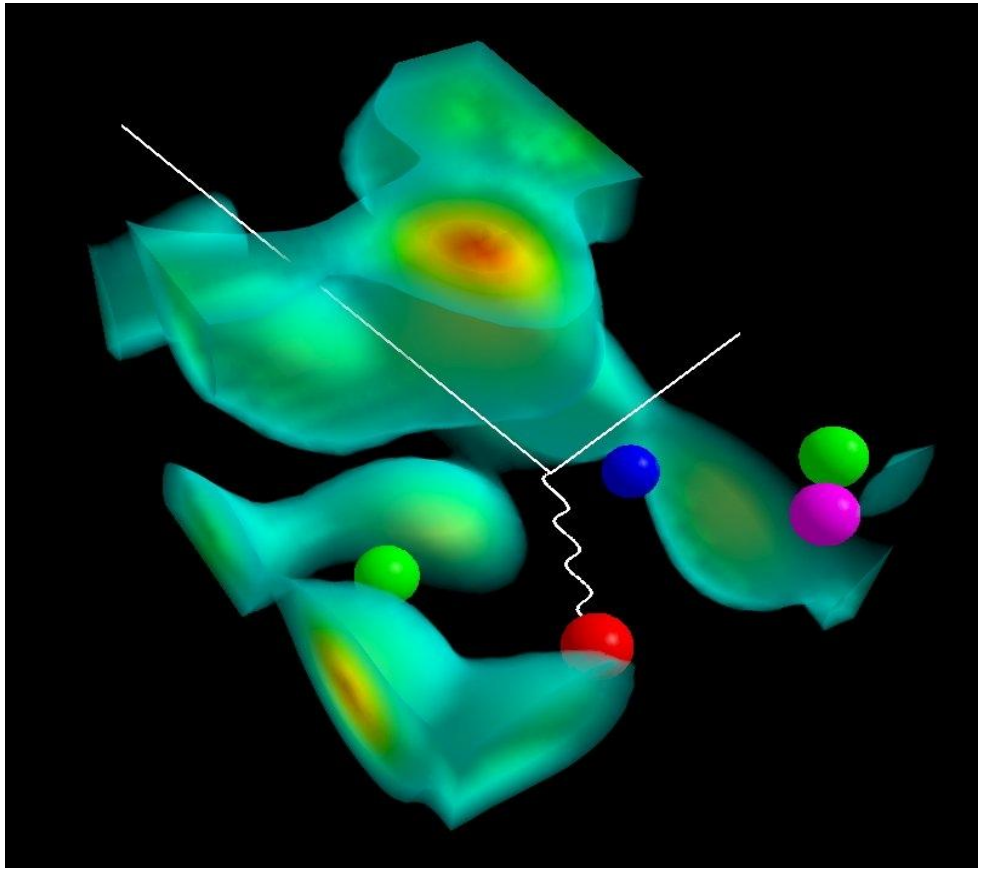
# Structure of Atomic Nuclei

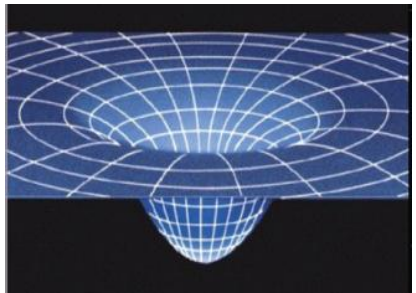



**Anthony W. Thomas**


**JLab Users Meeting**
**Jefferson Lab : June 2nd 2015**

# The Issues

- What lies at the heart of nuclear structure?
- Start from a QCD-inspired model of *hadron* structure
- Ask how that structure is modified in-medium
- This naturally leads to saturation
  + predictions for all hadrons
- Derive effective forces (Skyrme type): apply to finite nuclei
- Test predictions for structure functions and form factors in-medium



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# A different approach : QMC Model

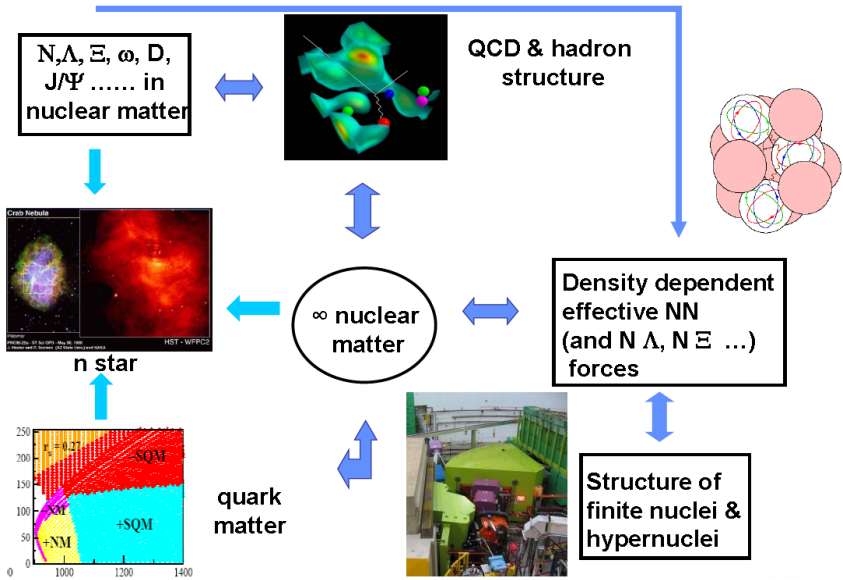
(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 for a review)

