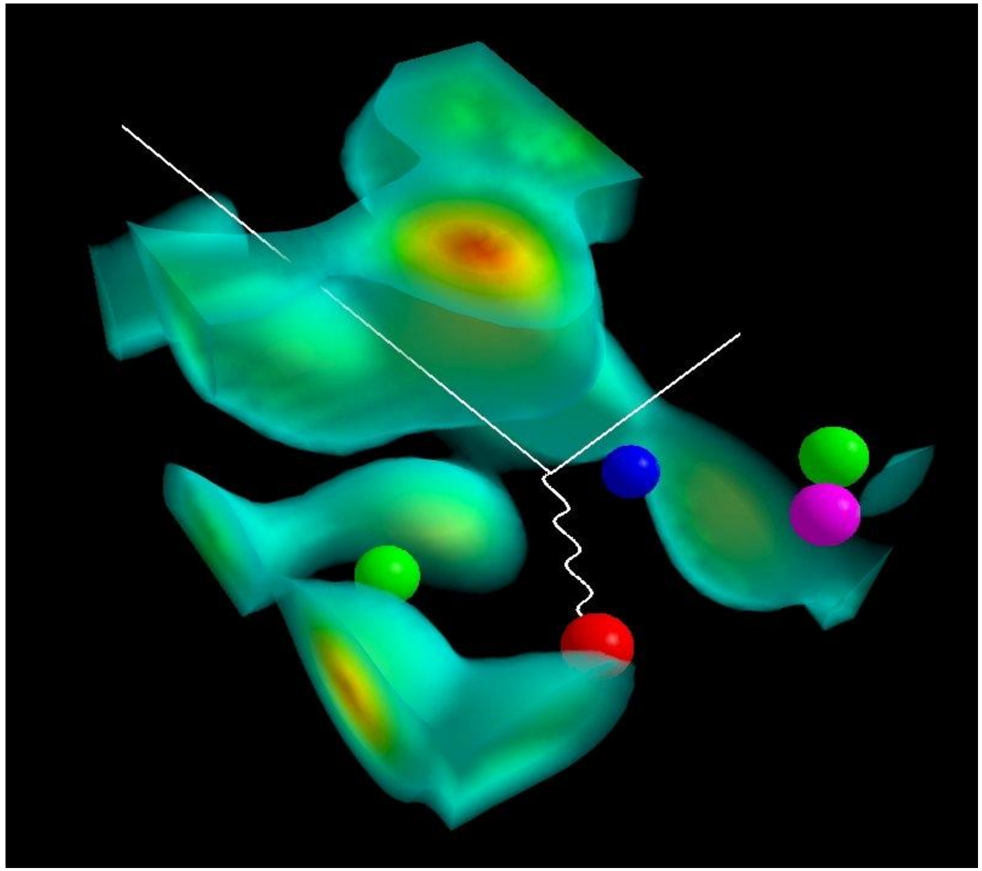
QCD and a New Paradigm for Nuclear Structure



Anthony W. Thomas

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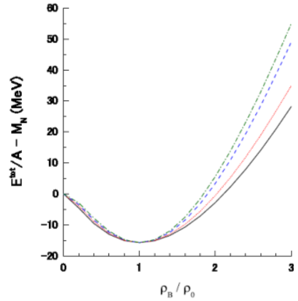
QCD TNT4

QCD-TNT-4

Ilhabela: September 2nd 2015

Relevance of QCD to Nuclear Structure



- **Insight into origin of saturation?**
  − minimum of binding/nucleon vs ρ

- **Behaviour at very high density (neutron star)**
  − transition from hadronic to quark matter

- **EFT *assumes* relevant d.o.f. :**
  beware lesson of drunk looking for keys under lamp post

  − EFT has symmetries of QCD but is this enough?
  We need to know the relevant d.o.f. too

- **Working at quark level can provide guidance**

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and now for something really different.....

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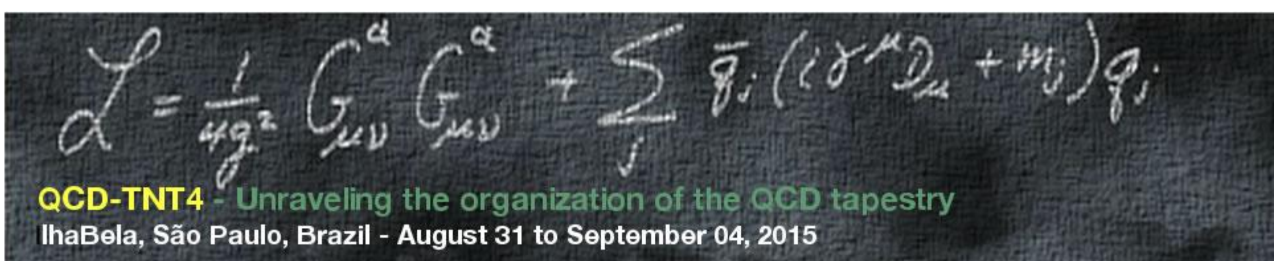
Outline

- **Start from a QCD-inspired model of *hadron* structure**
- **Ask how that internal structure is modified in-medium**
- **This naturally leads to saturation**
  + predictions for all hadrons (e.g. hypernuclei...)
- **Derive effective forces (Skyrme type): apply to finite nuclei**
- **Test predictions for quantities sensitive to internal structure: e.g. DIS structure functions and form factors in-medium**



A different approach : QMC Model

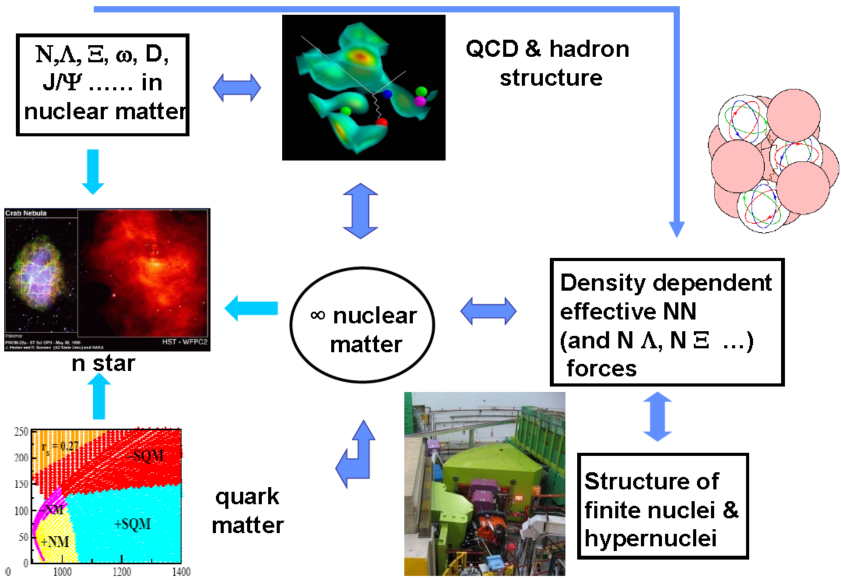
(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 for a review)

- 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 : $g^{q}_{\sigma,\omega,\rho}$

  − determine by fitting to saturation properties of nuclear matter (ρ_0, E/A and symmetry energy)



- Must solve self-consistently for the internal structure of baryons in-medium

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Effect of scalar field on quark spinor

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

$$\frac{\mathcal{N}}{4\pi}\left(\begin{array}{c} j_0(xu'/R_B) \\ i\beta_q \vec{\sigma}\cdot\hat{u}' j_1(xu'/R_B) \end{array}\right)\chi_m$$

- **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***

$$g_\sigma = 3g_\sigma^q \int_{\mathrm{Bag}} d\vec{r}\,\bar{q}q(\vec{r}\,) \sim \frac{\Omega_0/2 + m_q^* R_B(\Omega_0 - 1)}{\Omega_0(\Omega_0 - 1) + m_q^* R_B/2}$$

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

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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

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

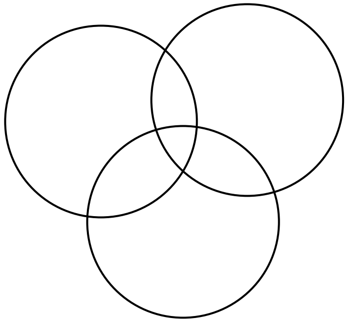
Non-linear dependence through the scalar polarizability
d ~ 0.22 R in original QMC (MIT bag)

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

Summary so far .....

- QMC looks superficially like QHD but it's fundamentally different from *all* other approaches

- Self-consistent adjustment of hadron structure opposes applied scalar field ("scalar polarizability")

- Naturally leads to saturation of nuclear matter
  − effectively because of natural 3- and 4-body forces

- Only 3 parameters: σ, ω and ρ couplings to light quarks

- Fit to nuclear matter properties and then *predict* the interaction of <u>any</u> hadrons <u>in-medium</u>

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Linking QMC to Familiar Nuclear Theory

Since early 70's tremendous amount of work in nuclear theory is based upon effective forces

- **Used for everything from nuclear astrophysics to collective excitations of nuclei**
- **Skyrme Force: Vautherin and Brink**

$$
\begin{aligned}
H_{QMC} &= \sum_i \frac{\overleftrightarrow{\nabla}_i . \overleftrightarrow{\nabla}_i}{2M} + \frac{G_\sigma}{2M^2} \sum_{i \neq j} \overleftrightarrow{\nabla}_i \delta(\vec{R}_{ij}) . \overleftrightarrow{\nabla}_i \\
&+ \frac{1}{2} \sum_{i \neq j} \left[\nabla_i^2 \delta(\vec{R}_{ij}) \right] \left[\frac{G_\omega}{m_\omega^2} - \frac{G_\sigma}{m_\sigma^2} + \frac{G_\rho}{m_\rho^2} \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right] \\
&+ \frac{1}{2} \sum_{i \neq j} \delta(\vec{R}_{ij}) \left[G_\omega - G_\sigma + G_\rho \frac{\vec{\tau}_i . \vec{\tau}_j}{4} \right] \\
&+ \frac{d G_\sigma^2}{2} \sum_{i \neq j \neq k} \delta^2(ijk) - \frac{d^2 G_\sigma^3}{2} \sum_{i \neq j \neq k \neq l} \delta^3(ijkl) \\
&+ \frac{i}{4M^2} \sum_{i \neq j} A_{ij} \overleftrightarrow{\nabla}_i \delta(\vec{R}_{ij}) \times \overleftrightarrow{\nabla}_i . \vec{\sigma}_i \, ,
\end{aligned}
$$

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Guichon and Thomas, Phys. Rev. Lett. 93, 132502 (2004)

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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):**

$$E = \sum_i \left(\sqrt{P_i^2 + M_{\text{eff}}(\sigma)^2} + g_\omega \omega + V_{\text{so}} \right) + E_{\text{mesons}}$$

where:

$$E_{\text{mesons}} = \frac{1}{2} \int d\vec{r} \left[(\nabla\sigma)^2 + m_\sigma^2 \sigma^2 \right] - \frac{1}{2} \int d\vec{r} \left[(\nabla\omega)^2 + m_\omega^2 \omega^2 \right]$$

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Derivation of effective Force (cont.)

