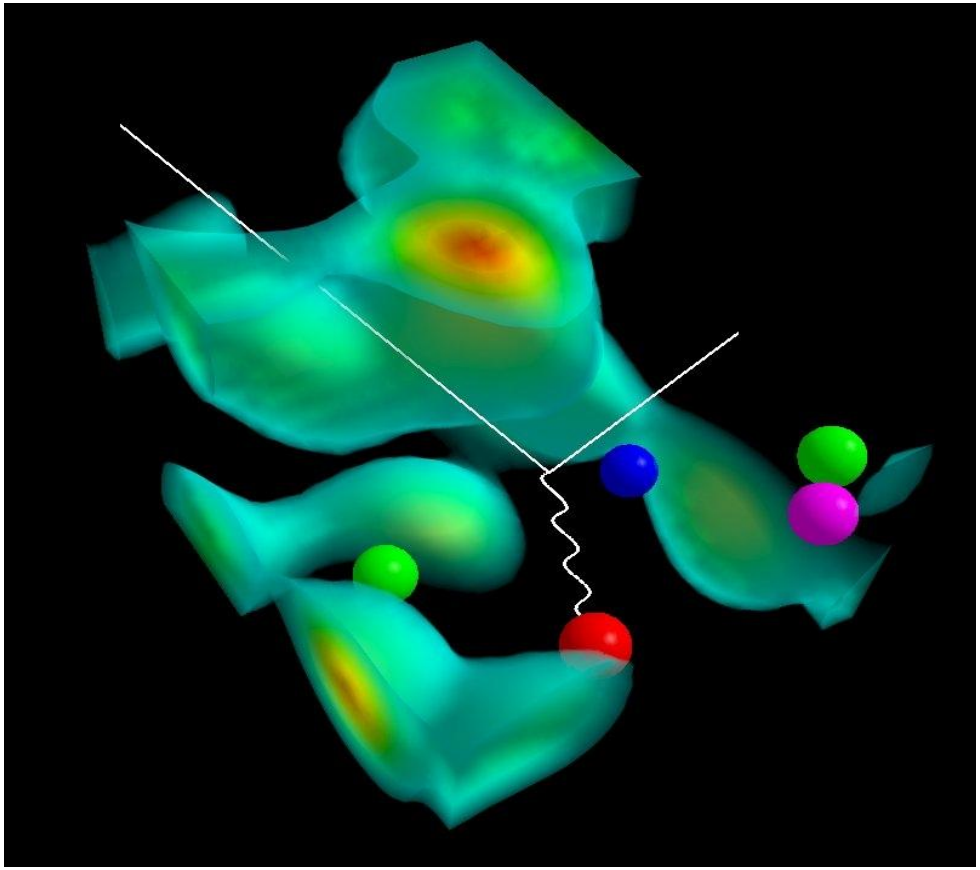
QCD and a New Paradigm for Nuclear Structure



Australian Government

Australian Research Council

CoEPP

ARC Centre of Excellence for Particle Physics at the Terascale

Anthony W. Thomas

ADELAIDE UNIVERSITY AUSTRALIA

Next generation nuclear physics with JLab12 and EIC

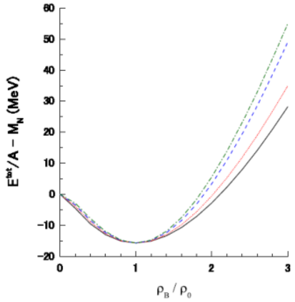
FIU Miami: February 10th 2016

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Fundamental Question for Nuclear Physics

- **Is the nucleon immutable?**
- **i.e. When immersed in a nuclear medium with applied scalar field strength of order half its mass *is it really unchanged*??**
- **When looked at in the context of QCD as the theory of the strong force clearly NO.**
- **Is this irrelevant to nuclear structure? NO**
- **Indeed, we argue it is of fundamental importance.....**

Relevance of QCD to Nuclear Structure



- **Insight into origin of saturation – unexpected!**

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

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

  − i.e. EFT has symmetries of QCD ....
  BUT we need to know the relevant d.o.f. too

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

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: DIS structure functions, form factors in-medium....**

A different approach : QMC Model

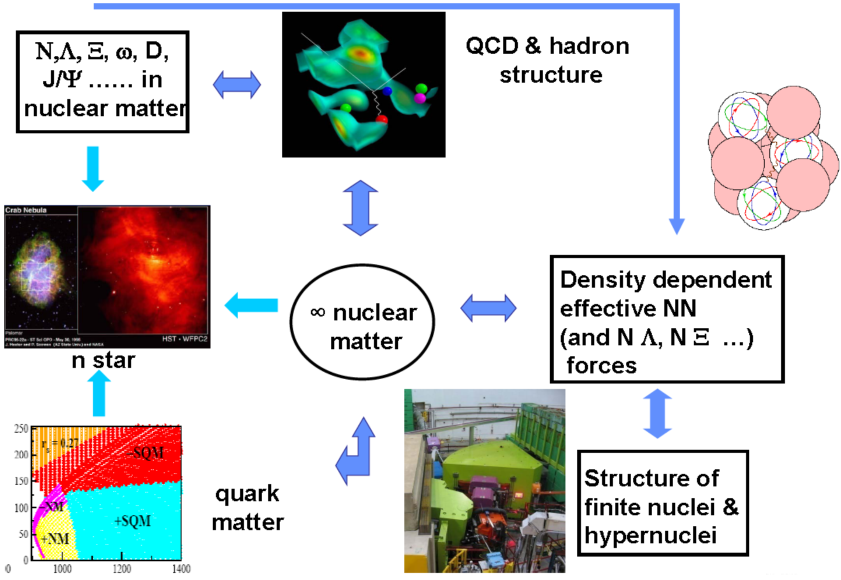
(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Progress Part. Nucl. Phys. 58 (2007) 1 for a review)

- 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)



N,Λ, Ξ, ω, D, J/Ψ ...... in nuclear matter

QCD & hadron structure

n star

∞ nuclear matter

Density dependent effective NN (and N Λ, N Ξ ...) forces

quark matter

Structure of finite nuclei & hypernuclei

- 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

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

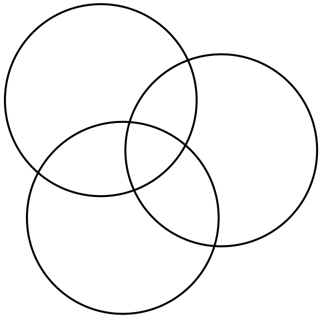
Non-linear dependence through the scalar polarizability

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

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



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

- **same is true in nuclear physics:**
- **scalar polarizability is natural source of 3-body force**

Explicit Demonstration of Origin of 3-Body Force

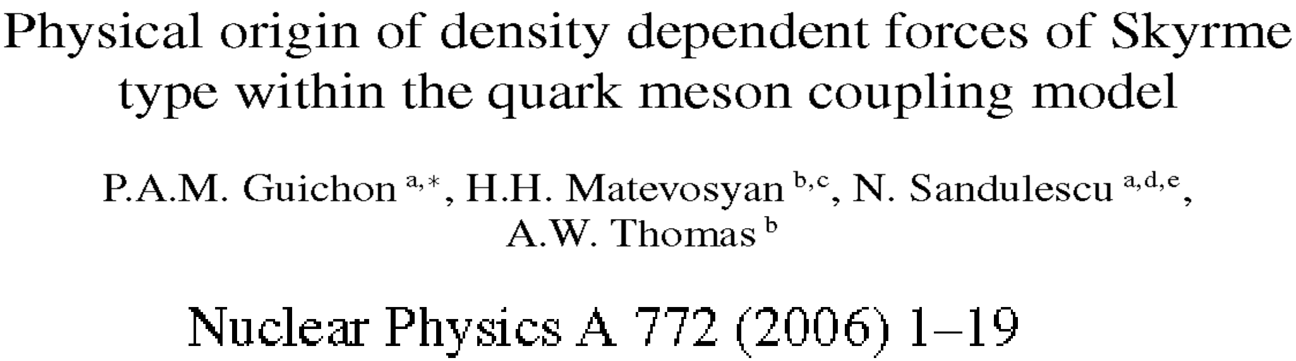
Since early 70's tremendous amount of work in nuclear theory is based upon effective forces

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

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

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

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:**

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

Derivation of effective Force (cont.)

