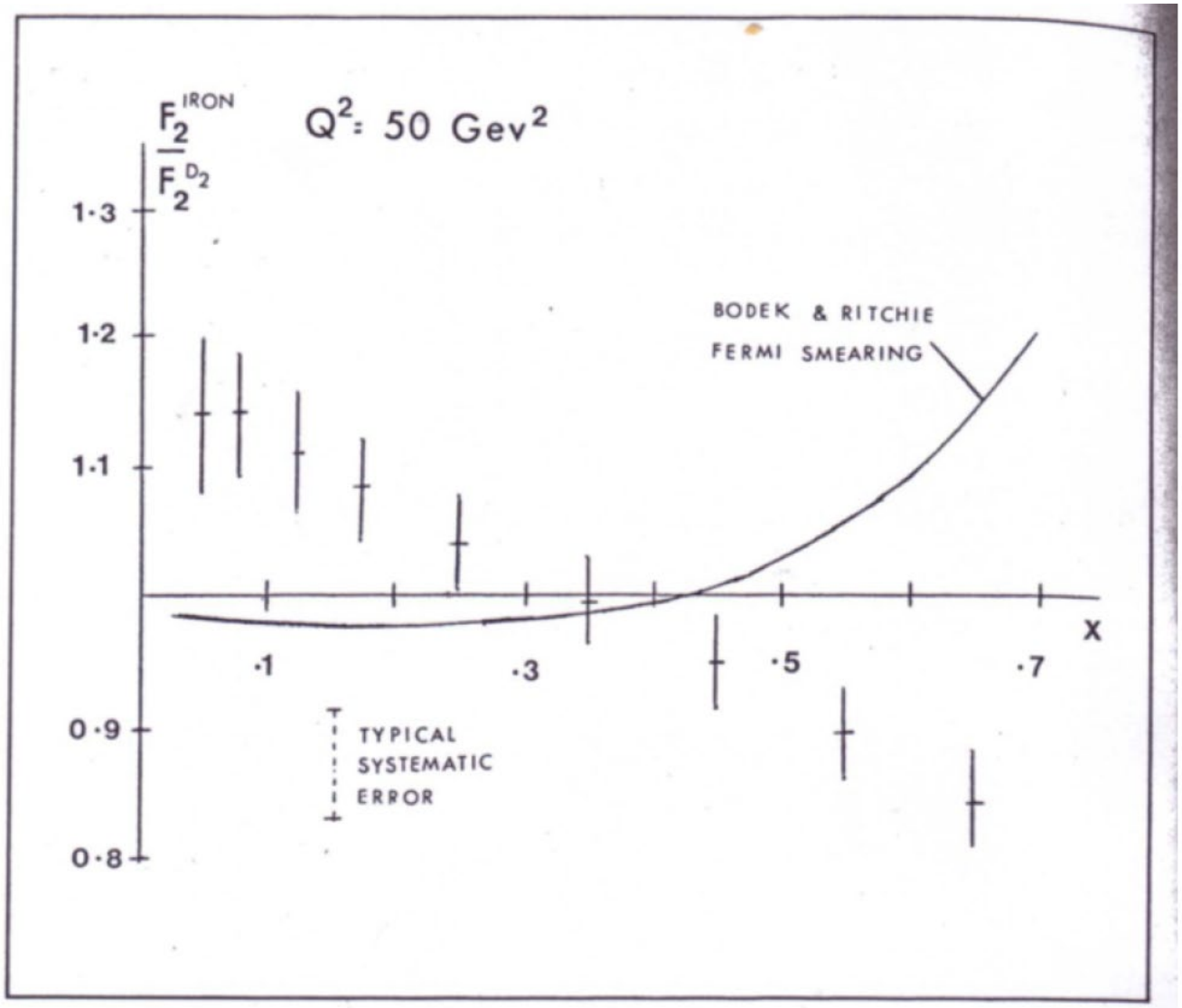


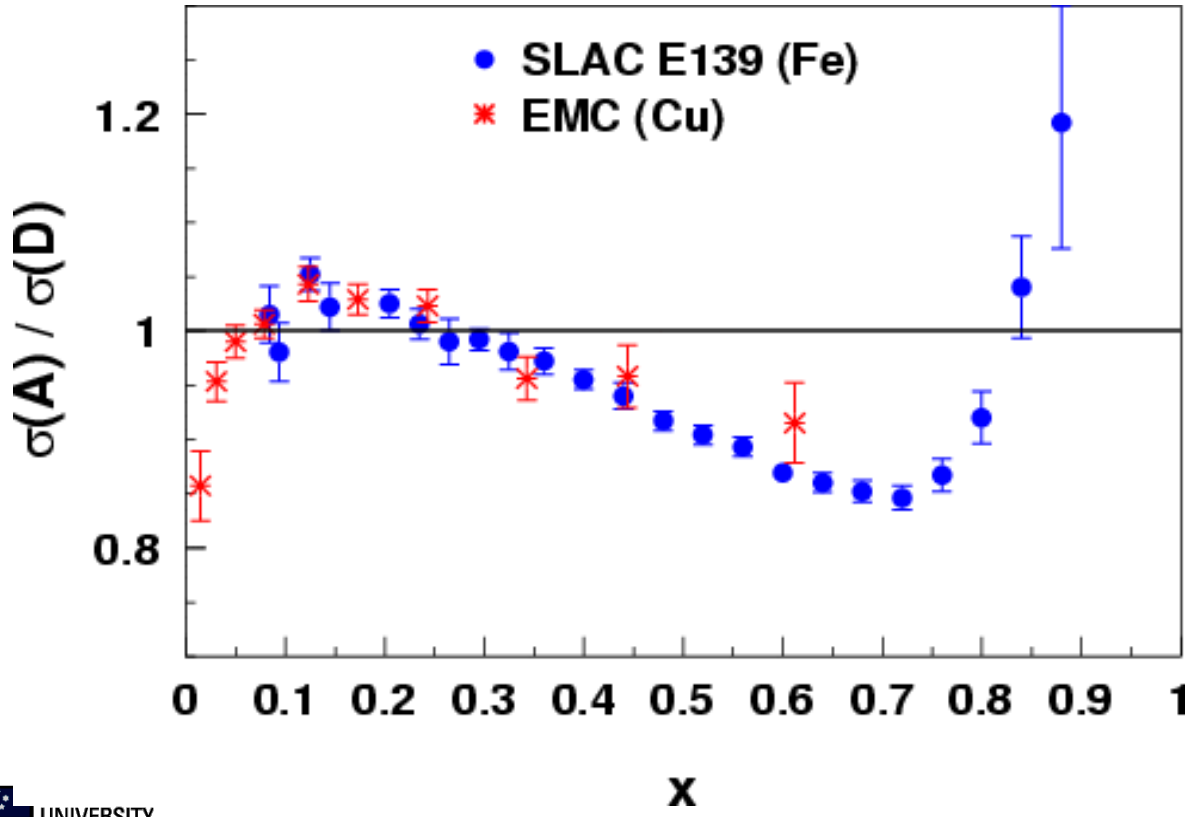
Fig. 1: Image of the EMC data as it appeared in the November 1982 issue of the CERN Courier. This image nearly derailed the highly cited refereed publication (Aubert et al., 1983), as the editor argued that the data had already been published.