- **Nucleon Effective Mass in-medium is:**

$$M_{\text{eff}}(\sigma) = M - g_\sigma \sigma + \frac{d}{2}(g_\sigma \sigma)^2$$

and the σN coupling constant in free space is:

$$g_\sigma = 3 g_\sigma^q \int_{\text{Bag}} d\vec{r}\, \bar{q} q(\vec{r})$$

The classical Hamiltonian is:

$$H(R_i, P_i) = E(R_i, P_i, \sigma \rightarrow \sigma_{\text{sol}}, \omega \rightarrow \omega_{\text{sol}})$$

where $\frac{\delta E}{\delta \sigma} = \frac{\delta E}{\delta \omega} = 0$ **yields** $\sigma_{\text{sol}}, \omega_{\text{sol}}$

- **Include fluctuations and expand in** $\delta\sigma$ **; quantise nucleon motion; make non-relativistic expansion...**

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Derivation of effective Force (cont.)

- **We get the Hamiltonian of the system. We use the Hartree-Fock approximation to evaluate the energy functional (in which case $\langle \delta\sigma \rangle = 0$). The result is:**

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

where, if we define (m = p,n**):**

$$\vec{J}_m(\vec{r}\,) = i \sum_{i\in F} \sum_{\sigma\sigma'} \vec{\sigma}_{\sigma'\sigma} \times \left[\vec{\nabla}\Phi^i(\vec{r},\sigma,m)\right]\Phi^{i*}(\vec{r},\sigma',m)$$

the pieces are summarised on the next page.

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Derivation of effective Force (cont.)

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

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

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

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

Note the totally new, subtle density dependence

Global search on Skyrme forces

The Skyrme Interaction and Nuclear Matter Constraints

Phys. Rev. C85 (2012) 035201

M. Dutra, O. Lourenço, J. S. S. Martins, and A. Delfino

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These authors tested 233 widely used Skyrme-type forces against 12 standard nuclear properties: only 17 survived including two QMC potentials

Furthermore, we considered weaker constraints arising from giant resonance experiments on isoscalar and isovector effective nucleon mass in SNM and BEM, Landau parameters and low-mass neutron stars. If these constraints are taken into account, the number of CSkP reduces to to 9, GSkI, GSkII, KDE0v1, LNS, NRAPR, QMC700, QMC750 and SKRA, the CSkP* list.

Truly remarkable – force derived from quark level does a better job of fitting nuclear structure constraints than phenomenological fits with many times # parameters!

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Systematic Study of Finite Nuclei

Systematic approach to finite nuclei

(This work is *in preparation* for publication: collaborators are J.R. Stone, P.A.M. Guichon and P. G. Reinhard)

- **Allow 3 basic quark-meson couplings to vary so that nuclear matter properties reproduced within errors**

$$-17 < E/A < -15 \text{ MeV}$$
$$0.14 < \rho_0 < 0.18 \text{ fm}^{-3}$$
$$28 < S_0 < 34 \text{ MeV}$$
$$L > 20 \text{ MeV}$$
$$250 < K_0 < 350 \text{ MeV}$$

- **Fix at overall best description of finite nuclei**

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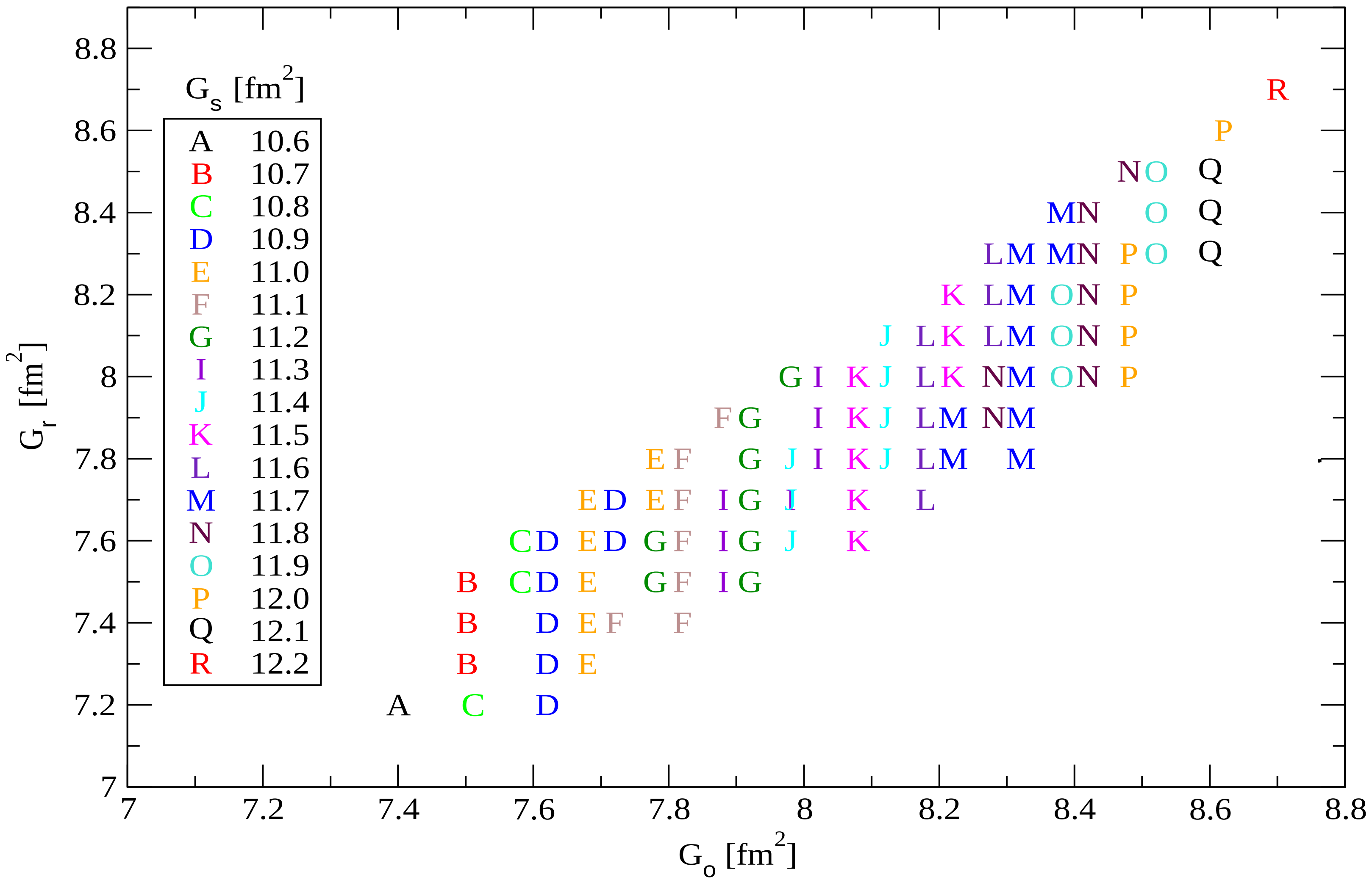
Overview of Allowed Parameters



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Overview of Nuclei Studied – Across Periodic Table

Element	Z	N	Element	Z	N
C	6	6 -16	Pb	82	116 - 132
O	8	4 -20	Pu	94	134 - 154
Ca	20	16 – 32	Fm	100	148 - 156
Ni	28	24 – 50	No	102	152 - 154
Sr	38	36 – 64	Rf	104	152 - 154
Zr	40	44 -64	Sg	106	154 - 156
Sn	50	50 – 86	Hs	108	156 - 158
Sm	62	74 – 98	Ds	110	160
Gd	64	74 -100			

N	Z	N	Z
20	10 – 24	64	36 - 58
28	12 – 32	82	46 - 72
40	22 – 40	126	76 - 92
50	28 – 50		

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i.e. We look at most challenging cases of p- or n-rich nuclei

Overview

data	rms error %	
	QMC	SV-min
fit nuclei:		
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