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

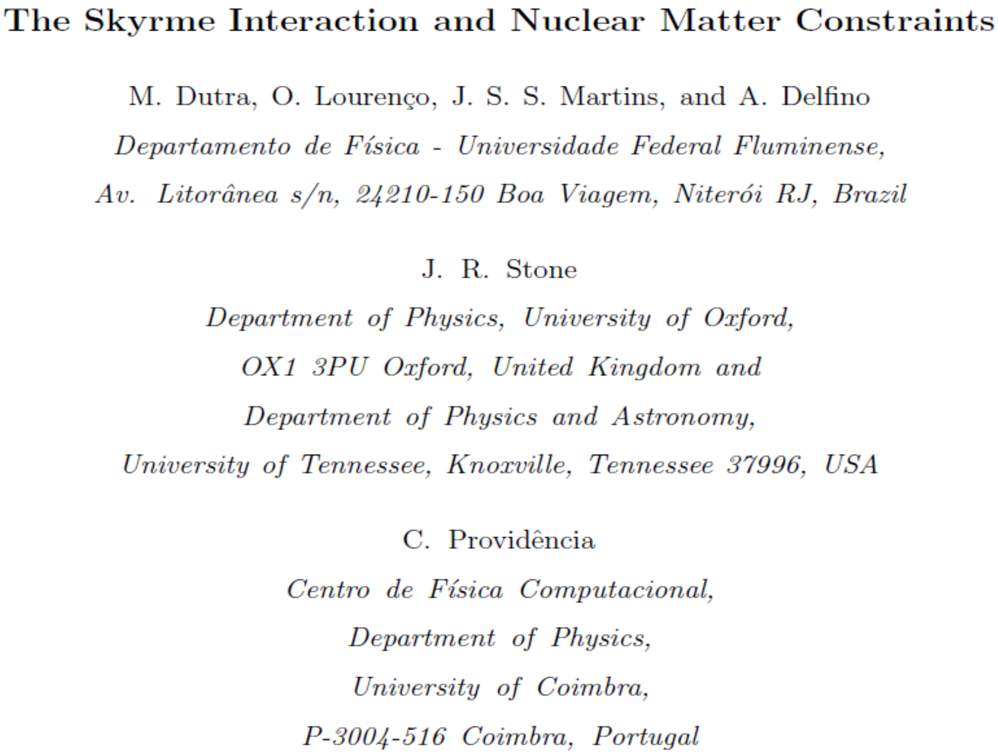
$$\begin{aligned}\mathcal{H}_{\rm eff}=\left[\left(\frac{G_\rho}{8m_\rho{}^2}-\frac{G_\sigma}{2m_\sigma{}^2}+\frac{G_\omega}{2m_\omega{}^2}+\frac{G_\sigma}{4M_N{}^2}\right)\rho_n+\left(\frac{G_\rho}{4m_\rho^2}+\frac{G_\sigma}{2M_N^2}\right)\rho_p\right]\tau_n\\
+p\leftrightarrow n,\end{aligned}$$

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

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

Note the totally new, subtle density dependence

Global search on Skyrme forces



The Skyrme Interaction and Nuclear Matter Constraints

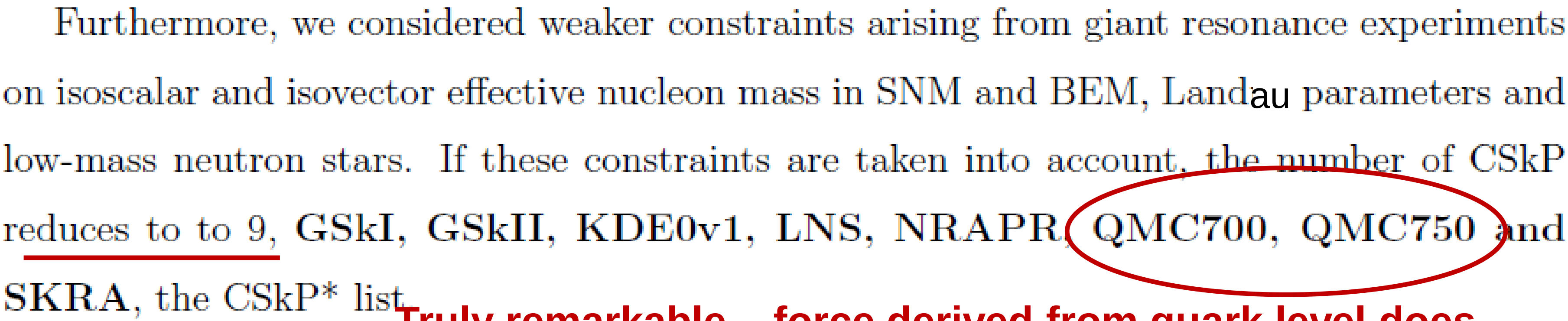
M. Dutra, O. Lourenço, J. S. S. Martins, and A. Delfino
Departamento de Física - Universidade Federal Fluminense,
Av. Litorânea s/n, 24210-150 Boa Viagem, Niterói RJ, Brazil

J. R. Stone
Department of Physics, University of Oxford,
OX1 3PU Oxford, United Kingdom and
Department of Physics and Astronomy,
University of Tennessee, Knoxville, Tennessee 37996, USA

C. Providência
Centro de Física Computacional,
Department of Physics,
University of Coimbra,
P-3004-516 Coimbra, Portugal

Phys. Rev. C85 (2012) 035201

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!

Systematic Study of Finite Nuclei

Systematic approach to finite nuclei

J.R. Stone, P.A.M. Guichon, P. G. Reinhard & A.W. Thomas:

axViv:1601.08131, to appear in PRL

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

$-17 < E/A < -15$ MeV

$0.14 < \rho_0 < 0.18$ fm^{-3}

$28 < S_0 < 34$ MeV

$L > 20$ MeV

$250 < K_0 < 350$ MeV

- Fix at overall best description of finite nuclei

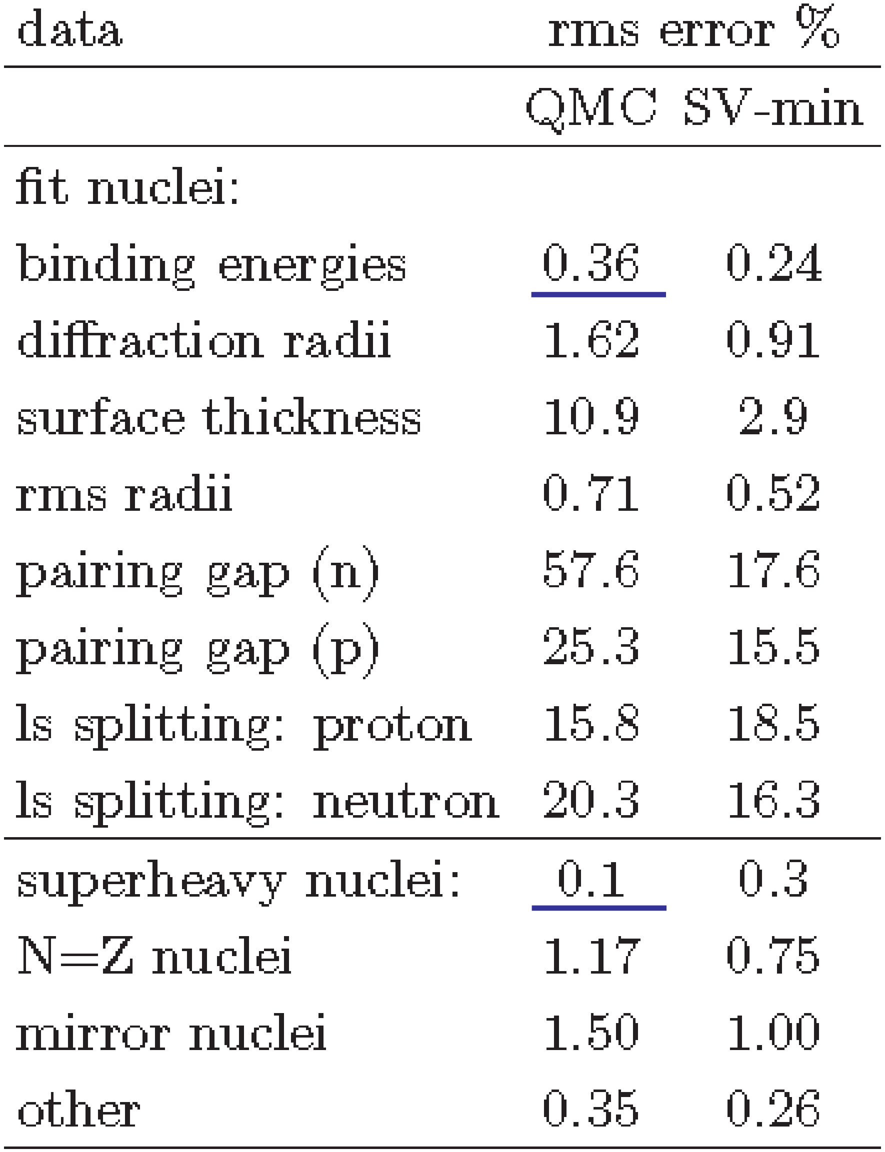
Overview of 106 Nuclei Studied – Across Periodic Table