- **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 <u>only 3 parameters</u>**

  – **determine by fitting to saturation properties of nuclear matter ($\rho_0$ , E/A and symmetry energy)**




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

# 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 $\rho_0$ ) *increase in bag radius***

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

$$\frac{\Omega_0/2 + m_q^* R_B(\Omega_0 - 1)}{\Omega_0(\Omega_0 - 1) + m_q^* R_B/2}$$

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

# 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**

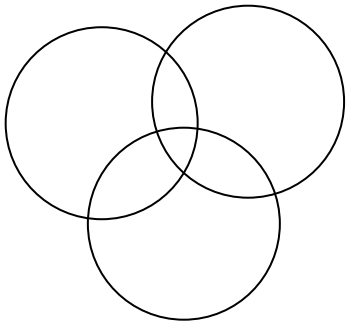
**d ~ 0.22 R in original QMC (MIT bag)**

**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>

# 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**

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

**explicitly obtained effective force, 2- plus 3- body, of Skyrme type**

**- <u>density-dependent forces now used more widely</u>**

# Physical Origin of Density Dependent Force of the Skyrme Type within the Quark Meson Coupling Model

P.A.M. Guichon[1], H.H. Matevosyan[2,3], N. Sandulescu[1,4,5] and A.W. Thomas[2]

| | $E_B$ (MeV, exp) | $E_B$ (MeV, QMC) | $r_c$ (fm, exp) | $r_c$ (fm, QMC) |
|---|---|---|---|---|
| $^{16}O$ | 7.976 | 7.618 | 2.73 | 2.702 |
| $^{40}Ca$ | 8.551 | 8.213 | 3.485 | 3.415 |
| $^{48}Ca$ | 8.666 | 8.343 | 3.484 | 3.468 |
| $^{208}Pb$ | 7.867 | 7.515 | 5.5 | 5.42 |

~ 4%

~ 1%

- **Where analytic form of (e.g. $H_0 + H_3$) piece of energy functional derived from QMC is:**

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

**highlights scalar polarizability**

**Paper II: N P A772 (2006) 1 (nucl-th/0603044)**

# Global search on Skyrme forces

The Skyrme Interaction and Nuclear Matter Constraints

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

( 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

$$-17 < E/A < -15 \text{ MeV}$$
$$0.15 < \rho_0 < 0.17 \text{ fm}^{-3}$$
$$28 < J < 34 \text{ MeV}$$
$$L > 25 \text{ MeV}$$
$$250 < K_0 < 350 \text{ MeV}$$

- Fix at overall best description of finite nuclei

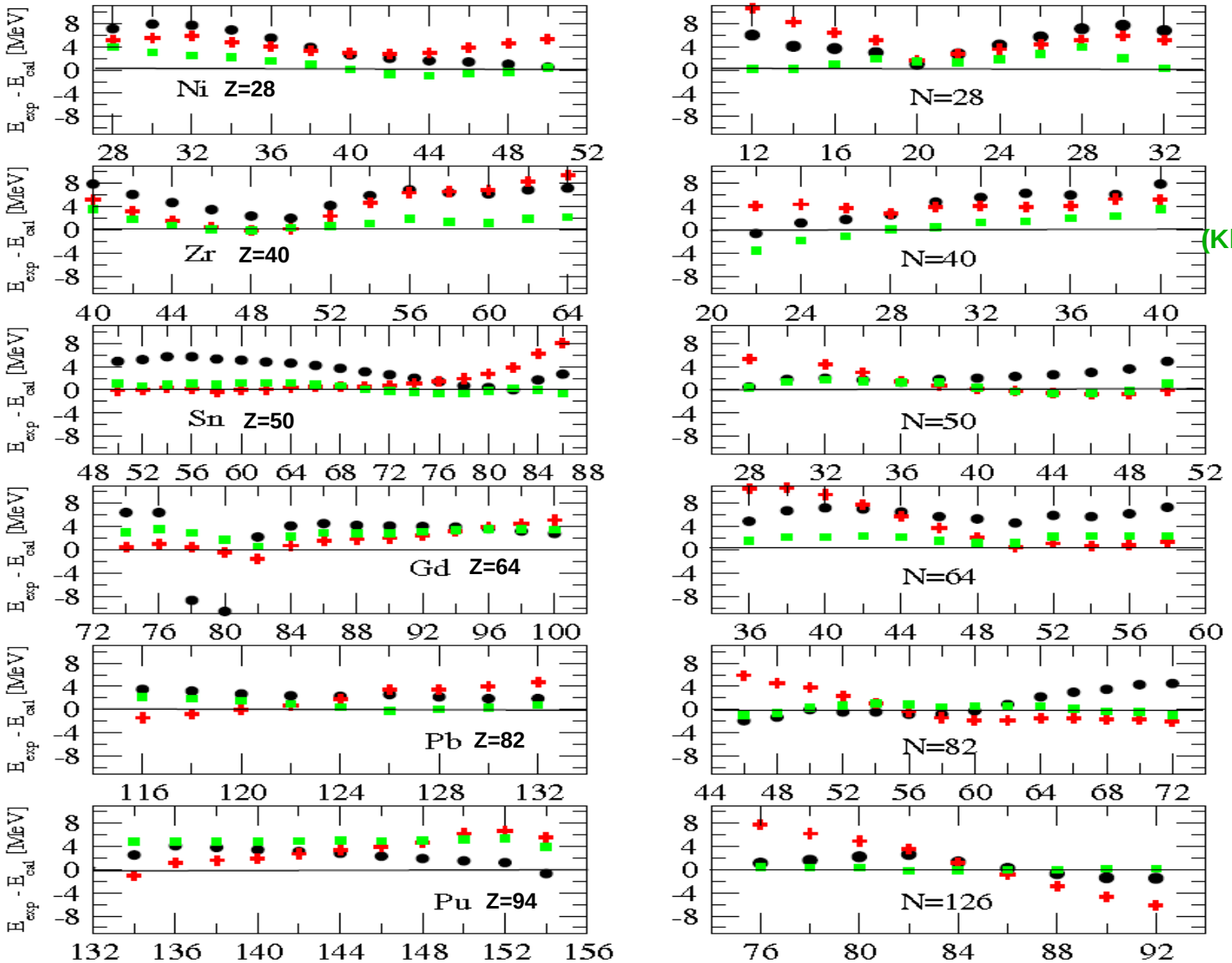
# Overview of Nuclei Studied – Across Periodic Table