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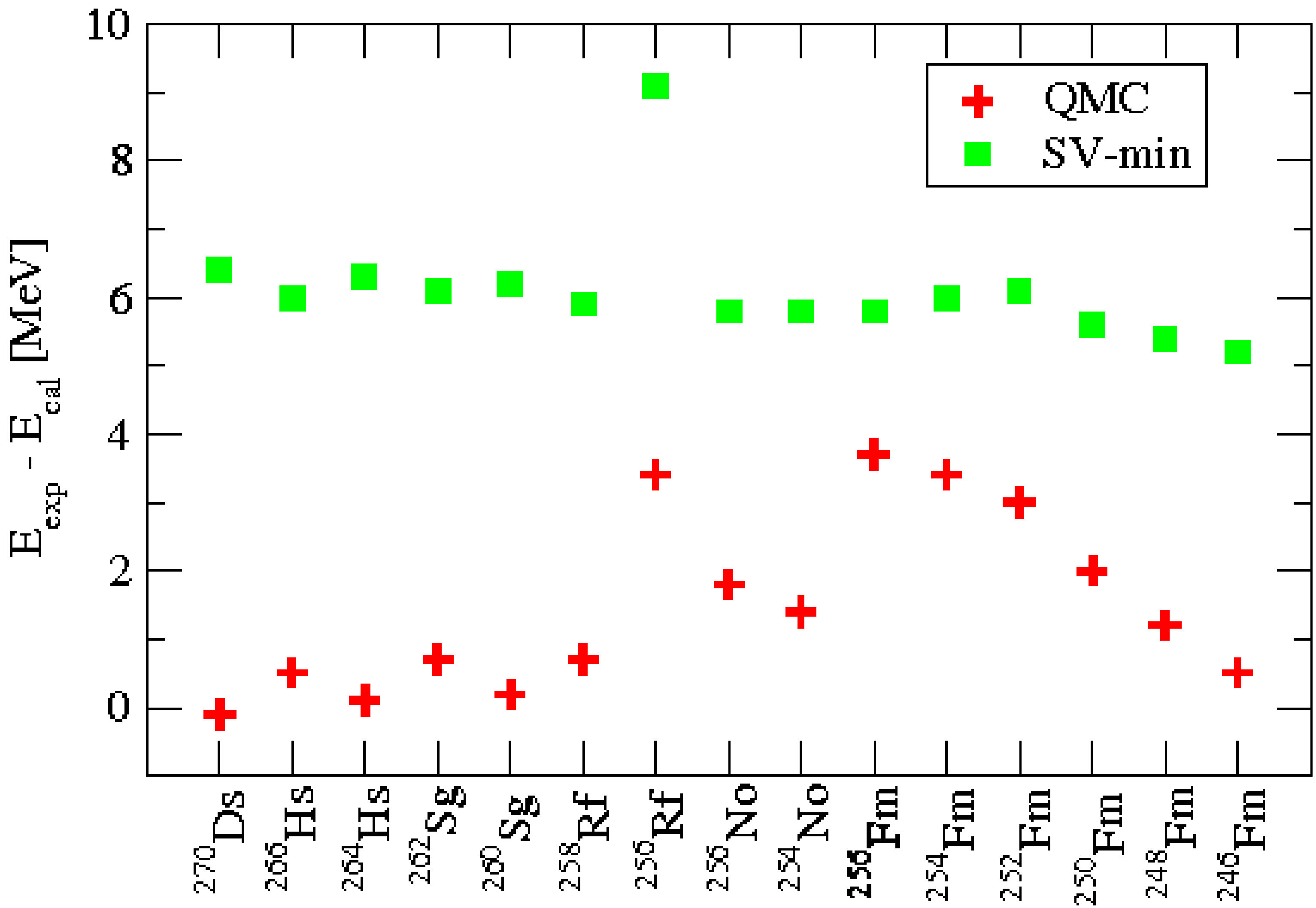
Superheavies : 0.1% accuracy



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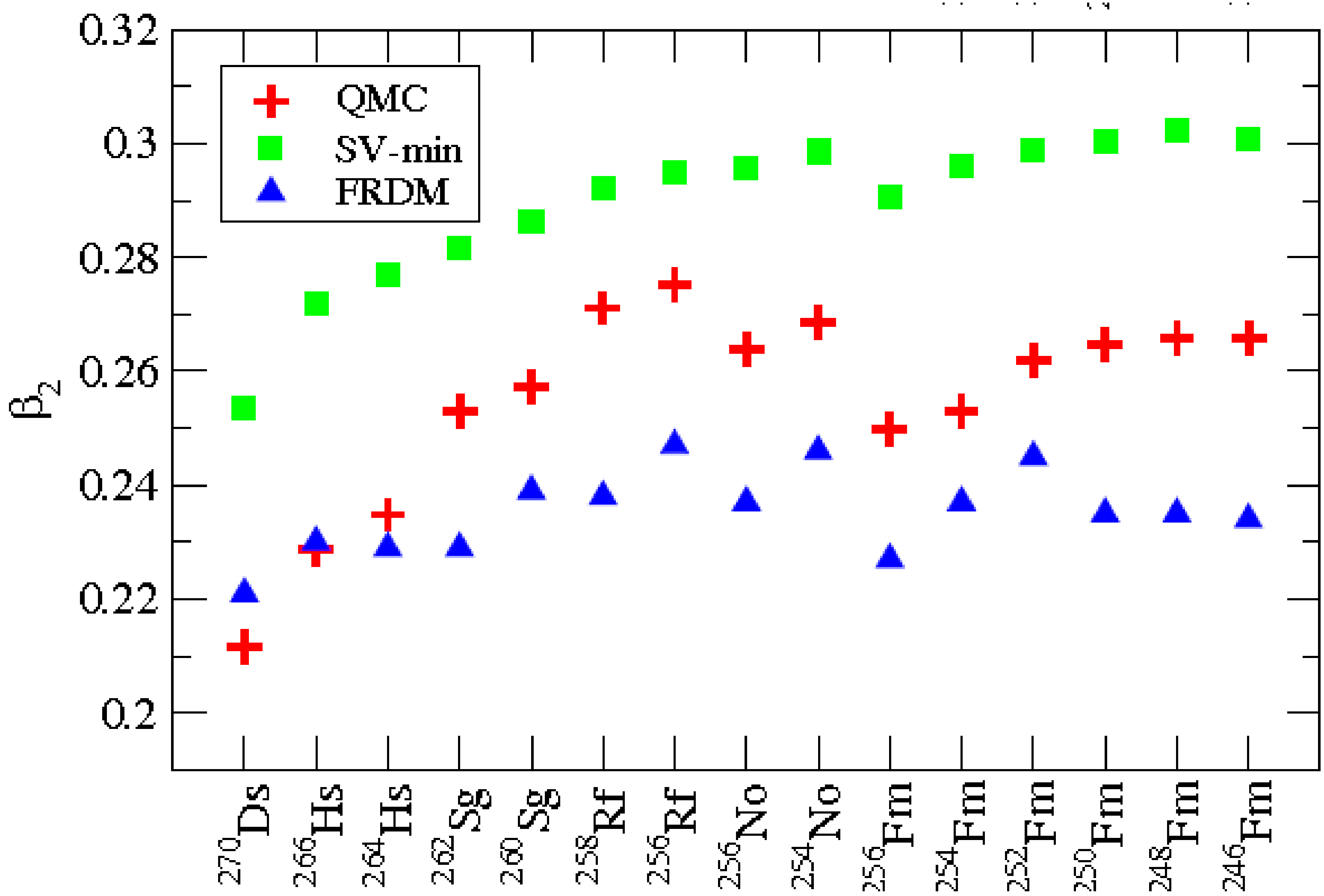
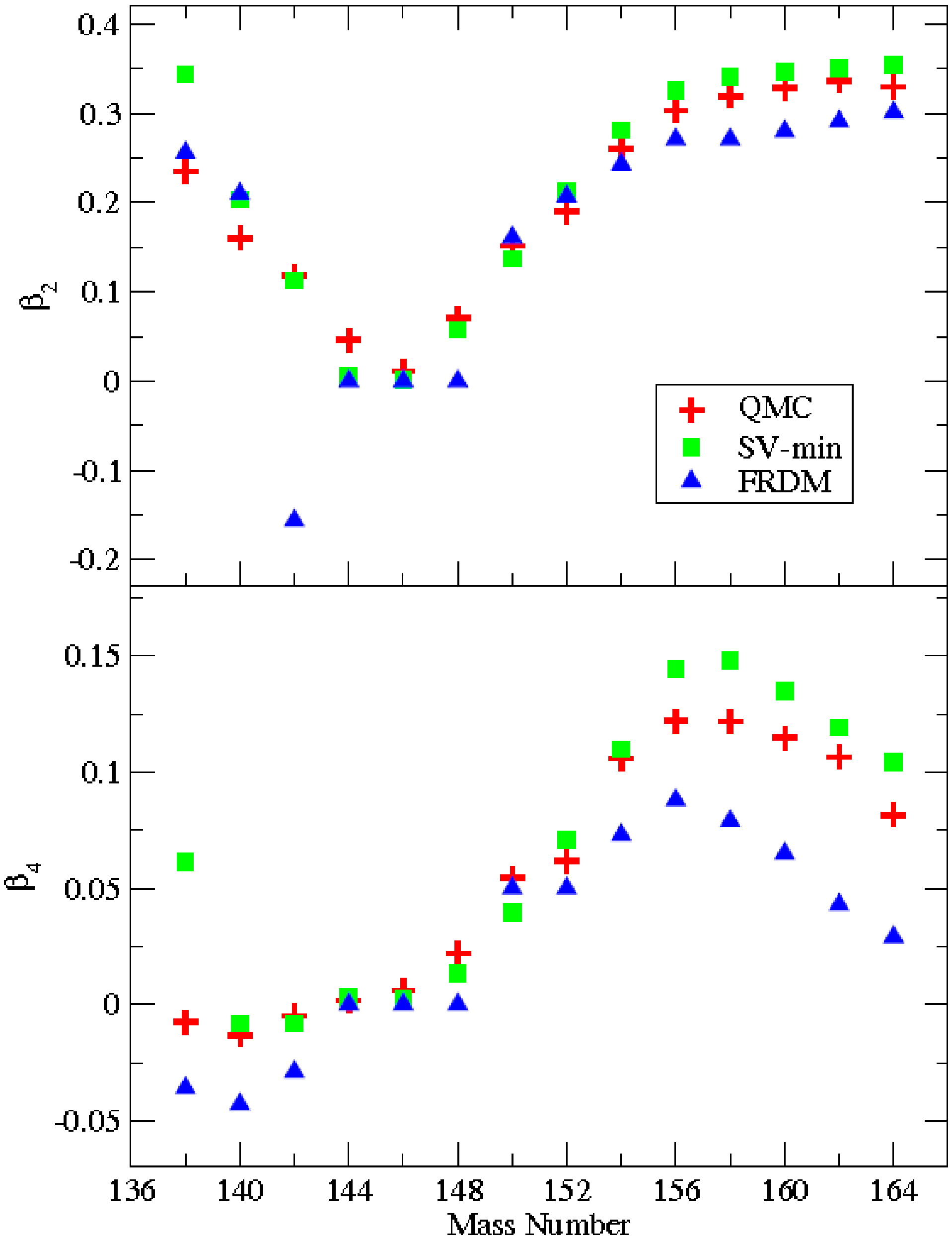
Quadrupole Deformation of Superheavies