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		

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

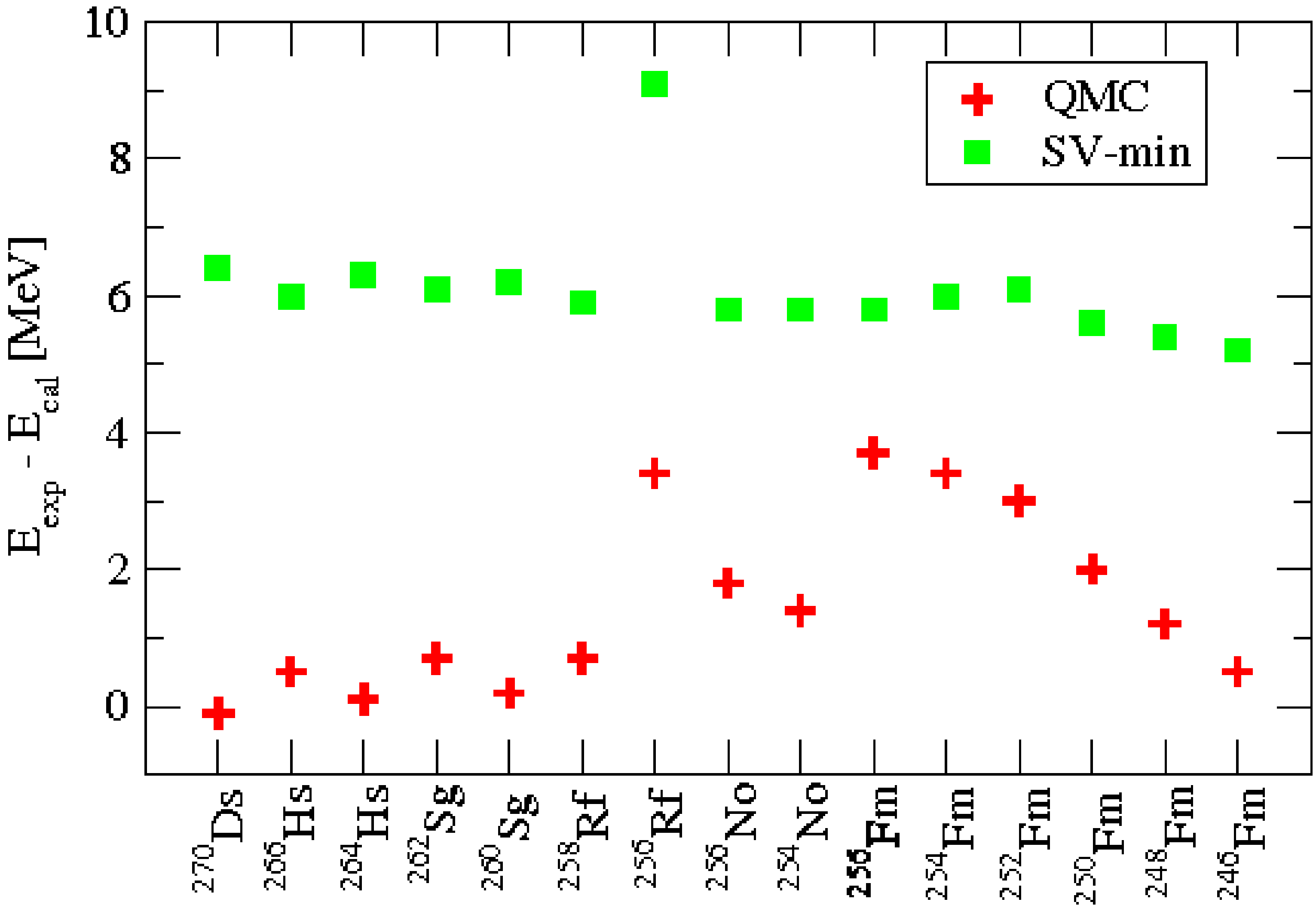
Overview



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

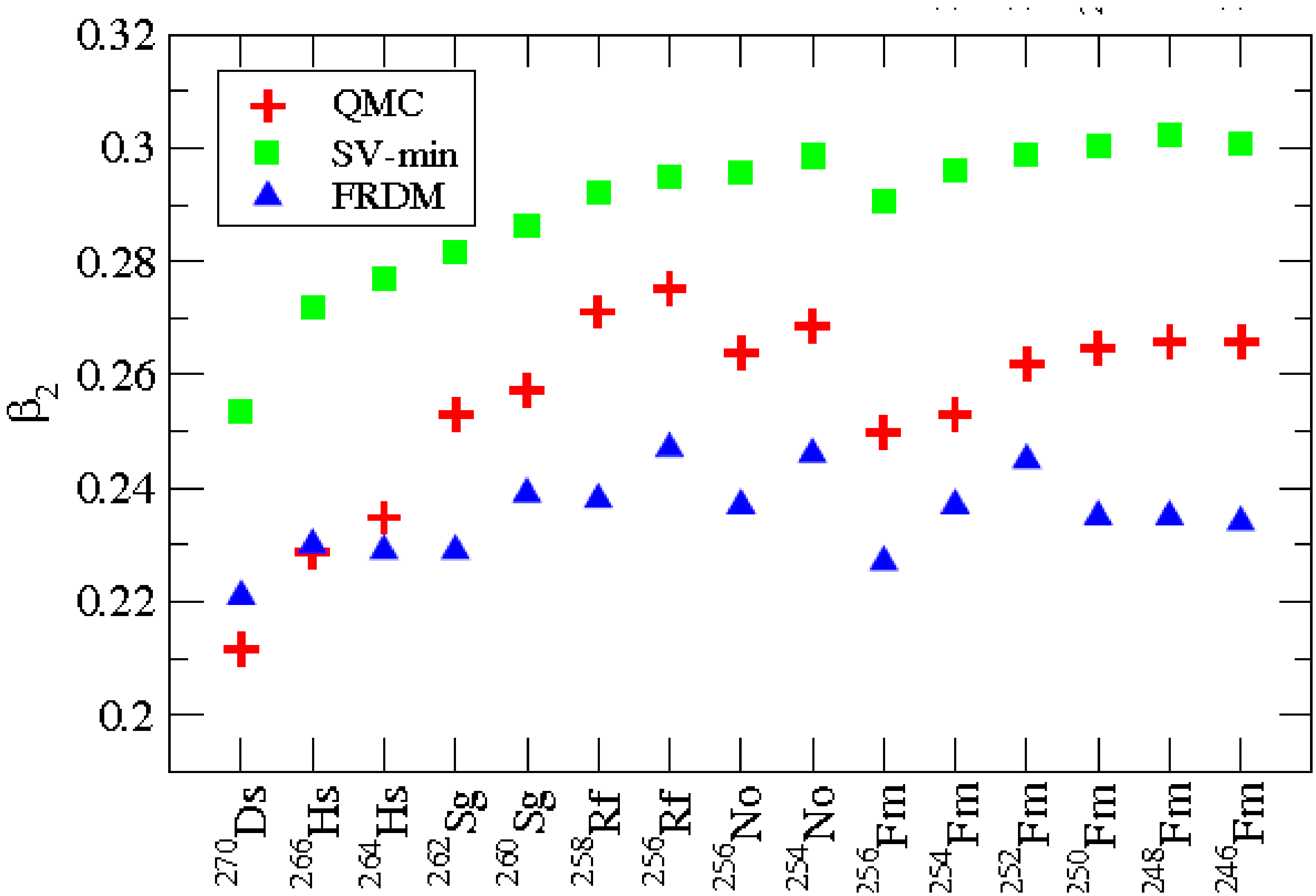
Stone et al., PRL (2016)

Superheavies : 0.1% accuracy



Stone et al., PRL (2016)

Quadrupole Deformation of Superheavies



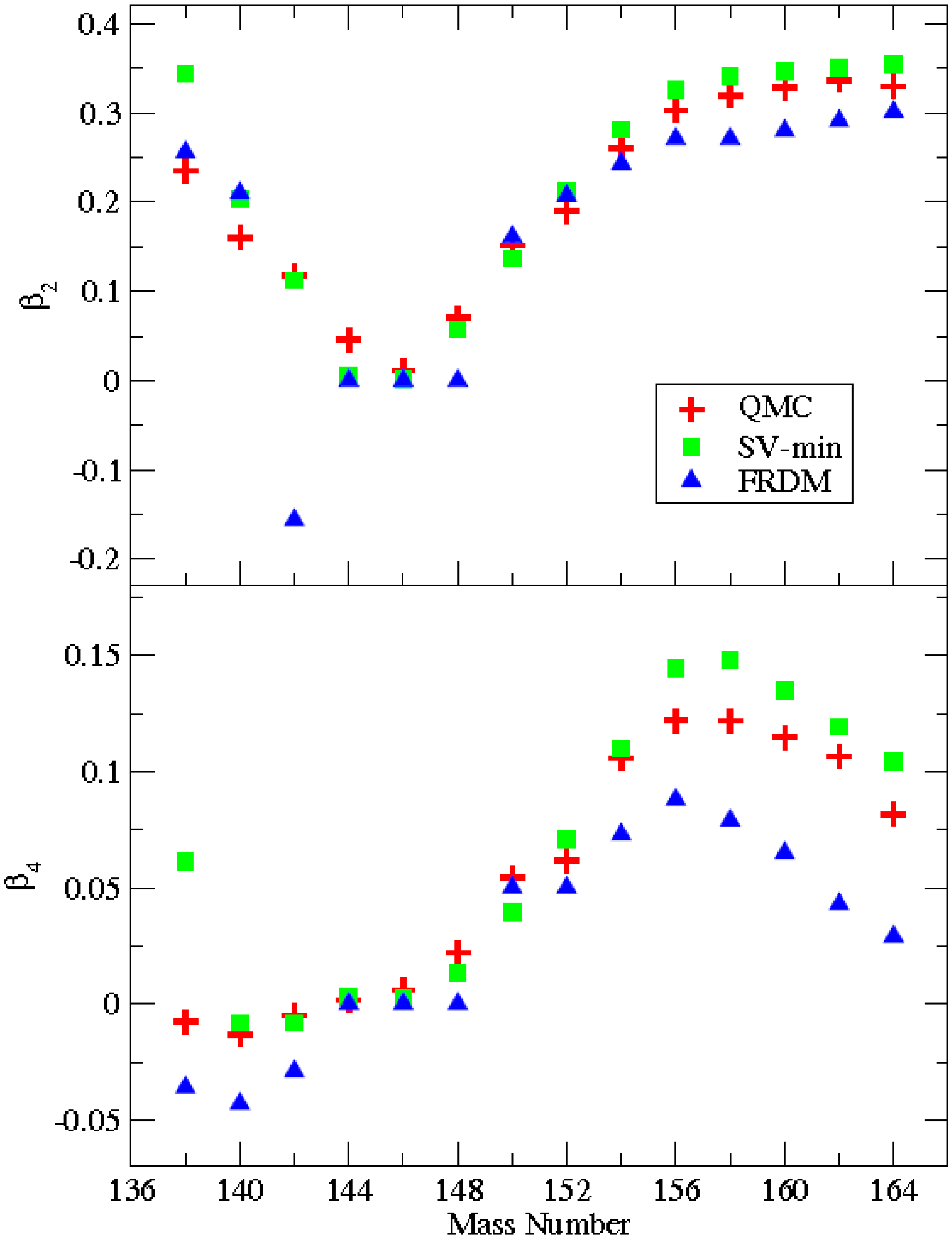
CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

Stone et al., PRL (2016)