Higinbotham *et al.*, CERN Courier 2013

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 37 years ago

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



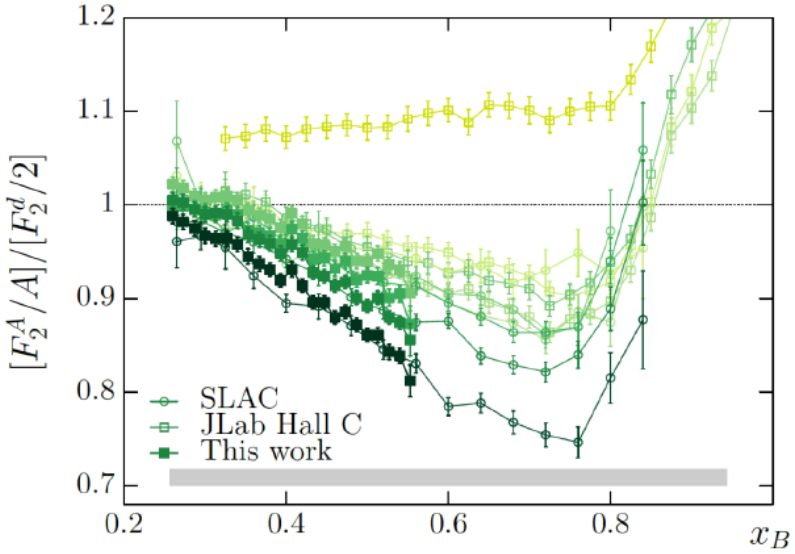
J. Ashman *et al.*, Z. Phys. C57, 211 (1993)

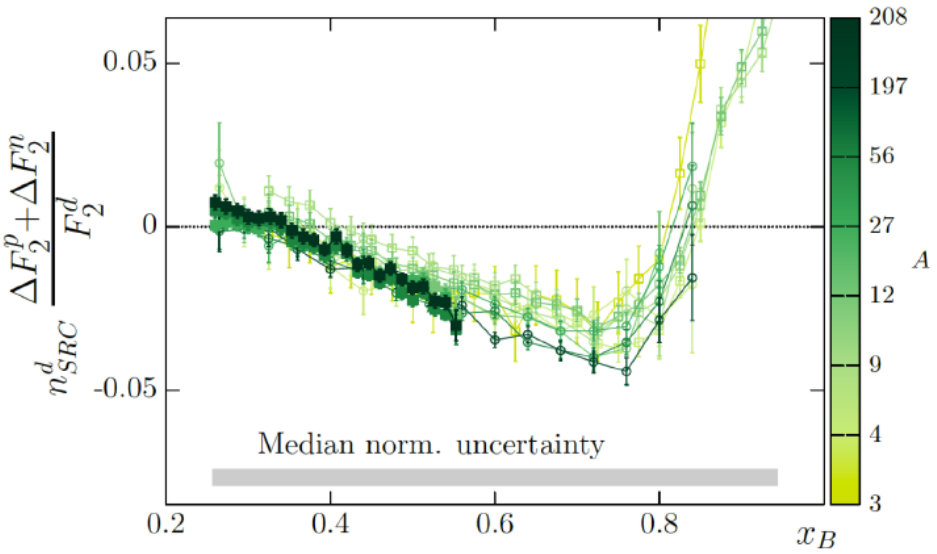
J. Gomez *et al.*, Phys. Rev. D49, 4348 (1994)

Short-range correlations (SRC)

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

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



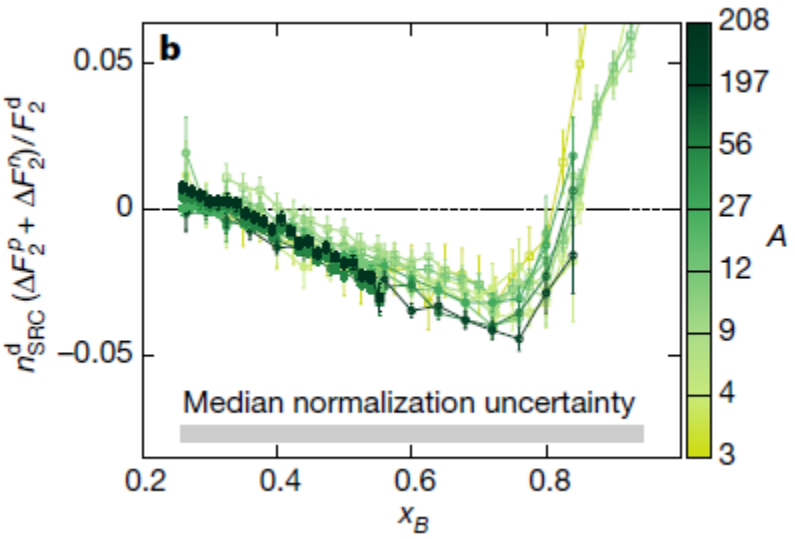


$$F_2^A = (Z - n_{SRC}^A)F_2^p + (N - n_{SRC}^A)F_2^n + n_{SRC}^A(F_2^{p*} + F_2^{n*})$$
$$= ZF_2^p + NF_2^n + n_{SRC}^A(\Delta F_2^p + \Delta F_2^n),$$