| 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 | | |

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

# Binding Energies: Isotopes & Isotones



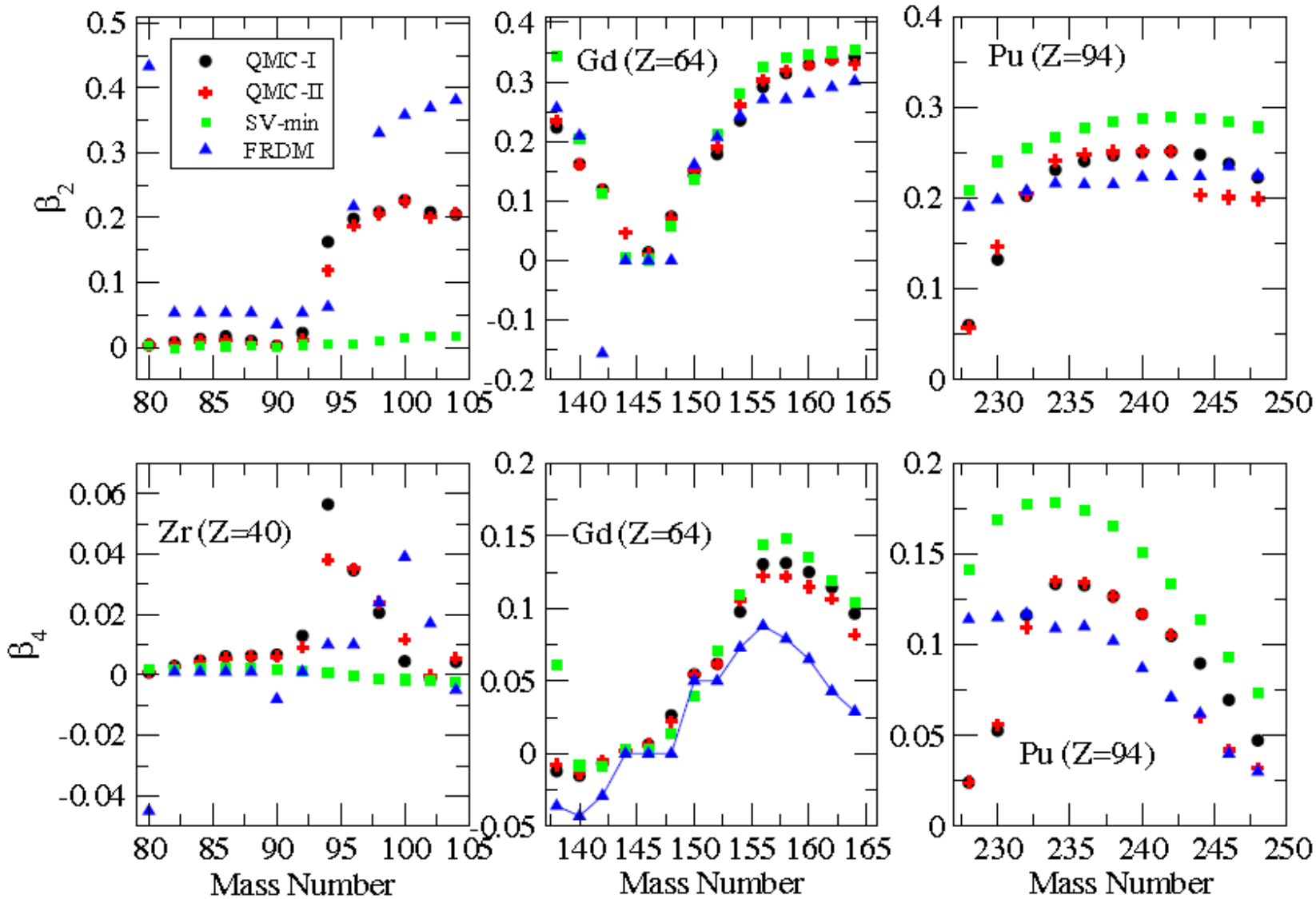

Svbas
(Kluepfel et al.)