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

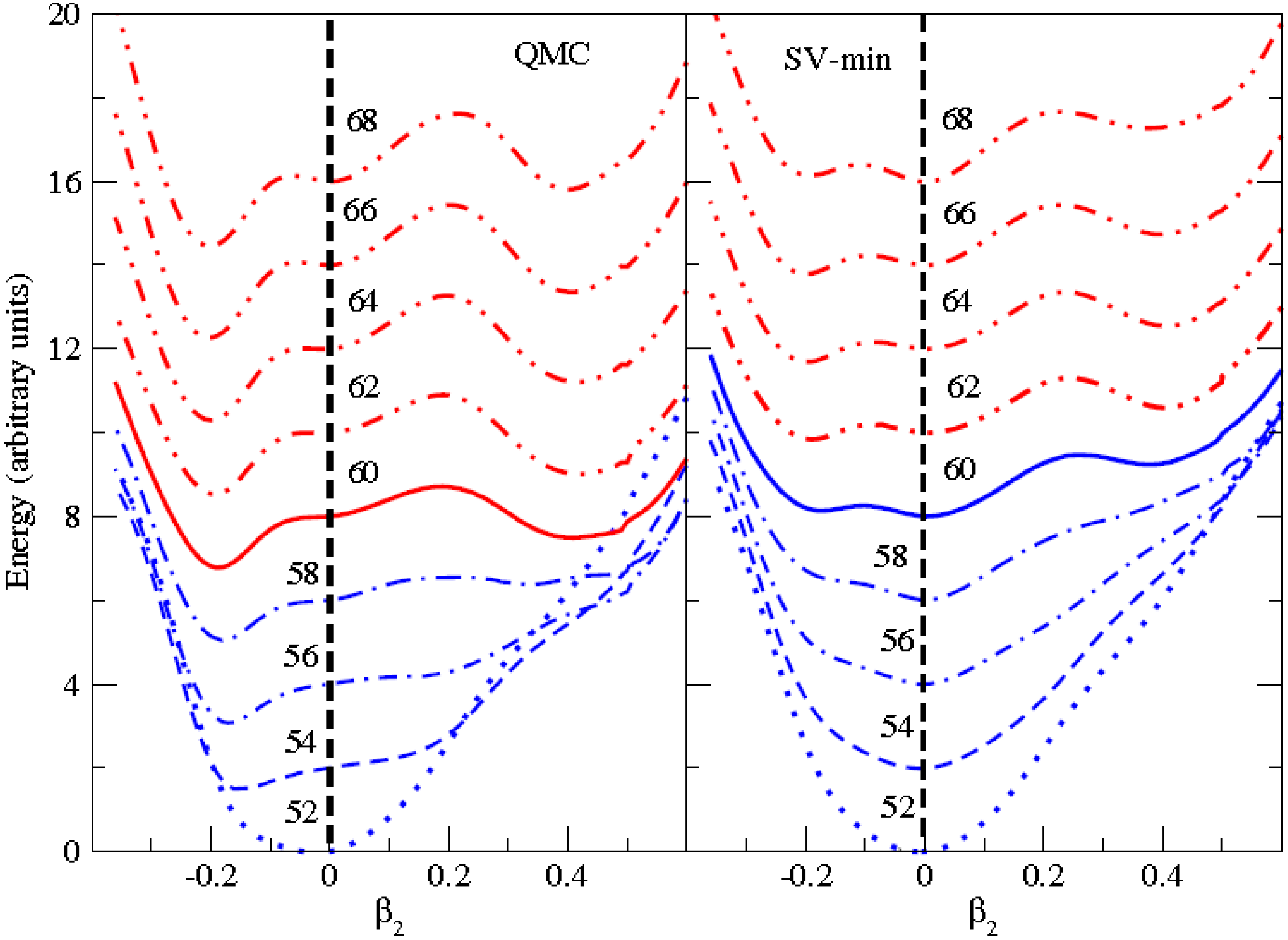
Deformation in Gd (Z=64) Isotopes



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 – Sotty *et al*.,PRL115 (2015)172501
- Usually difficult to describe
  - – e.g. Mei et al., PRC85, 034321 (2012)

Stone et al., PRL (2016)

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......**

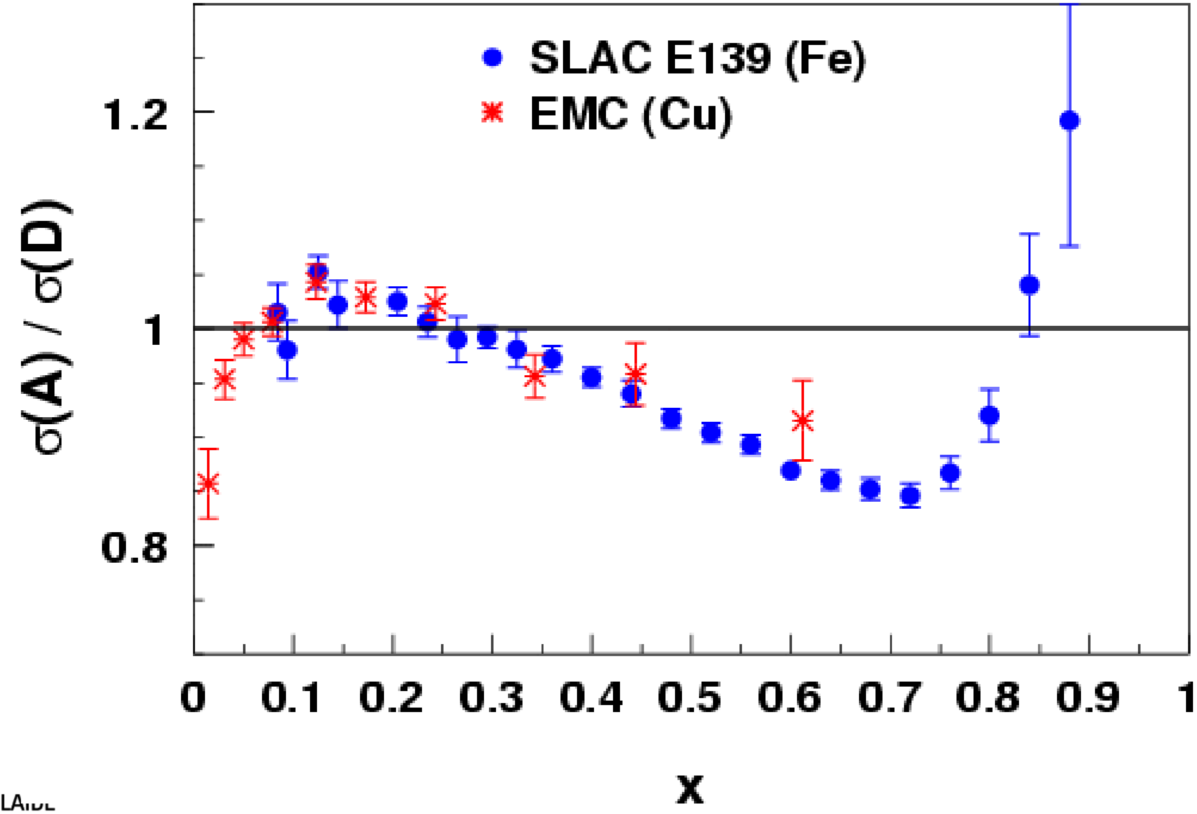
Nuclear DIS Structure Functions

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

- 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)

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)