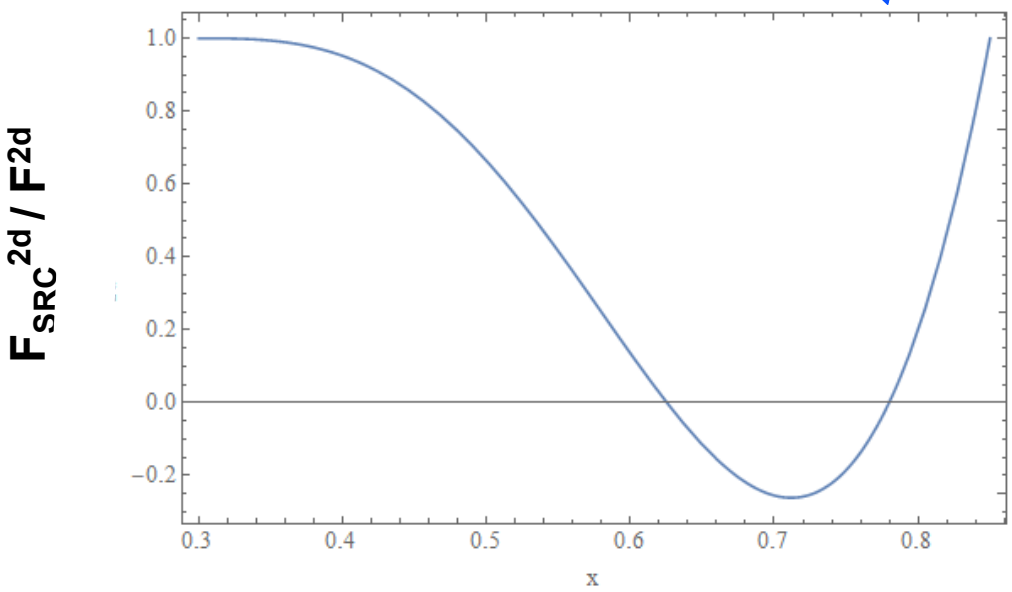
Entire EMC effect from the change in SF of nucleons in SRC

From Doug Higinbotham

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



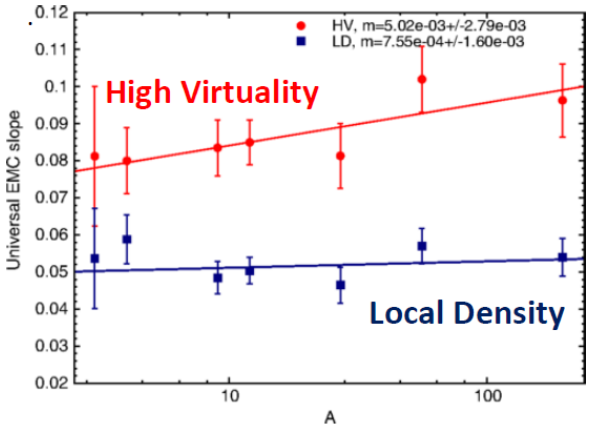
Such a dramatic change is not viable

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

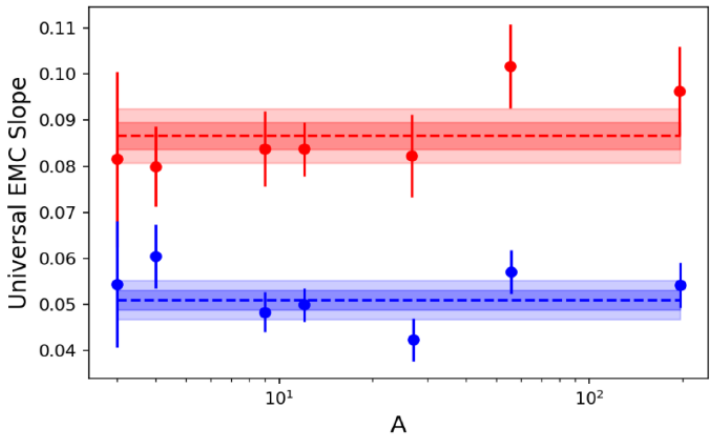
The same correlation applies to Local Density

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

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

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(Received 10 February 1992)

Very large scalar mean-fields are a fact

TABLE II. Results of a relativistic Dirac-Brueckner calculation in comparison to the tential B. As a function of the Fermi momentum k_F, it is listed: the energy per nucleon vector potentials U_S and U_V, and the wound integral κ.

			Relativistic		
k_F (fm^{-1})	$\mathcal{E}/A$ (MeV)	$\tilde{M}/M$	U_S (MeV)	U_V (MeV)	κ (%)
0.8	−7.02	0.855	−136.2	104.0	23.1
0.9	−8.58	0.814	−174.2	134.1	18.8
1.0	−10.06	0.774	−212.2	164.2	16.1
1.1	−11.18	0.732	−251.3	195.5	12.7
1.2	−12.35	0.691	−290.4	225.8	11.9
1.3	−13.35	0.646	−332.7	259.3	12.5
1.35	−13.55	0.621	−355.9	278.4	13.0
1.4	−13.53	0.601	−374.3	293.4	13.8
1.5	−12.15	0.559	−413.6	328.4	14.4
1.6	−8.46	0.515	−455.2	371.0	15.8