Deformation in Gd (Z=64) Isotopes



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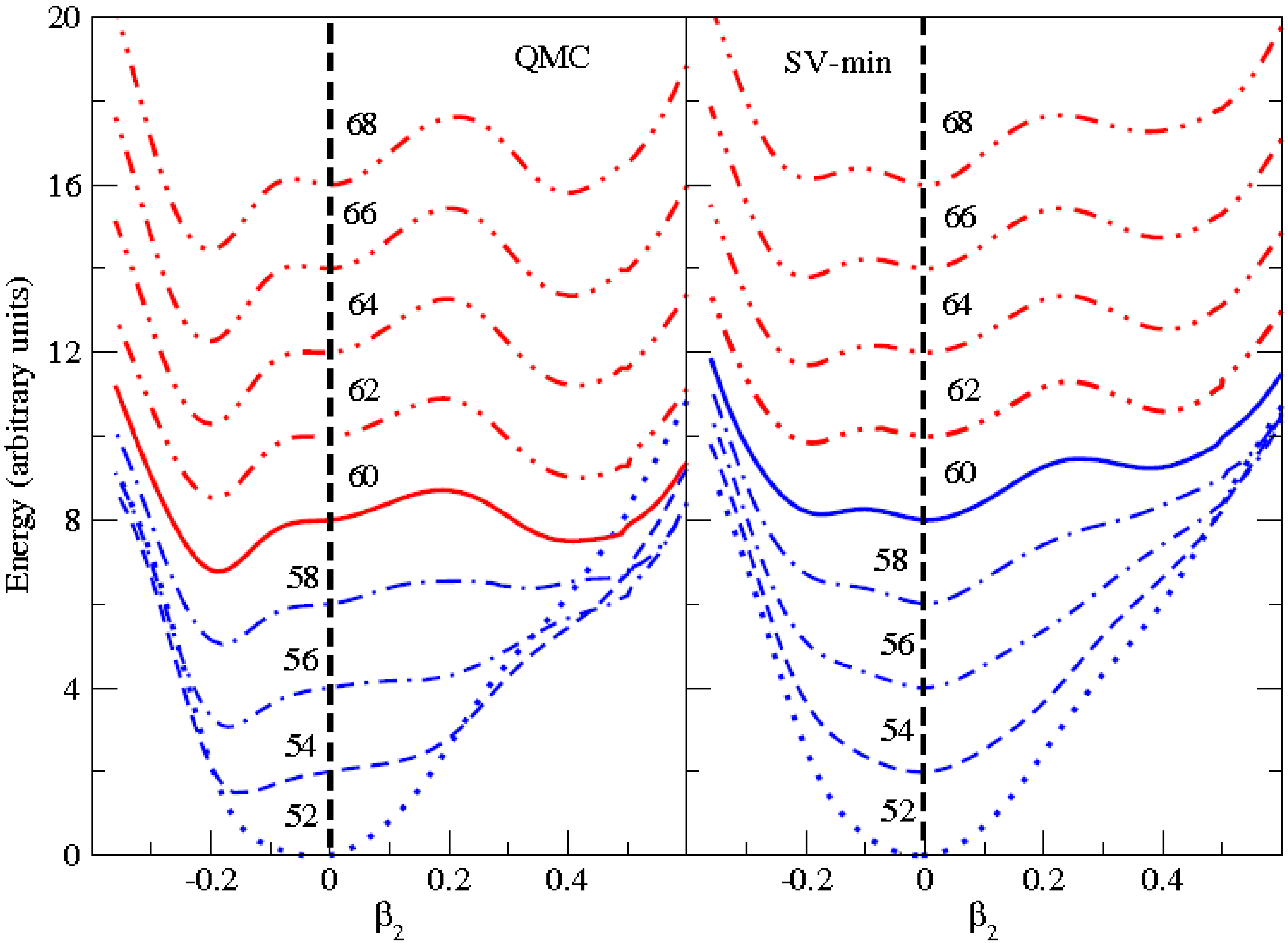
Spin-orbit splitting

Element		States	Exp [keV]	QMC [keV]	SV-bas [keV]
O16	proton	$1p_{1/2}$ - $1p_{3/2}$	6.3 (1.3)a)	5.8	5.0
	neutron	$1p_{1/2}$ - $1p_{3/2}$	6.1 (1.2)a)	5.7	5.1
Ca40	proton	$1d_{3/2}$ - $1d_{5/2}$	7.2 [b)]	6.3	5.7
	neutron	$1d_{3/2}$ - $1d_{5/2}$	6.3 [b)]	6.3	5.8
Ca48	proton	$1d_{3/2}$ - $1d_{5/2}$	4.3 [b)]	6.3	5.2
	neutron	$1d_{3/2}$ - $1d_{5/2}$		5.3	5.2
Sn132	proton	$2p_{1/2}$ - $2p_{3/2}$	1.35(27)[a)]	1.32	1.22
	neutron	$2p_{1/2}$ - $2p_{3/2}$	1.65(13)[a)]	1.47	1.63
	neutron	$2d_{3/2}$ - $2d_{5/2}$		2.71	2.11
Pb208	proton	$2p_{1/2}$ - $2p_{3/2}$		0.91	0.93
	neutron	$3p_{1/2}$ - $3p_{3/2}$	0.90(18)[a)]	1.11	0.89

Shape evolution of Zr (Z=40) Isotopes



- **Shape co-existence sets in at N=60**
- **Usually difficult to describe – e.g. Mei et al., PRC85, 034321 (2012)**

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**

- **Looks like standard nuclear force**

- **BUT underlying theory also predicts modified internal structure and hence modified**
  - **DIS structure functions**
  - **elastic form factors......**

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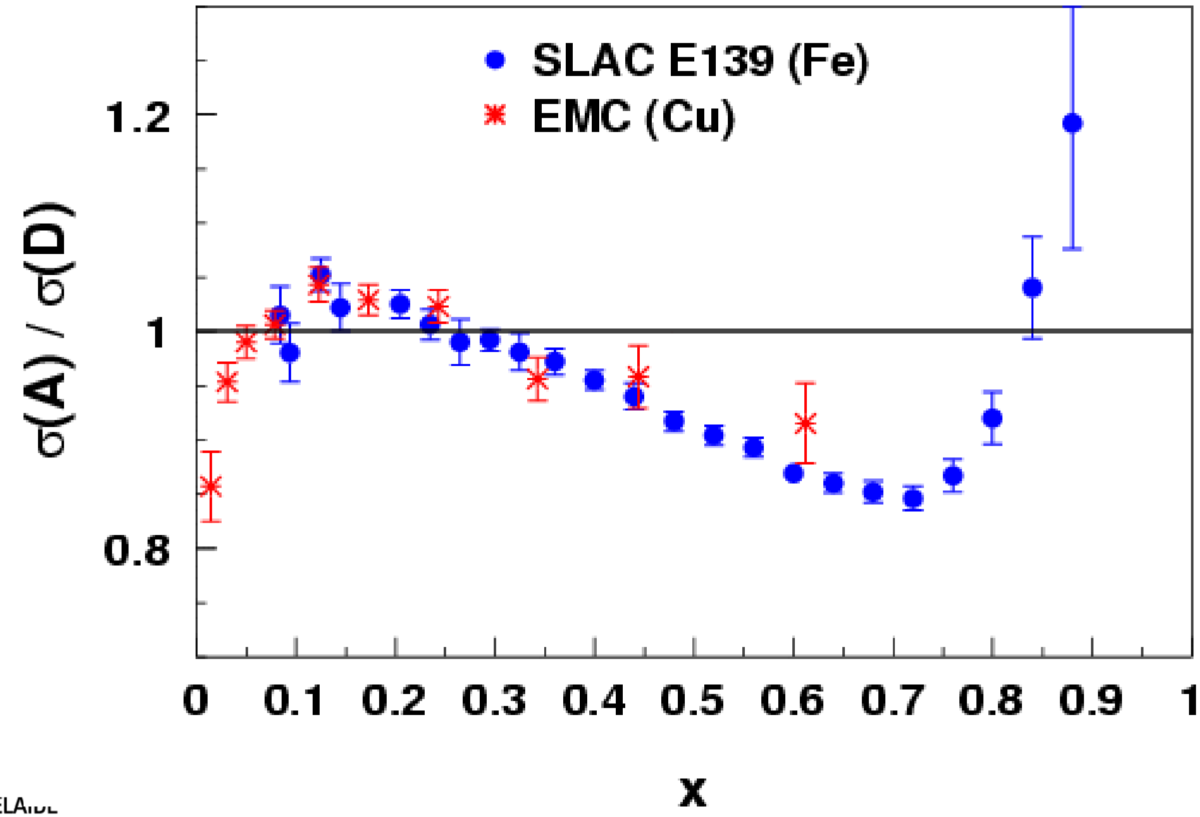
Nuclear DIS Structure Functions

To address questions like this one MUST start with a theory that quantitatively describes nuclear structure – very, very few examples.....

The EMC Effect: Nuclear PDFs

- Observation **stunned and electrified** the HEP and Nuclear communities 30 years ago
- Nearly 1,000 papers have been generated…..
- 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)

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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

Calculations for Finite Nuclei

(Spin dependent EMC effect TWICE as large as unpolarized)