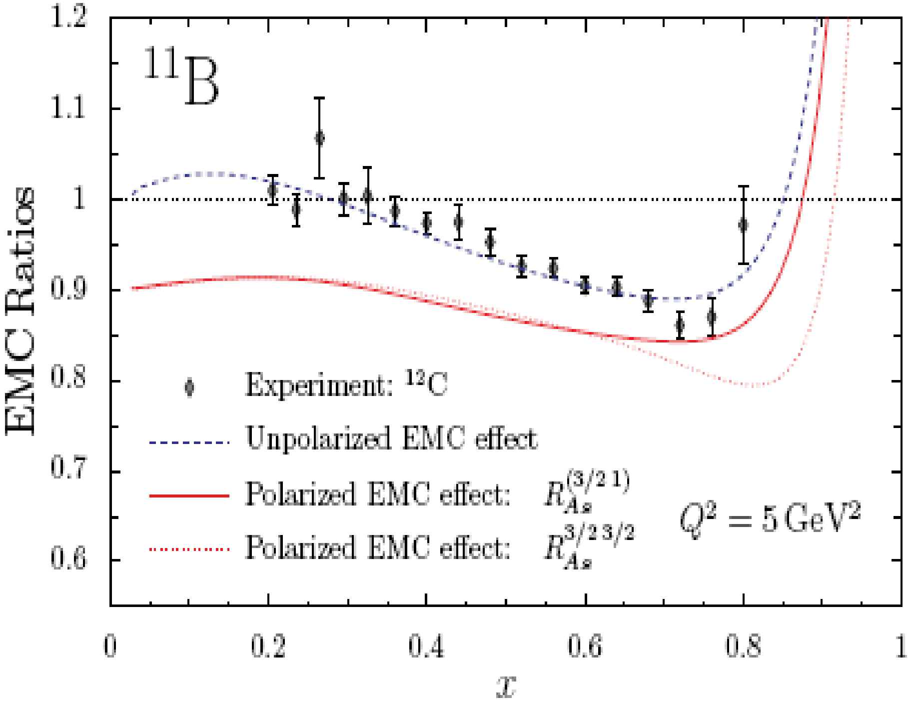


FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

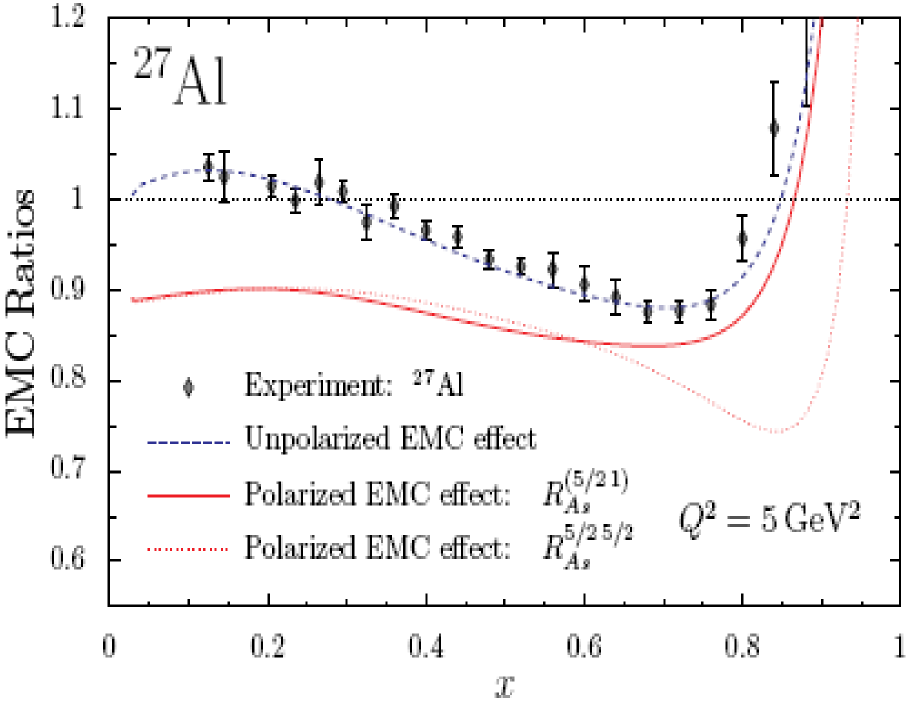


FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

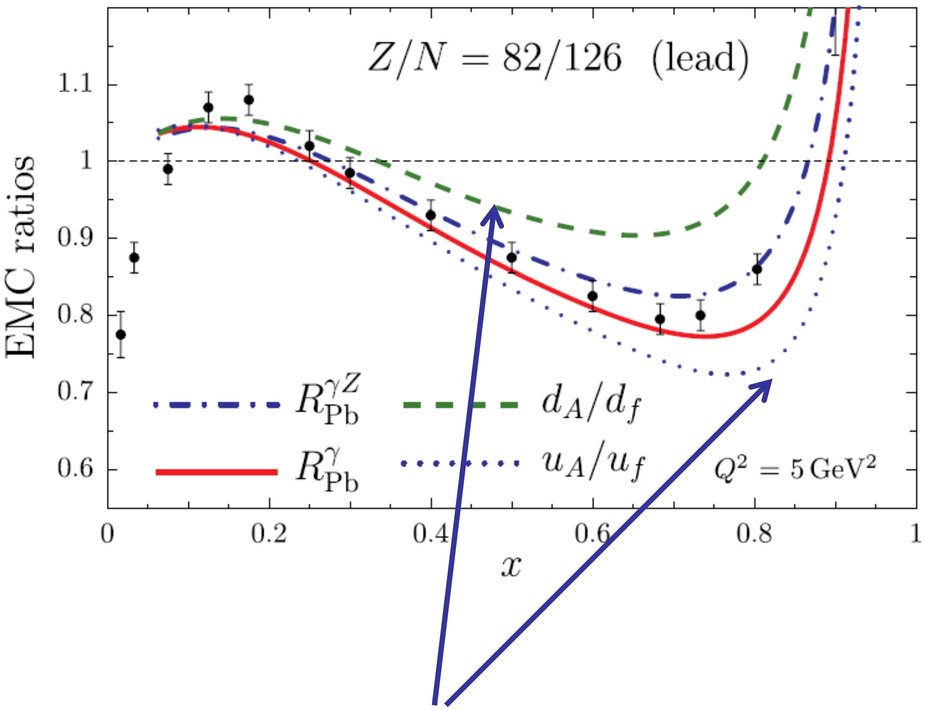
Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210 (nucl-th/0605061)

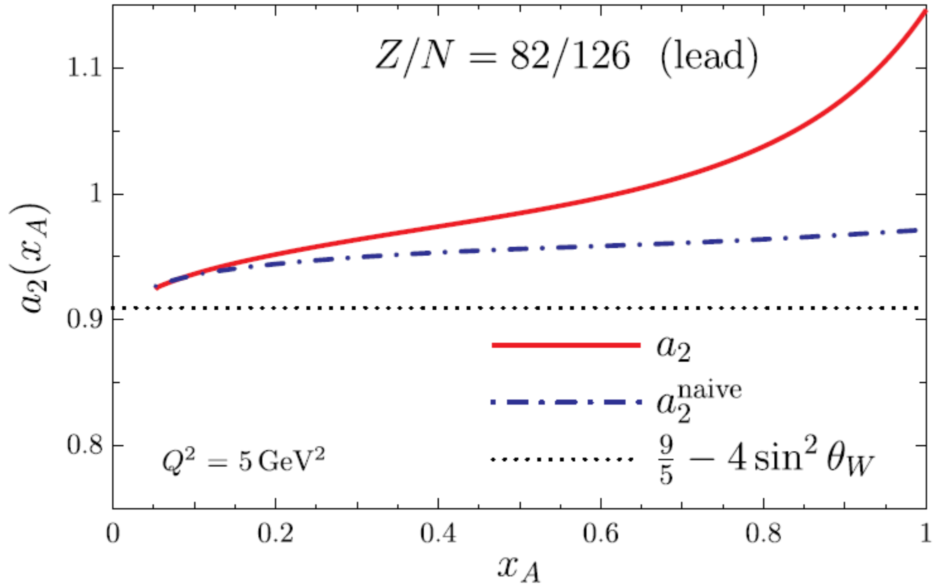
PRL **109,** 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