QMC II

QMC I

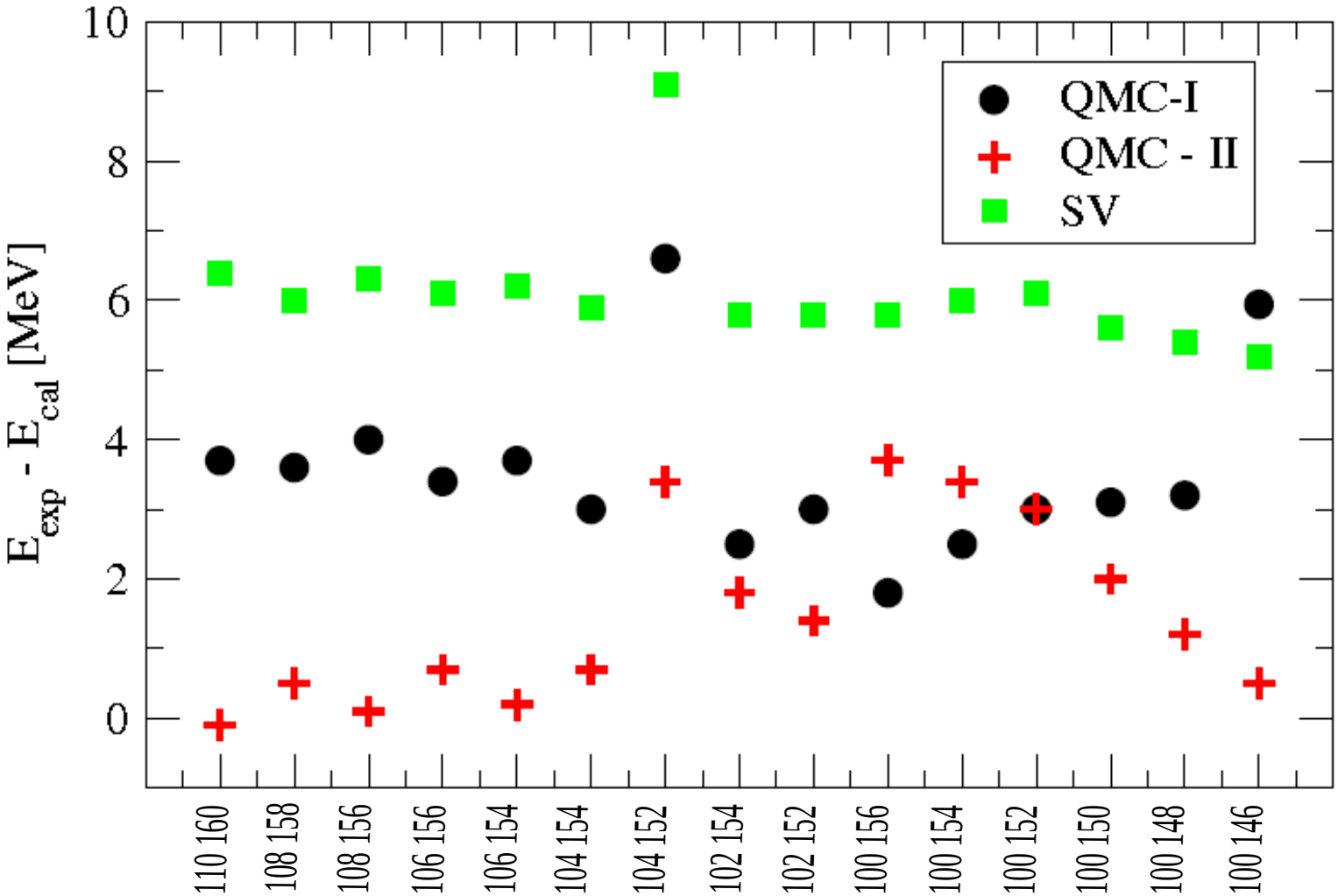
**Typically better than 0.5%**

# Deformation Impressive




SV-bas: P. Klupfel et al., Phys. Rev. C 79, 034310 (2009)
FDRM: P. Moller et al., ADNDT, 59, 185 (1995)

# Superheavies

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# Summary: Finite Nuclei

- **The effective force was *derived* at the quark level *based upon changing structure of bound nucleon***

- **Has less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces**

- **The force involves δ-functions**
  - **i.e. looks superficially like point-like nucleons**