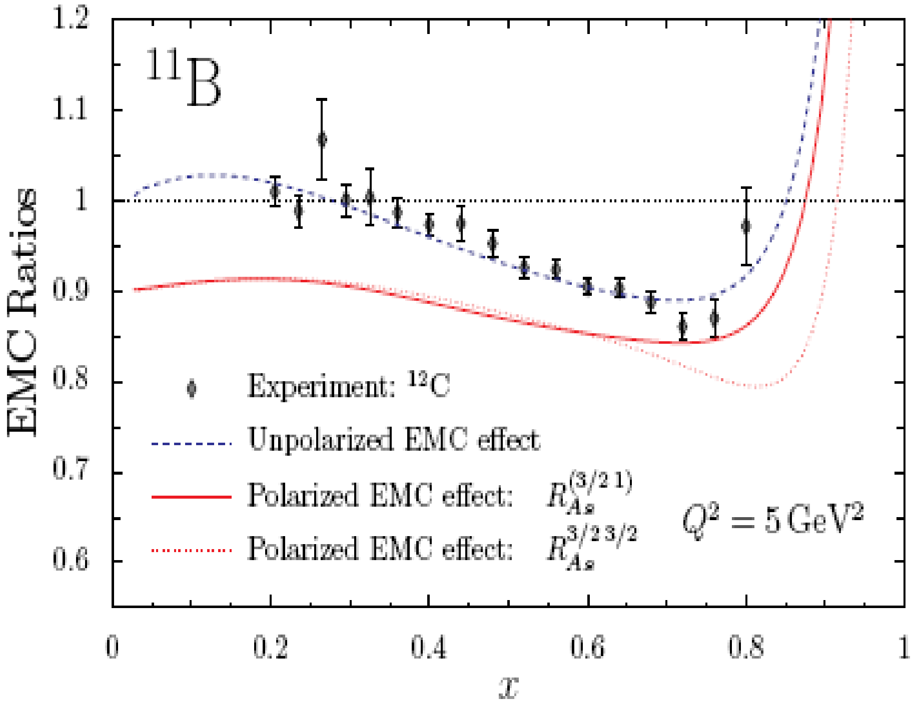

FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

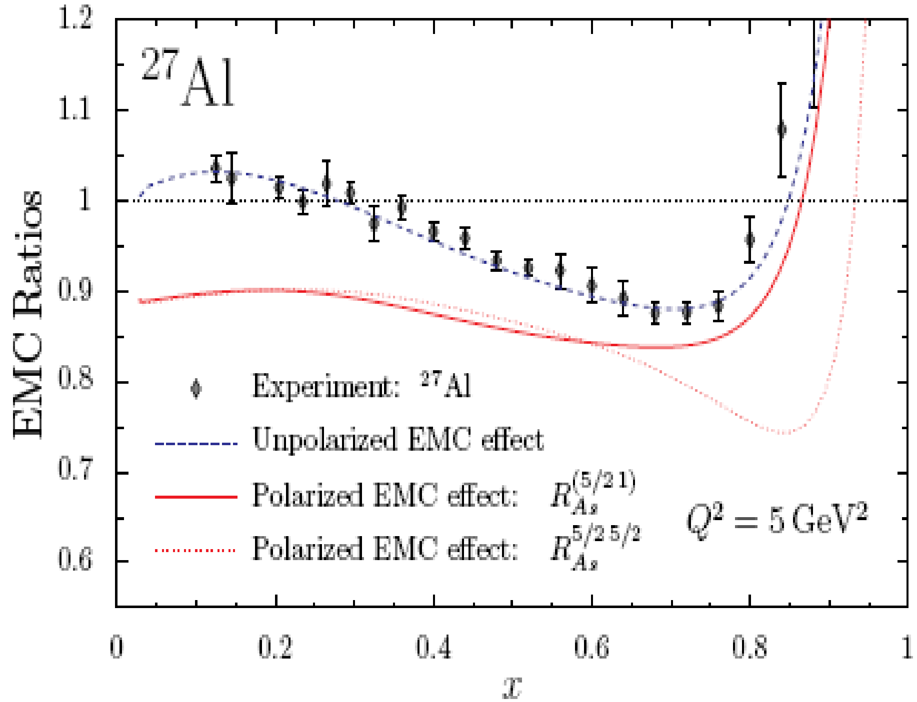

FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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

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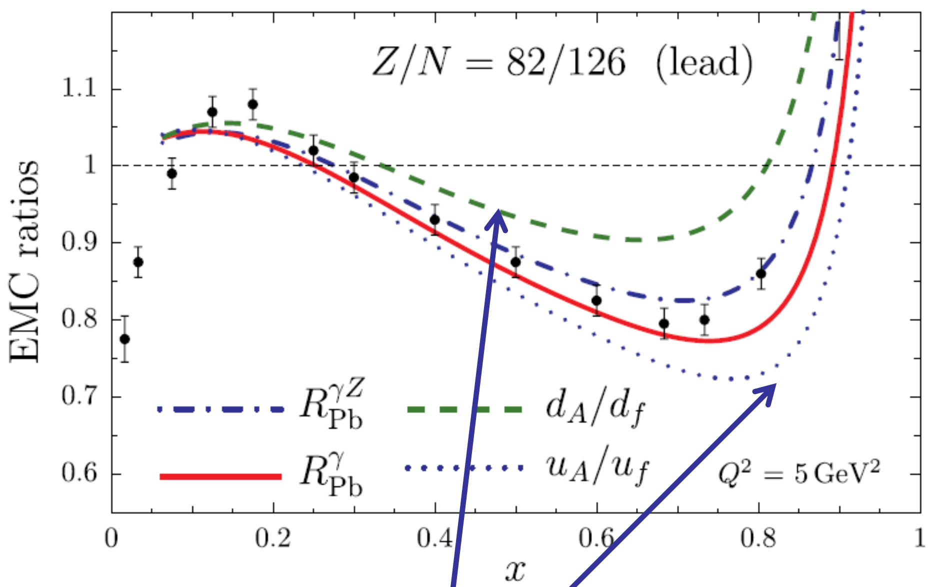
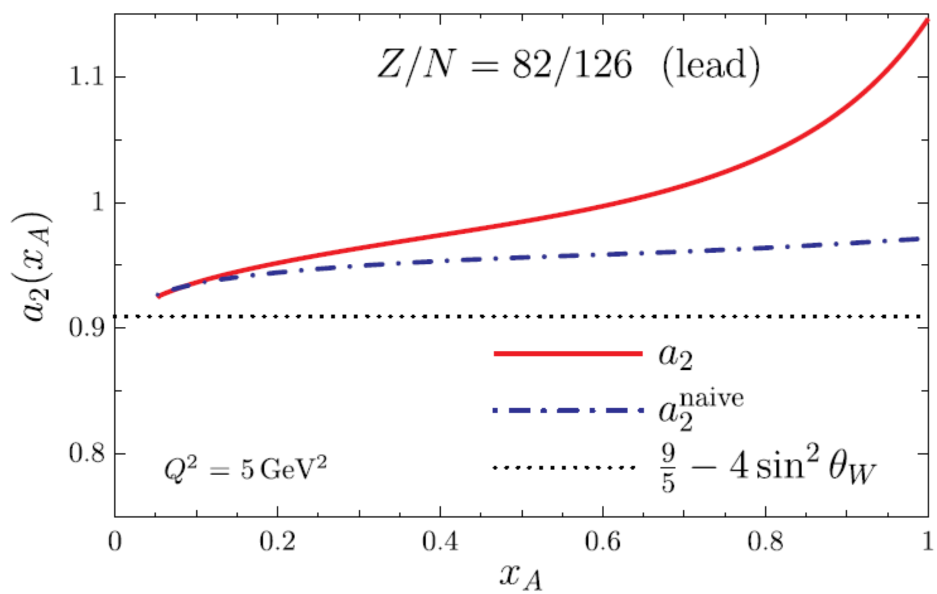
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Parity-Violating Deep Inelastic Scattering and the Flavor Dependence of the EMC Effect

I. C. Cloët,[1] W. Bentz,[2] and A. W. Thomas[1]

$$A_{PV} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha_{em}}\left[a_2(x_A) + \frac{1-(1-y)^2}{1+(1-y)^2}a_3(x_A)\right]$$





Ideally tested at EIC with CC reactions

Parity violating EMC will be tested at JLab 12 GeV

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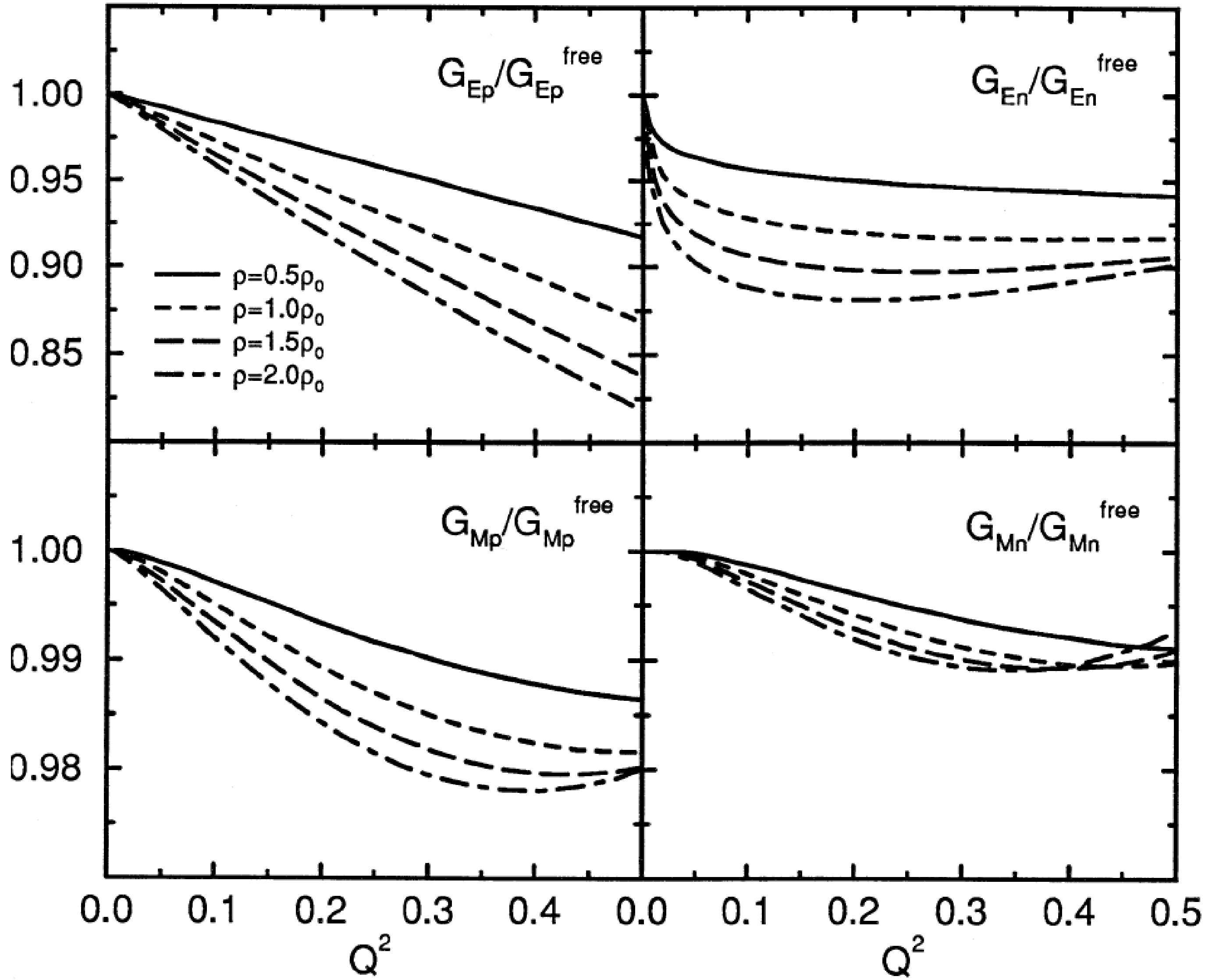
Modified Electromagnetic Form Factors In-Medium