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]

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





Ideally tested at EIC with CC reactions

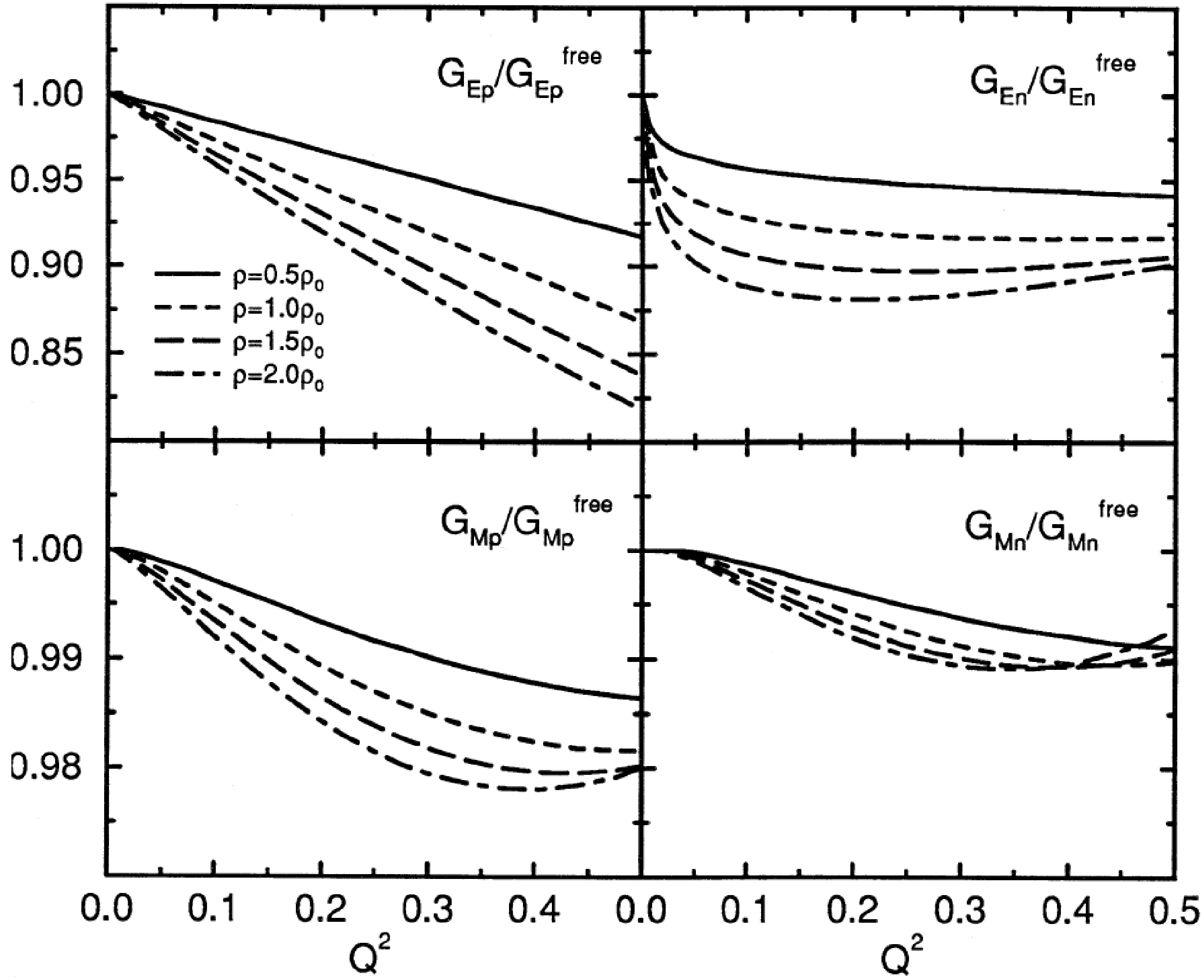
Parity violating EMC will test this at JLab 12 GeV

Modified Electromagnetic Form Factors In-Medium

In-medium electron-nucleon scattering

Archival

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



QMC

Physics Letters B 417 (1998) 217–223

Recent Calculations Motivated by:

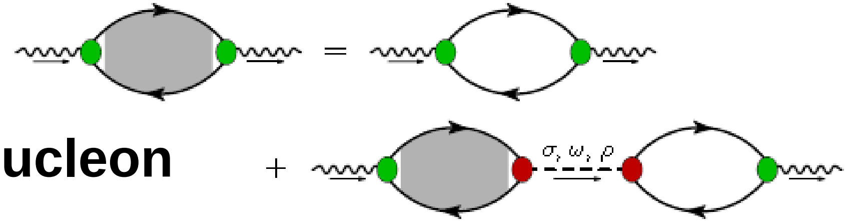
E01-015, PR-04-015 – Chen, Choi & Meziani

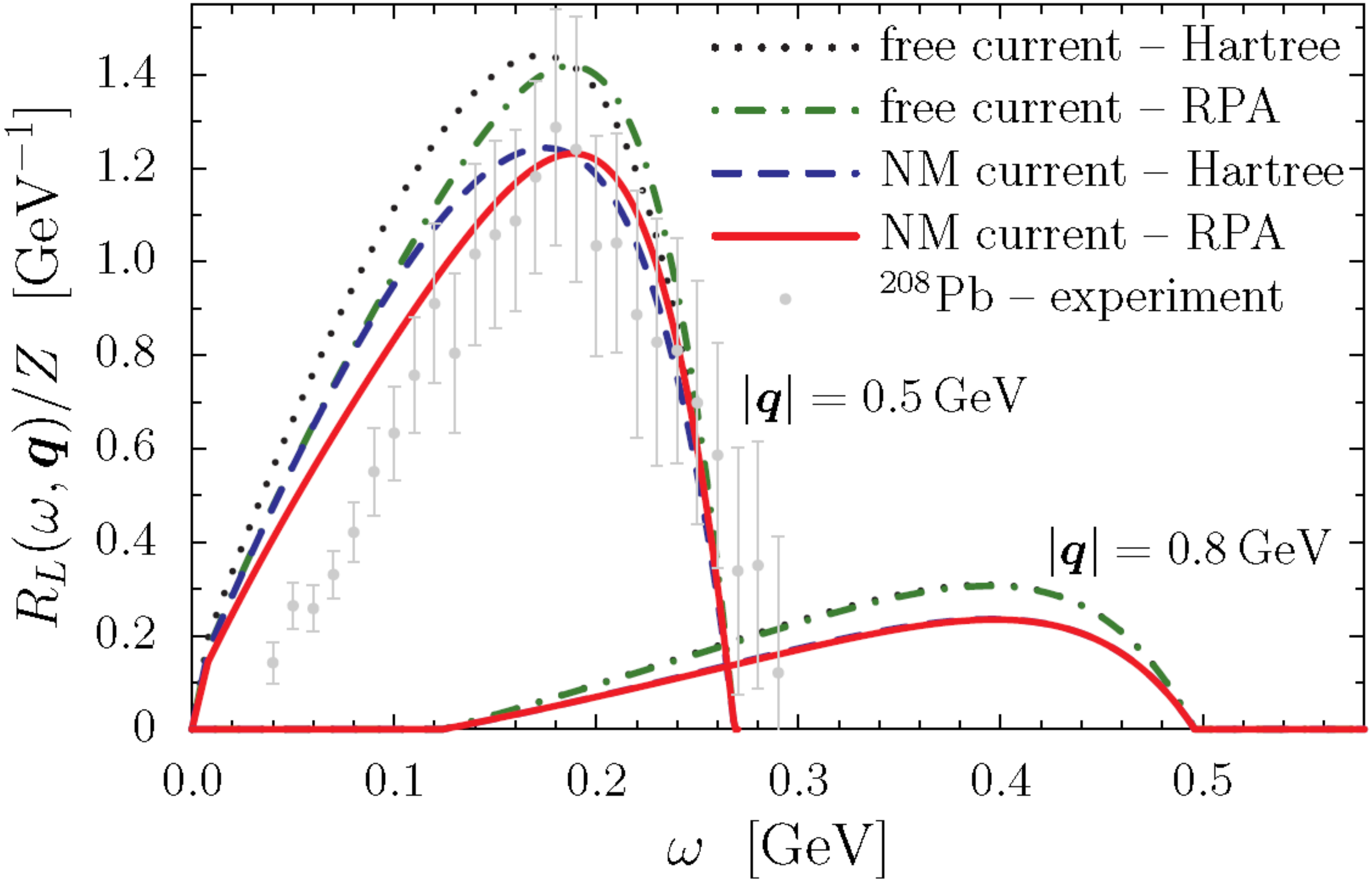
- Using NJL model with nucleon structure self-consistently solved in-medium
- Same model describing free nucleon form factors, structure functions and EMC effect