- **BUT underlying theory also predicts modified**
  - **structure functions**
  - **form factors**

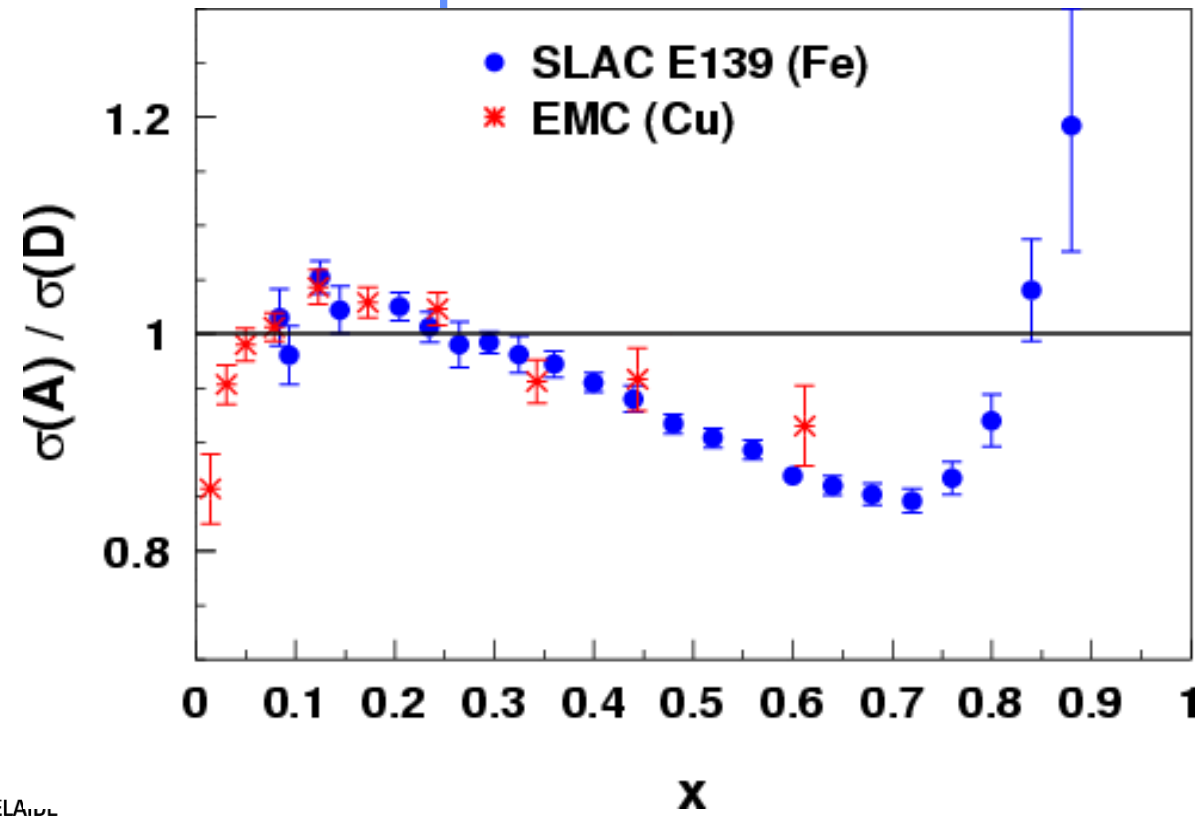
# Modified Structure Functions

# 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)

# Calculations for Finite Nuclei

**(Spin dependent EMC effect TWICE as large as unpolarized)**

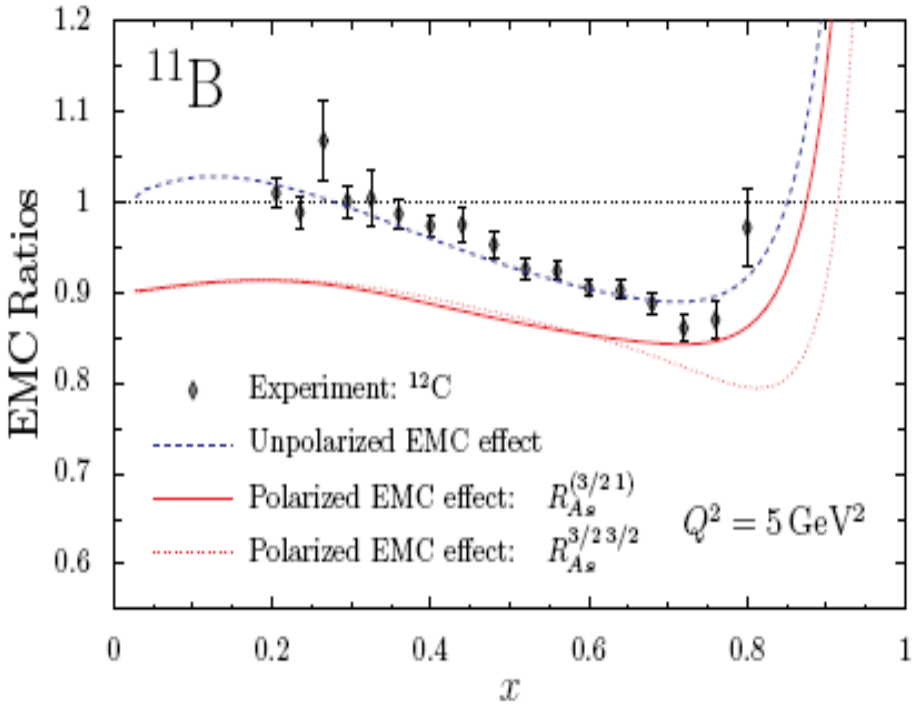



FIG. 7: The EMC and polarized EMC effect in $^{11}$B. The empirical data is from Ref. [31].