Archival

In-medium electron-nucleon scattering

D.H. Lu [a], A.W. Thomas [a], K. Tsushima [a], A.G. Williams [a], K. Saito



QMC

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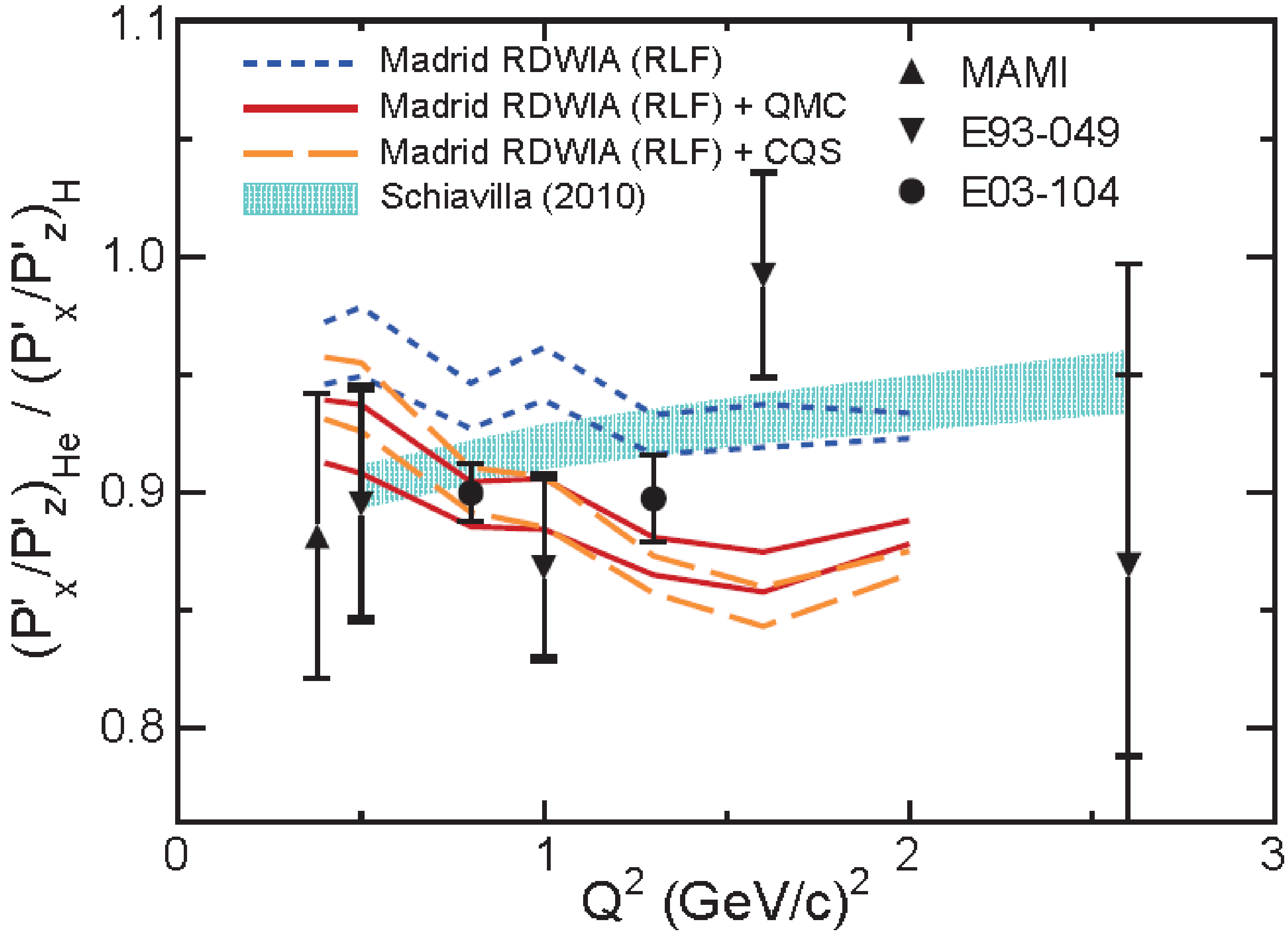
Physics Letters B 417 (1998) 217–223

Jefferson Lab & Mainz

Polarized $^4He(\vec{e},e'\vec{p})$ measuring recoil p polarization (T/L : G_E/G_M)

Strauch et al., EPJ Web of Conf. 36 (2012) 00016



QMC medium effect predicted more than a decade years before the experiment (D.H. Lu et al., Phys. Lett. B 417 (1998) 217)

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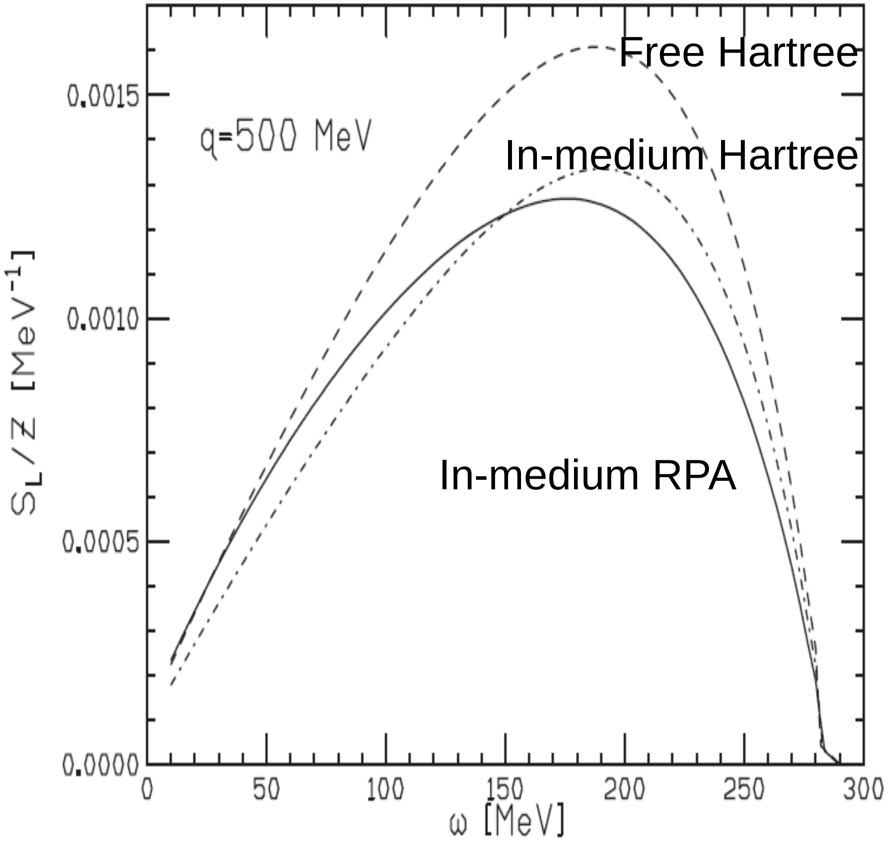
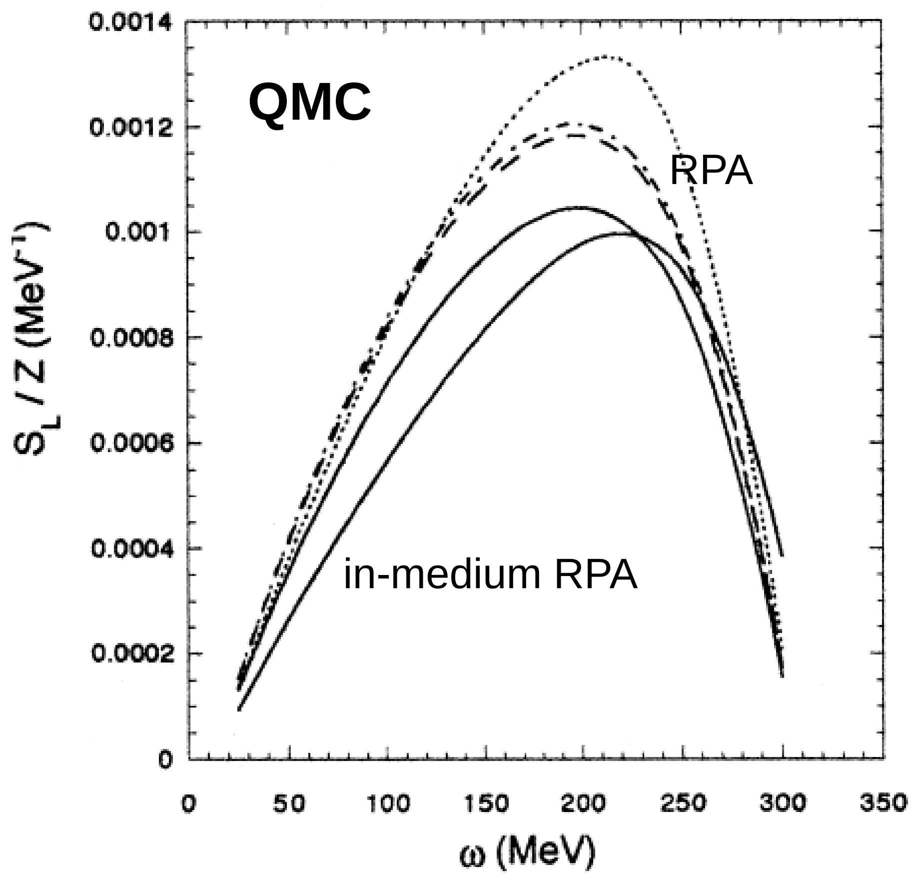
Longitudinal response function

− revisited in expectation of new results from JLab, Meziani et al.