Response Function

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

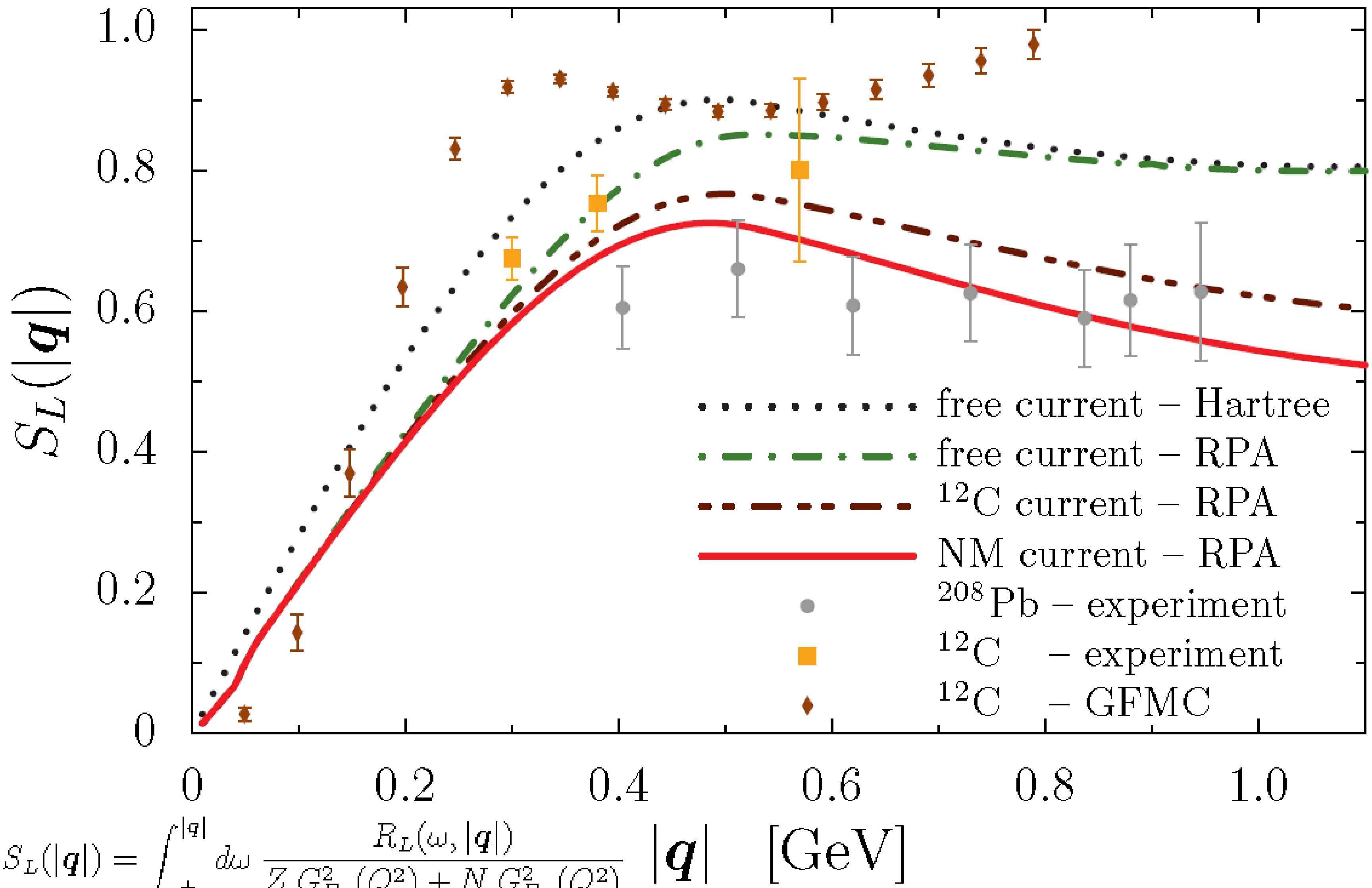
RPA correlations repulsive
Significant reduction in Response
Function from modification of bound-nucleon





Cloët, Bentz & Thomas (PRL 116 (2016) 032701)

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

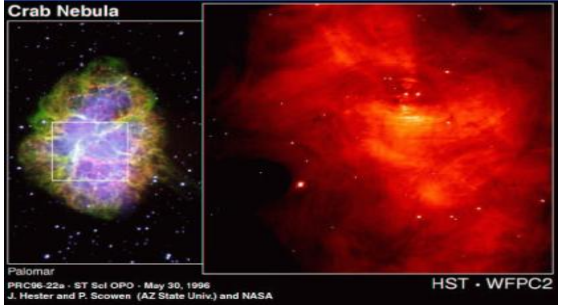
Calculations: Cloët, Bentz & Thomas (PRL 116 (2016) 032701)

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

ADELAIDE UNIVERSITY AUSTRALIA

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Summary



- Intermediate range NN attraction is 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

Summary

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

- Super-heavies (Z > 100) especially good
  (average difference 0.1%)

- Deformation, spin-orbit splitting and charge distributions all look good)

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

Special Mentions……

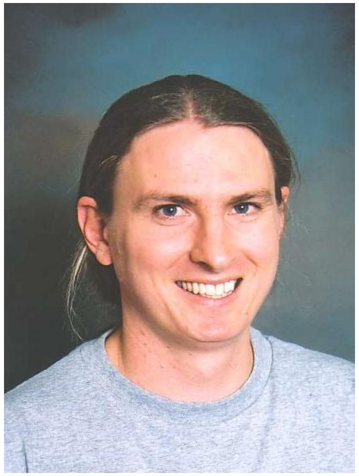
Guichon

Tsushima

Saito

Stone

Bentz



Cloët

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

September 11-16 2016

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

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**

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

- **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***

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

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

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.