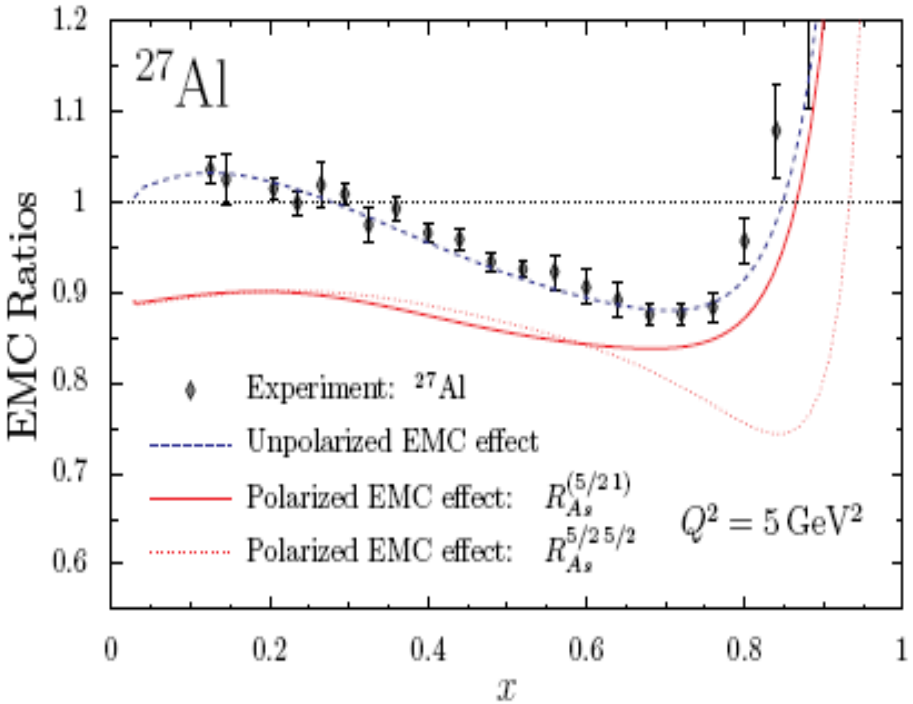



FIG. 9: The EMC and polarized EMC effect in $^{27}$Al. The empirical data is from Ref. [31].

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

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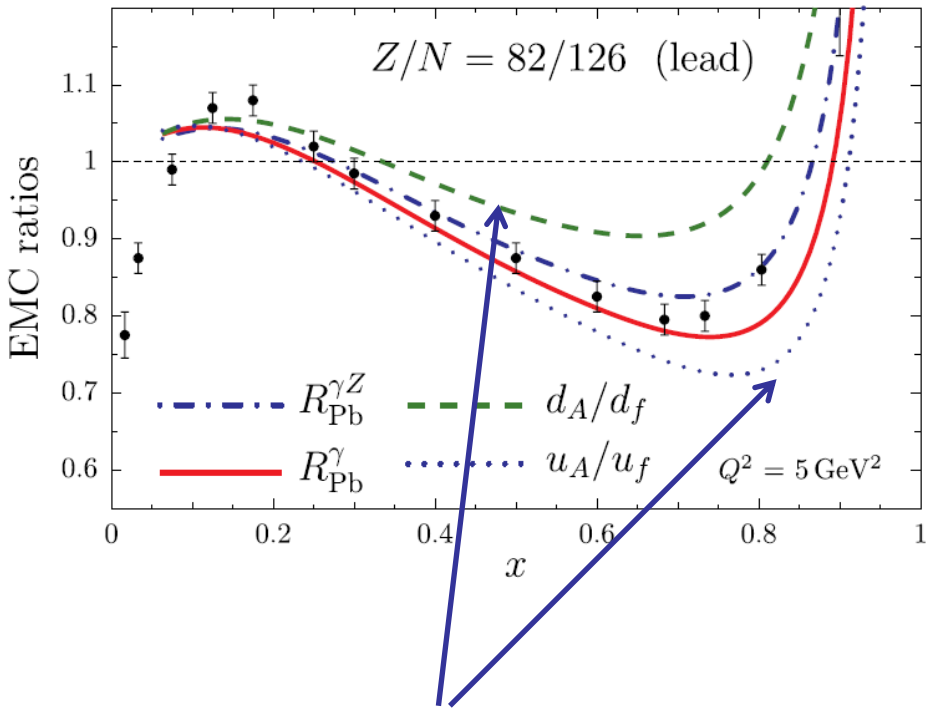
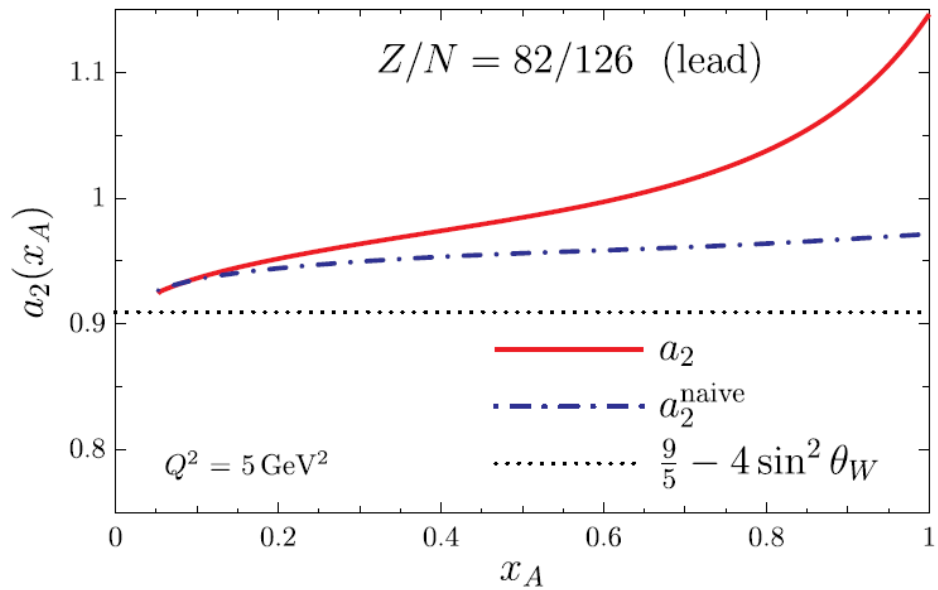
PRL 109, 182301 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