Horikawa and Bentz, nucl-th/0506021

K. Saito et al. / Physics Letters B 465 (1999) 27–35



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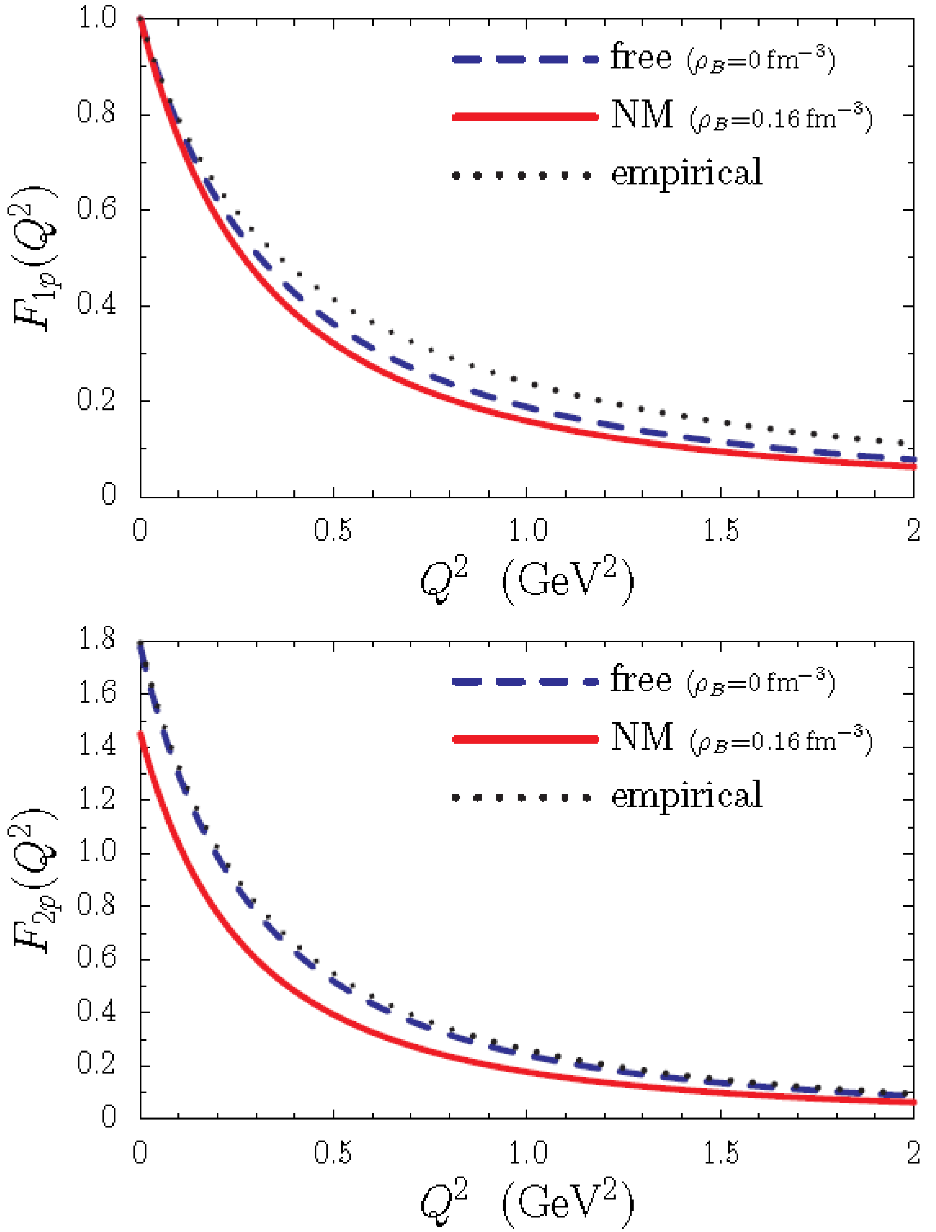
Recent Calculations Motivated by:

E01-015, PR-04-015 – Chen, Choi & Meziani

- Using NJL model with nucleon structure self-consistently solved in-medium

- Same model describing free nucleon form factors, structure functions and EMC effect

Modification of Proton Form Factors



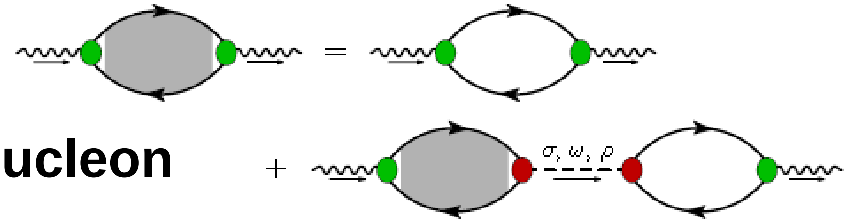
Free nucleon form factors
Bentz *et al.* Phys Rec C90, 045202 (2014)

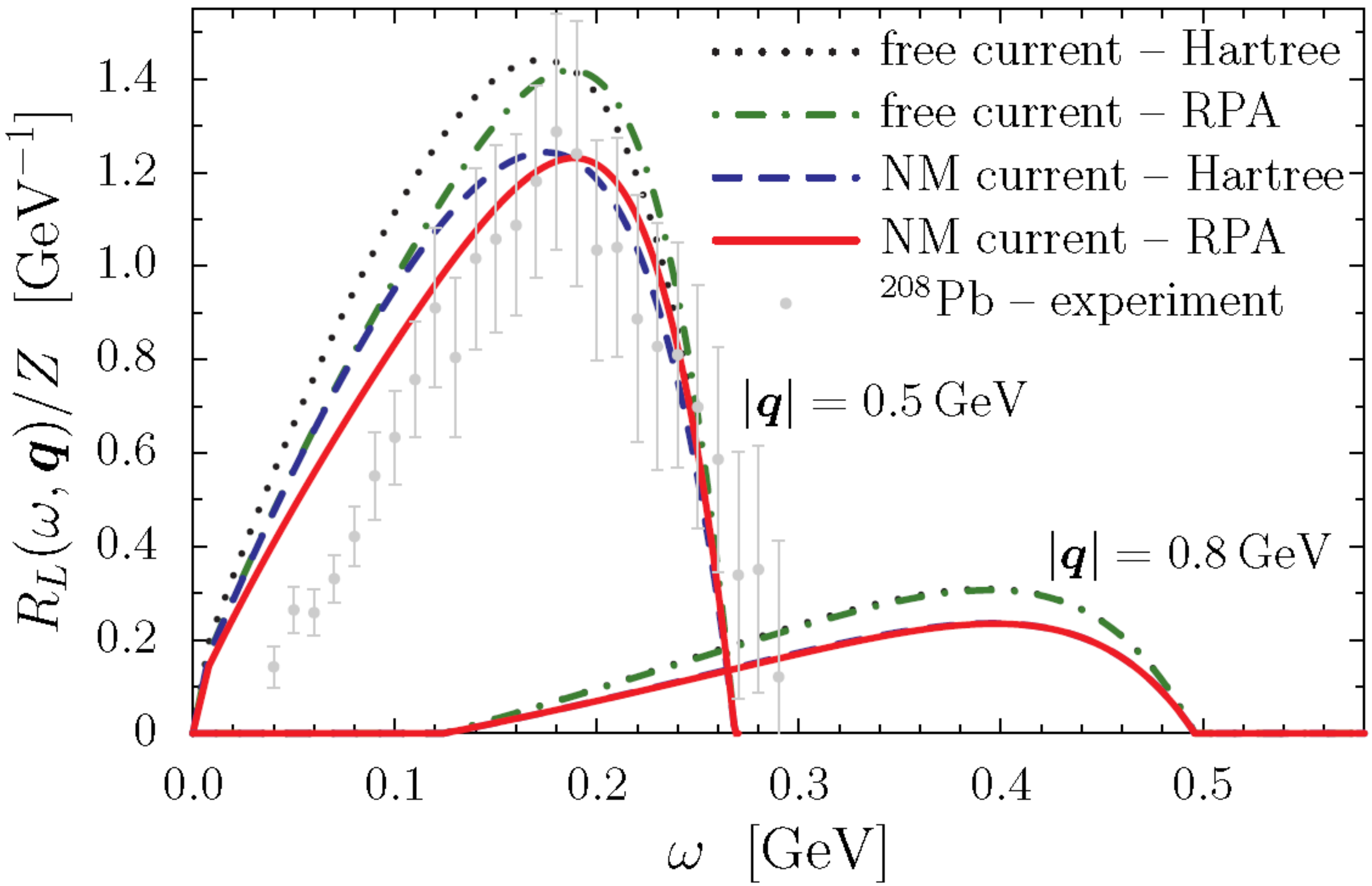
Cloët et al., arXiv:1405.5542

Response Function

$$\frac{d^2\sigma}{d\Omega\, d\omega} = \sigma_{\text{Mott}}\left[\frac{q^4}{|\boldsymbol{q}|^4} R_L(\omega, |\boldsymbol{q}|) + \left(\frac{q^2}{2|\boldsymbol{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(\omega, |\boldsymbol{q}|)\right]$$