Brockmann and Machleidt, Phys Rev C52 (1990) 1965

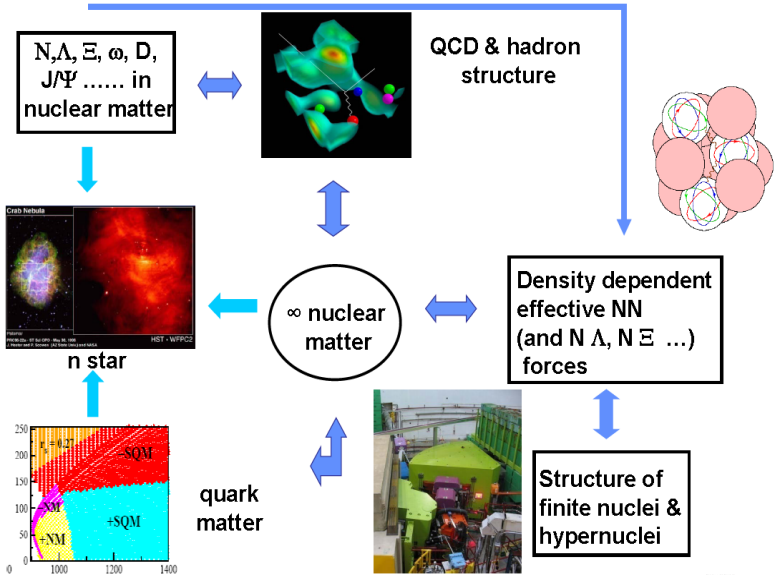
General Remarks

- Every nucleus is a different eigenstate of QCD
- Any theoretical explanation of EMC effect in terms of bound nucleons is a model
- Strong mean scalar and vector fields mean that it is inappropriate to characterize nuclear corrections in terms of how far off-mass-shell a bound nucleon may be
- The scalar and vector fields enter the calculation of a structure function in different ways

A new approach to nuclear matter: QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al., Stone
- see Saito *et al*., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Guichon *et al*., 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, initially only 3 parameters
  (4 if σ mass not 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

Application to nuclear structure

and Neutron Stars – cannot be discussed here….

The 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

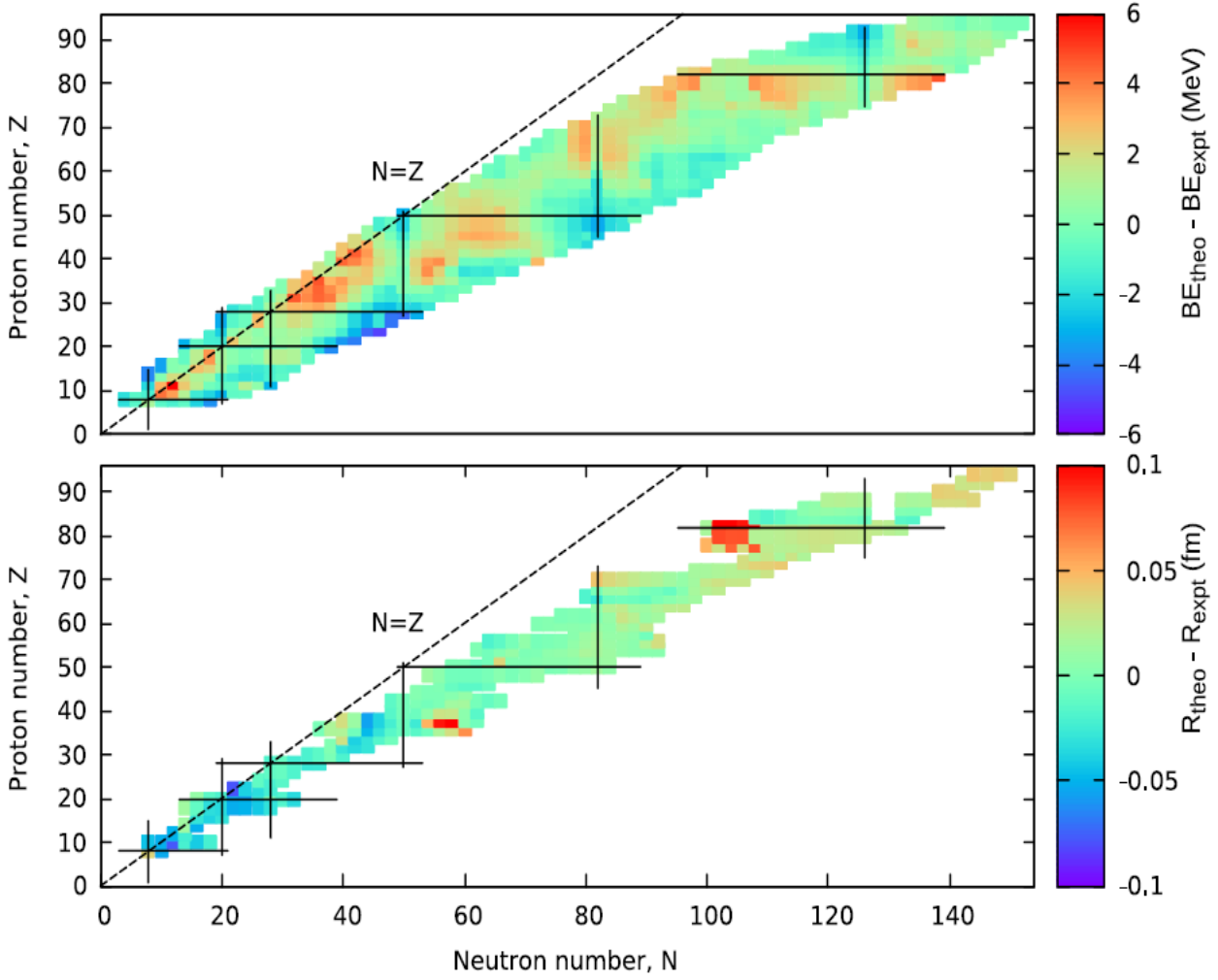
- **Start with classical theory of MIT-bag nucleons with structure modified self-consistently in medium to give M_{eff} (σ).**
- **Quantise nucleon motion (non-relativistic), expand in powers of derivatives**
- **Derive equivalent, local energy functional:**

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

First structure calculations: Phys Rev Lett 116 (2016) 092501

Latest development: QMC pi3

- Correct to all order in nuclear density; add σ^3 term; calculate pairing
- Now just 5 parameters – cf. 15+ in typical Skyrme calculations



Martinez et al., Phys Rev C106, 034304 (2020)