# 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]




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




**Ideally tested at EIC with CC reactions**

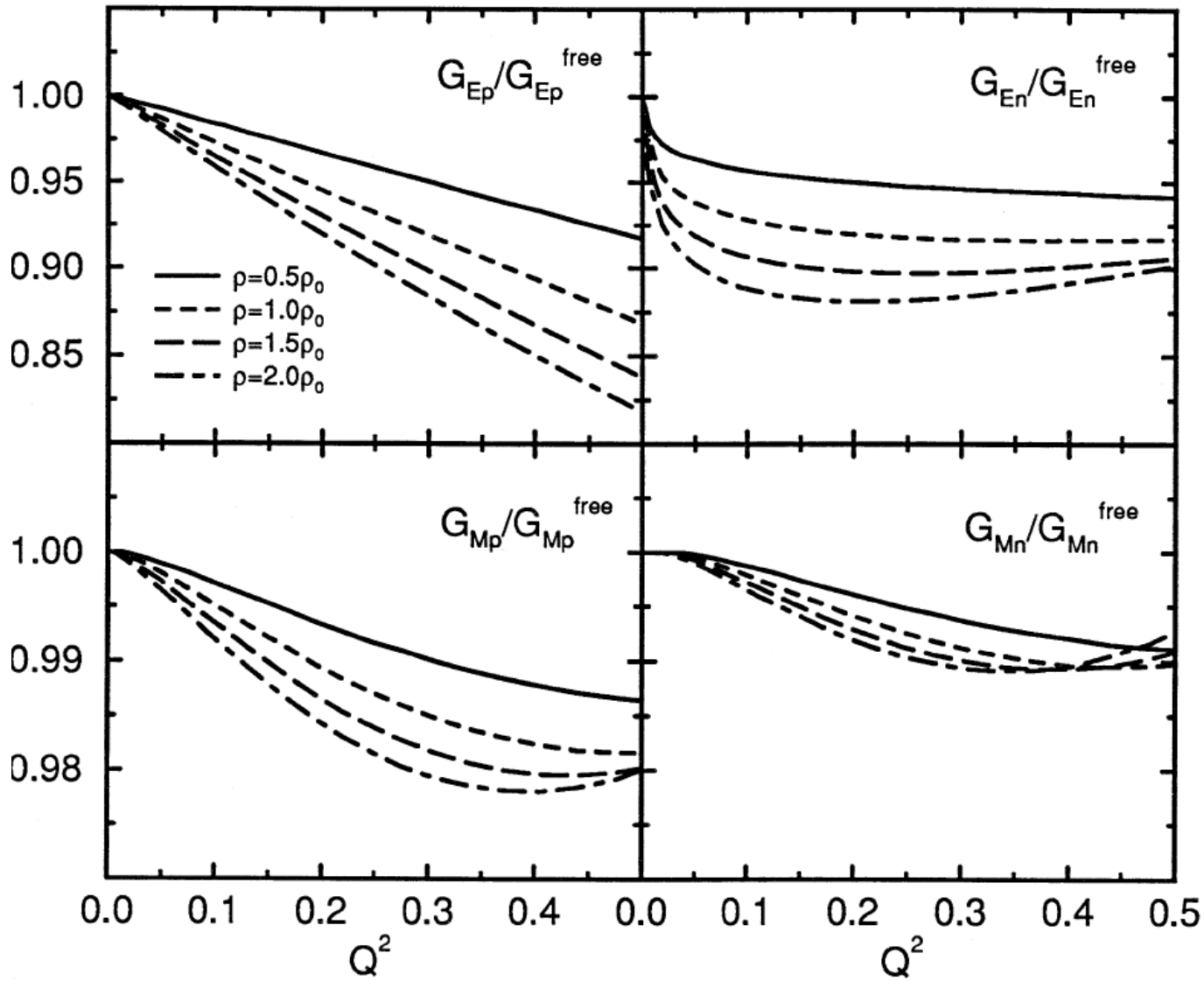
**Parity violating EMC will be tested at Jlab 12 GeV**