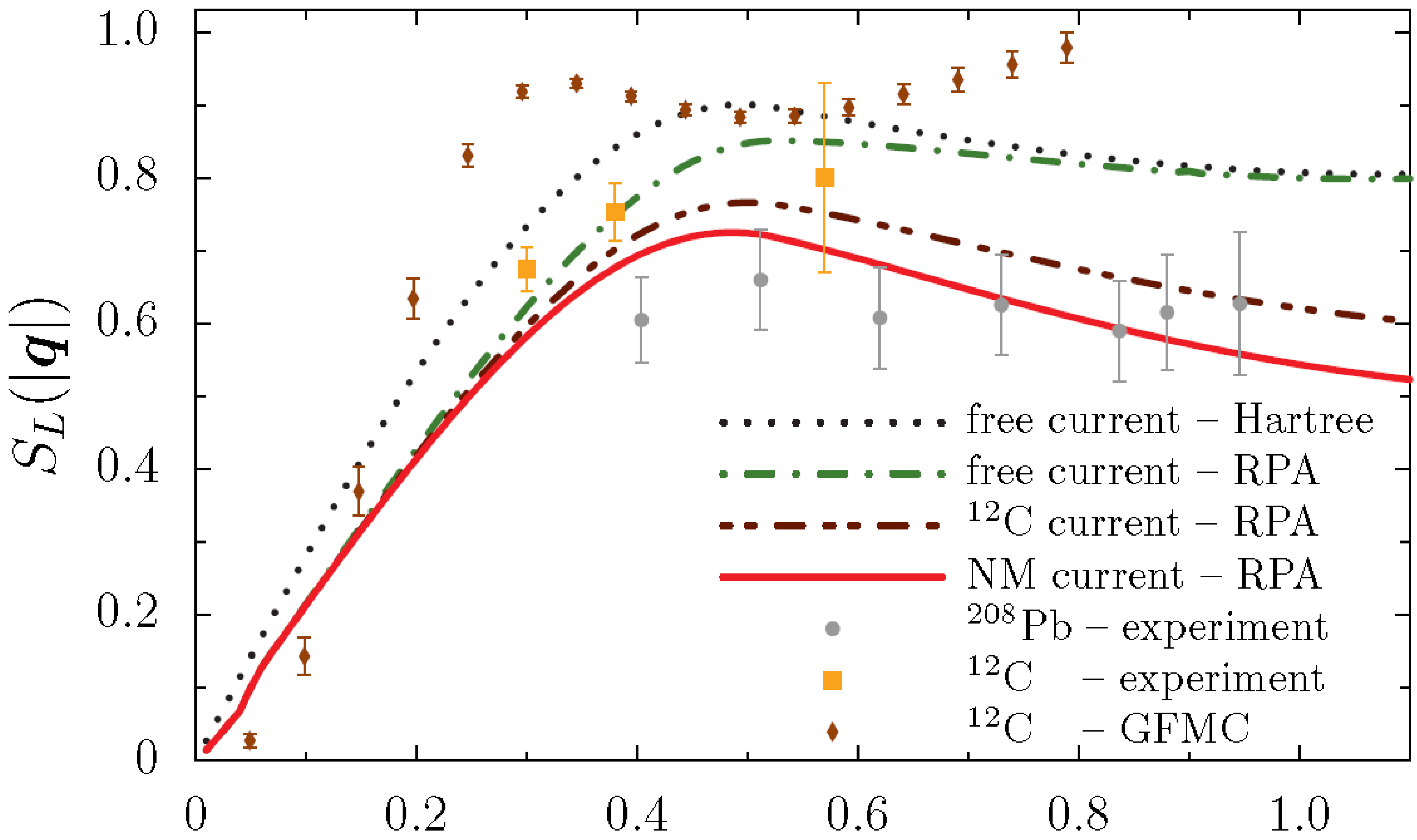
RPA correlations repulsive
Significant reduction in Response Function from modification of bound-nucleon





Cloët, Bentz & Thomas (arXiv:1506.05875)

Comparison with Unmodified Nucleon & Data

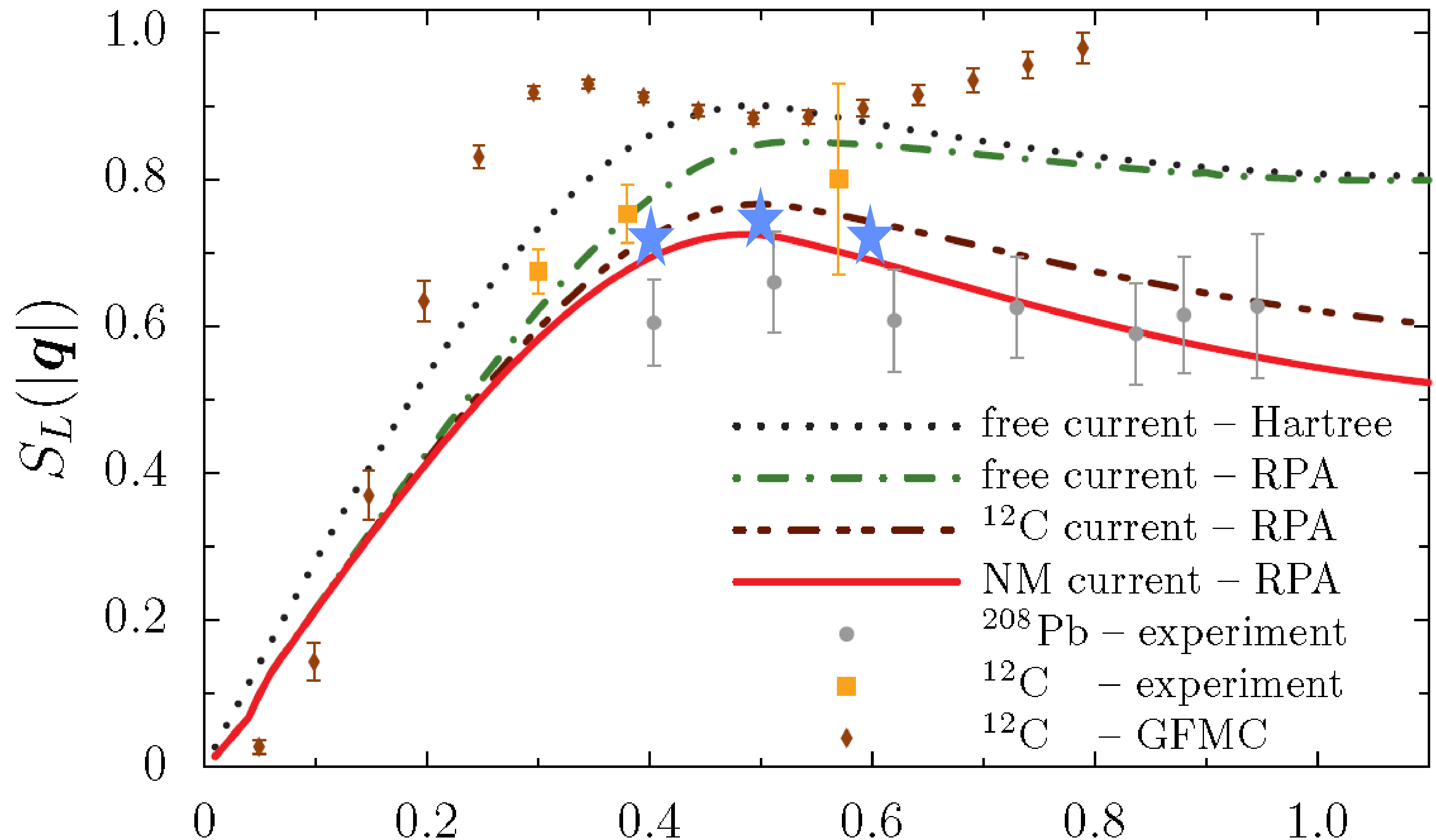


$$S_L(|\boldsymbol{q}|) = \int_{\omega+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

Data: Morgenstern & Meziani

Calculations: Cloët, Bentz & Thomas (arXiv:1506.05875)

and these predictions are stable!



$$S_L(|\boldsymbol{q}|) = \int_{\omega^+}^{|\boldsymbol{q}|} d\omega \, \frac{R_L(\omega, |\boldsymbol{q}|)}{Z\, G_{Ep}^2(Q^2) + N\, G_{En}^2(Q^2)}$$

★ Saito *et al.*, QMC 1999 (*op cit*)

Data: Morgenstern & Meziani

Calculations: Cloët, Bentz & Thomas (arXiv:1506.05875)

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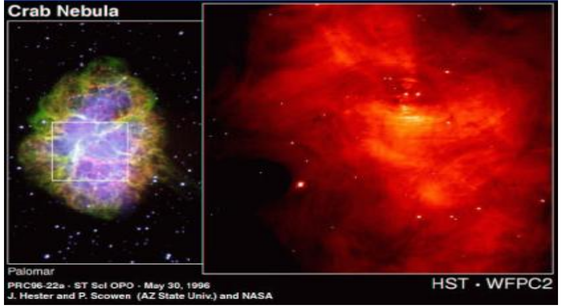
Summary



- Intermediate range NN attraction STRONG Lorentz scalar

- 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 force/ density dependence of effective forces
  - clear physical interpretation

- Derived, density-dependent effective force gives results better than most phenomenological Skyrme forces

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Summary

- **Initial systematic study of finite nuclei very promising**
  - **Binding energies typically within 0.5% or better across periodic table**

- **Super-heavies (Z > 100) especially good (typically better than 0.25%)!**

- **Deformation, spin-orbit splitting and charge distributions all look good (NOT fit – only binding)**

- **BUT need empirical confirmation:**
  - **Response Functions & Coulomb sum rule (soon)**
  - **Isovector EMC effect; spin EMC etc....**

  - **Lattice QCD etc. : any clever ideas?**

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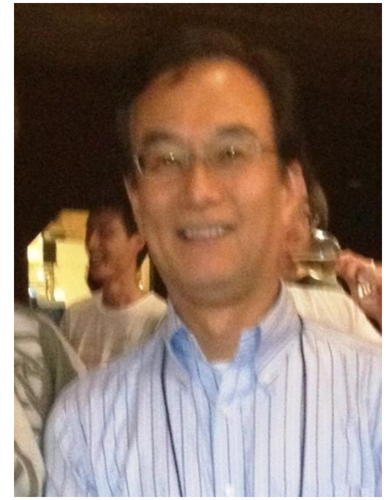
Special Mentions……

Guichon

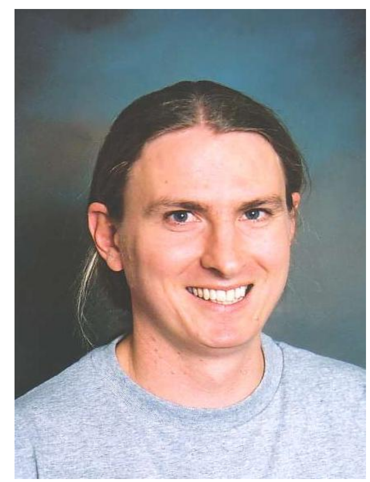
Tsushima



Saito

Stone

Bentz



Cloët

We look forward to welcoming delegates to Adelaide, Australia for INPC 2016

September 11-16 2016

exceptional!

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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**

Can we Measure Scalar Polarizability in Lattice QCD ?

- **IF we can, then in a real sense we would be linking nuclear structure to QCD itself, because scalar polarizability is sufficient in simplest, relativistic mean field theory to produce saturation**

- **Initial ideas on this published :**
  the trick is to apply a <u>chiral invariant</u> scalar field
  − do indeed find polarizability opposing applied σ field

18th Nishinomiya Symposium: nucl-th/0411014
− published in Prog. Theor. Phys.

Most recent nuclear structure results

- **Results obtained using SKYAX code of P. G. Reinhard**

- **2 BCS pairing parameters (density dependent, contact pairing force) fitted from pairing gaps in Sn isotopes**

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