Giant Monopole Resonances

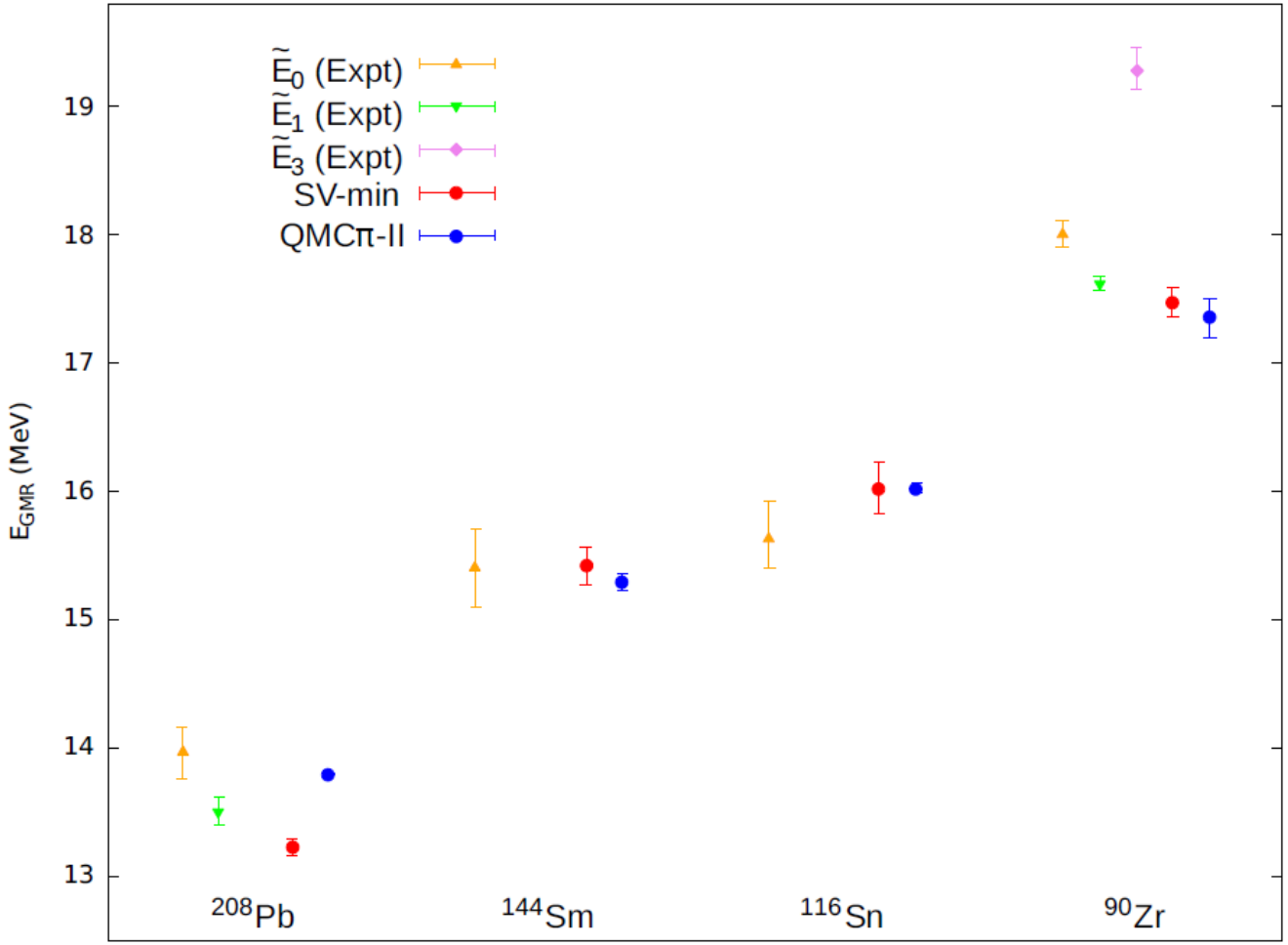
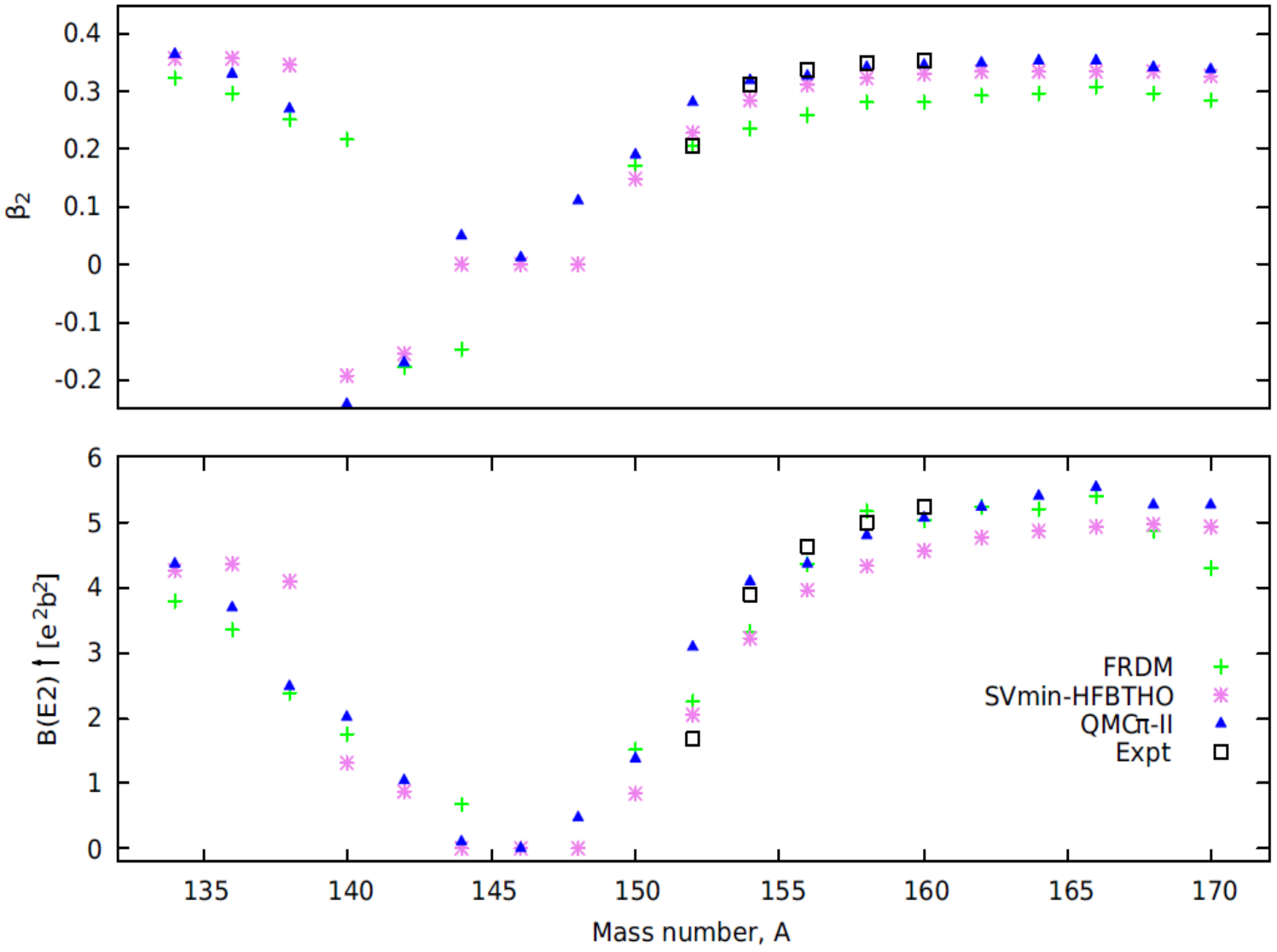


FIG. 13. GMR energies for ^{208}Pb, ^{144}Sm, ^{116}Sn, and ^{90}Zr from experiment and for the QMCπ-II and SVmin models. Experimental data are taken from Table 1 of Ref. [24].

Kay Martinez *et al.*, Phys Rev C100 (2019) 024333

Deformation of Gd isotopes



Kay Martinez *et al.*, Phys Rev C100 (2019) 024333

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)

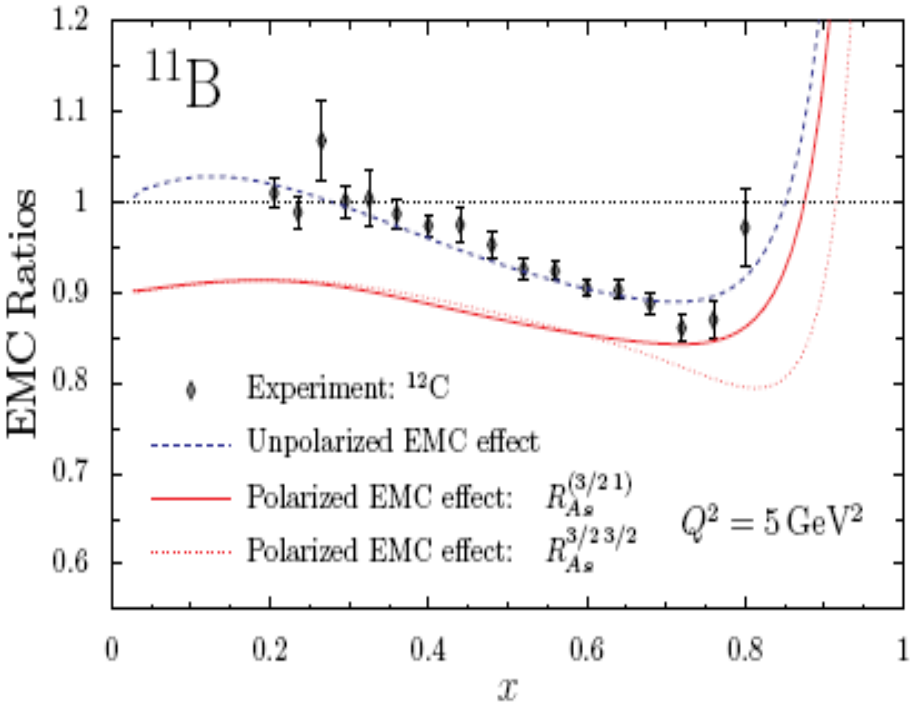


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

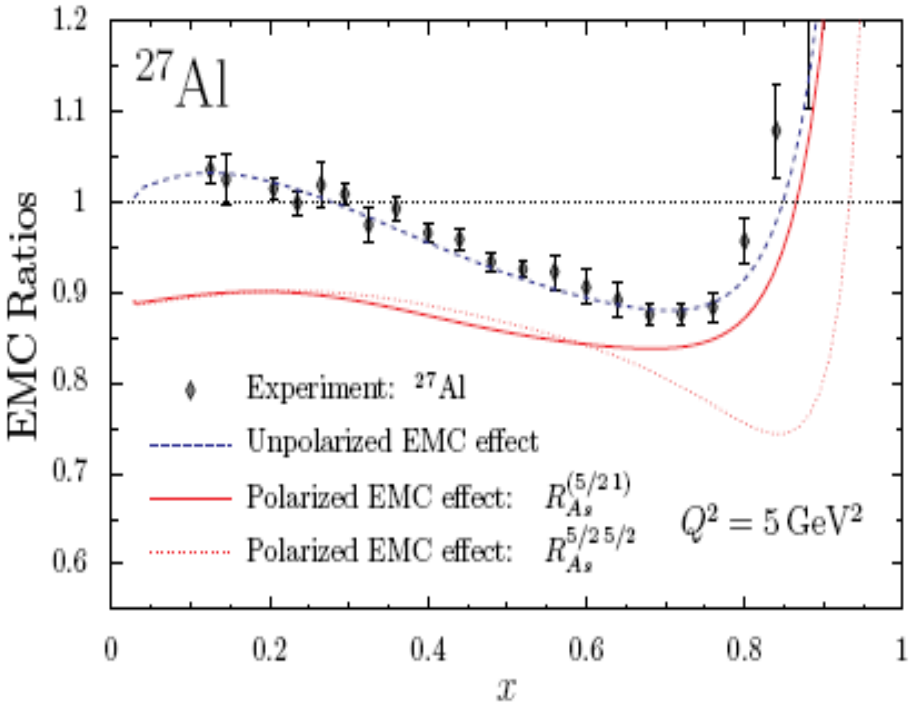


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

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**

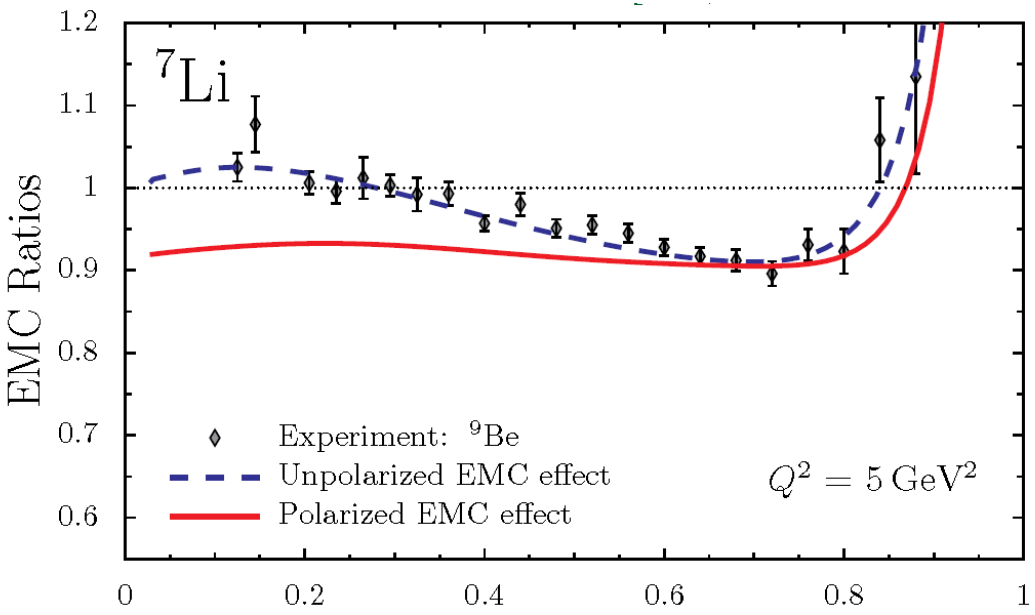
- **The tensor force scatters $^3S_1$ pairs almost entirely into $^3D_1$ at high momentum (~84% at p > 400 MeV/c)**

- **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**

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*

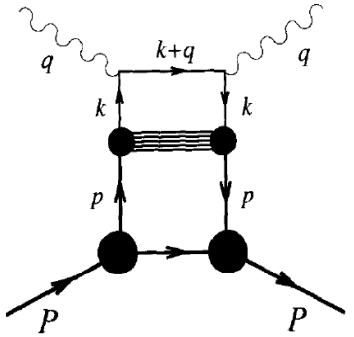


Other tests (e.g. Isovector EMC effect)

A Closer Look at 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: $q^N(x/y) = 4M\,\chi_0^{\text{on}} + 4M^2\,\chi_1^{\text{on}} + 4p\cdot q\,\chi_2^{\text{on}}$

Deuteron: $q^D(x) = \int_x^1 \frac{dy}{y}\,\varphi(y)\,q^N(x/y) + \delta^{(\mathcal{A})}q^D(x) + \delta^{(\chi)}q^D(x)$

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

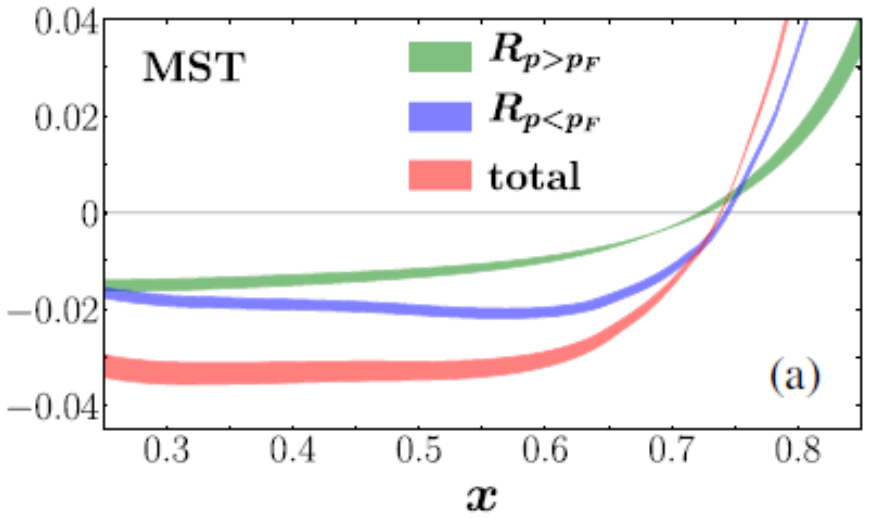
Off-shell effect in PDF

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

Nuclear correction from wave function ➡

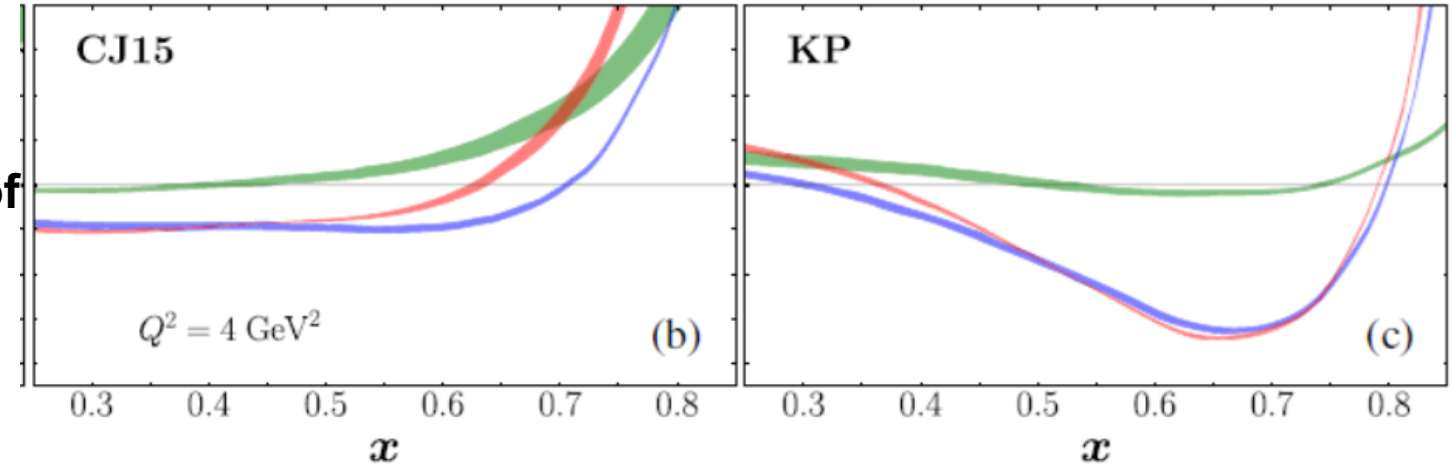
Melnitchouk, Schreiber and Thomas – Phys Lett B335 11 (1994)

Careful study of the EMC effect in the deuteron



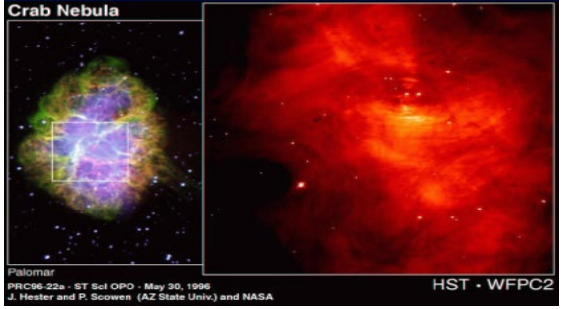
Microscopic model of Melnitchouk et al., shows little of valence EMC effect in D arises from nucleons in SRC

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



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

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

- The existence of these mean-fields means that characterizing changes in terms of $p^2 \neq m^2$ is quite inadequate

- Initial systematic study of finite nuclei very promising
  - Binding energies typically within 0.3%

- 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 an exceptionally large suppression of F_2 for correlated nucleons
  - SRC proposal predicts NO spin-EMC effect
  - SRC produce little of EMC effect in the deuteron

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What do we know?

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

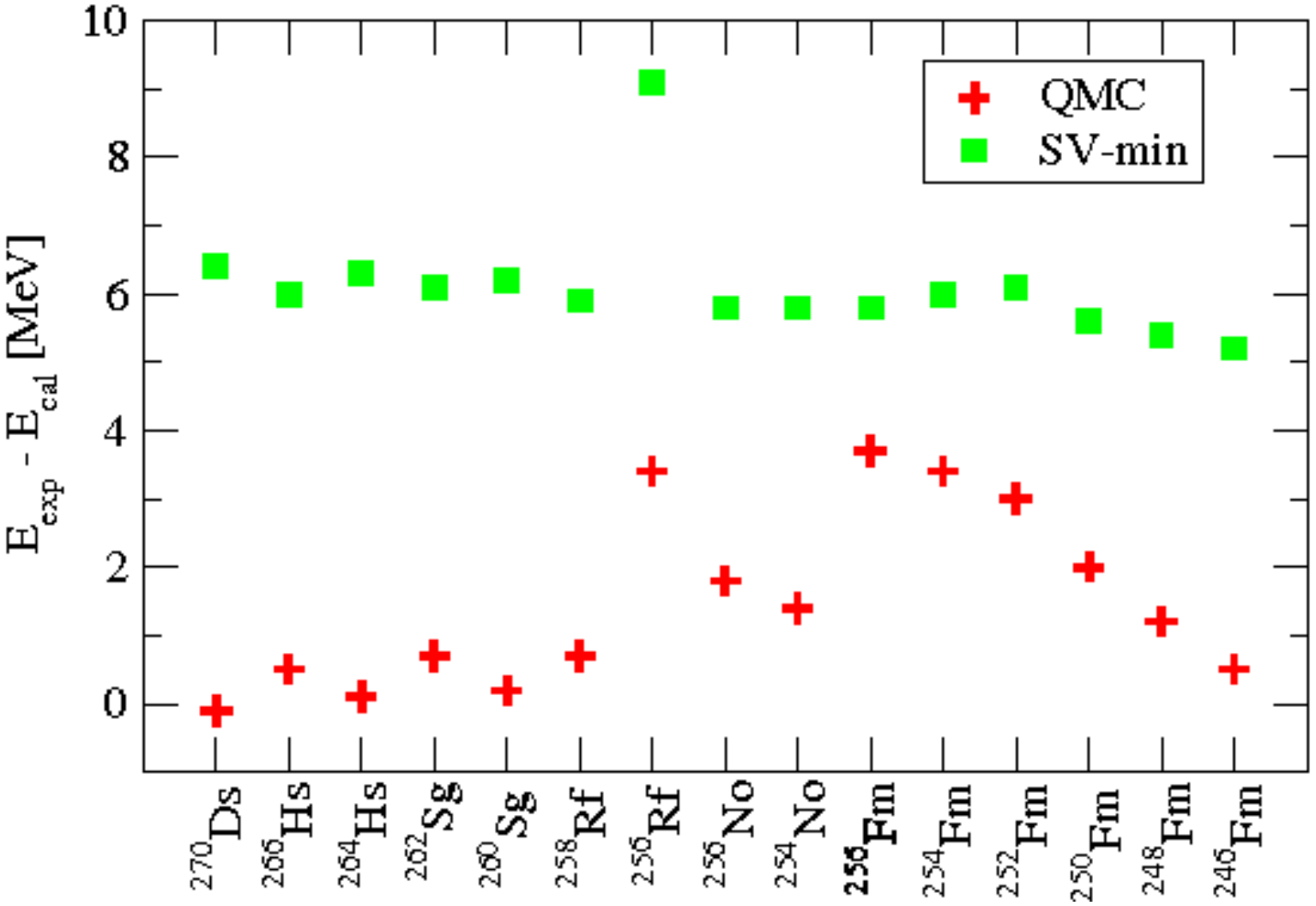
- **In relativistic treatments (RHF, RBHF, QHD…) this leads to mean scalar field on a nucleon ~300 to 500 MeV!!**

- ***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**

Superheavies (not fit) : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

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