# 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



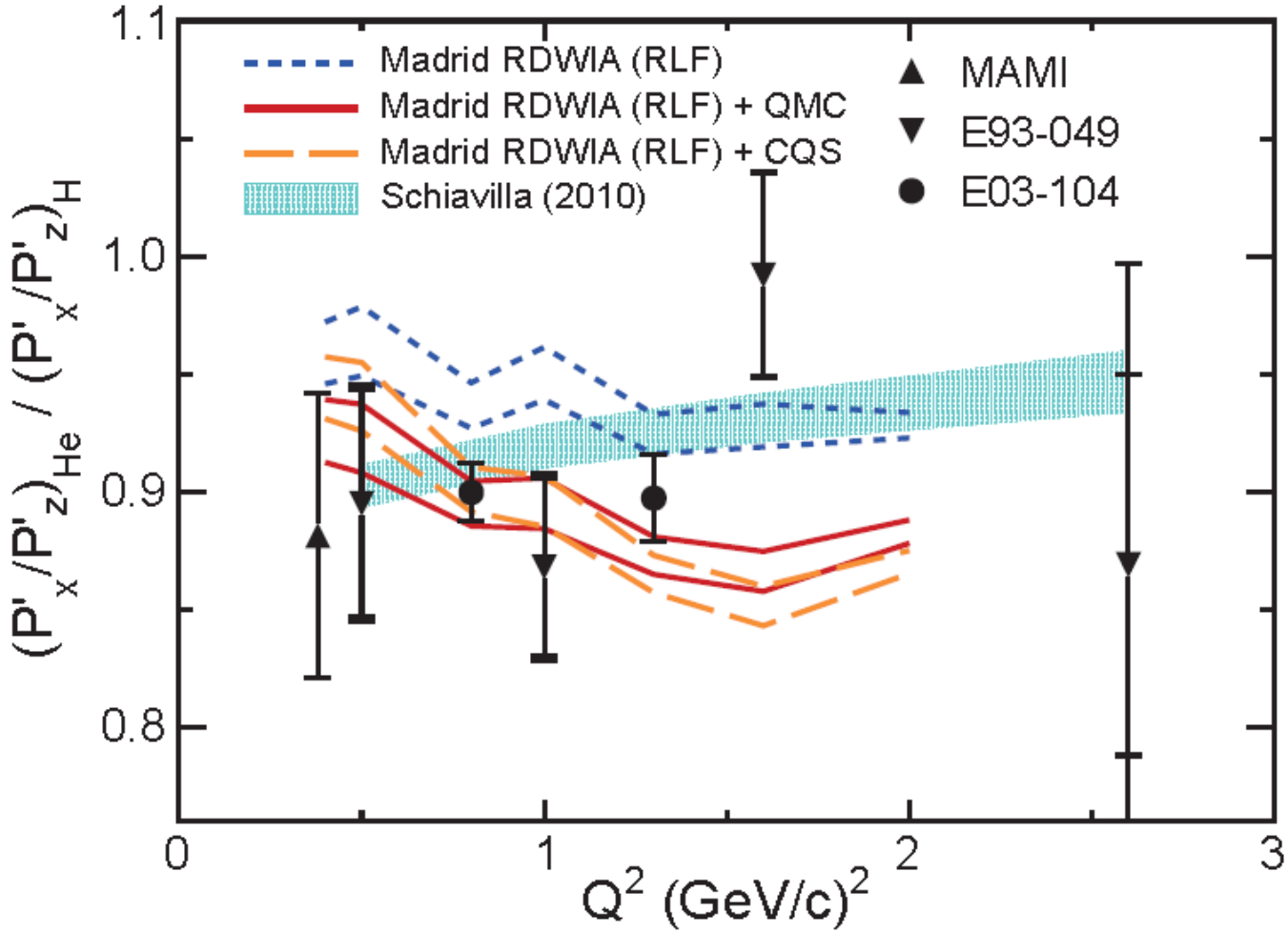

QMC

Physics Letters B 417 (1998) 217–223

# Jefferson Lab & Mainz : more from S. Strauch

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

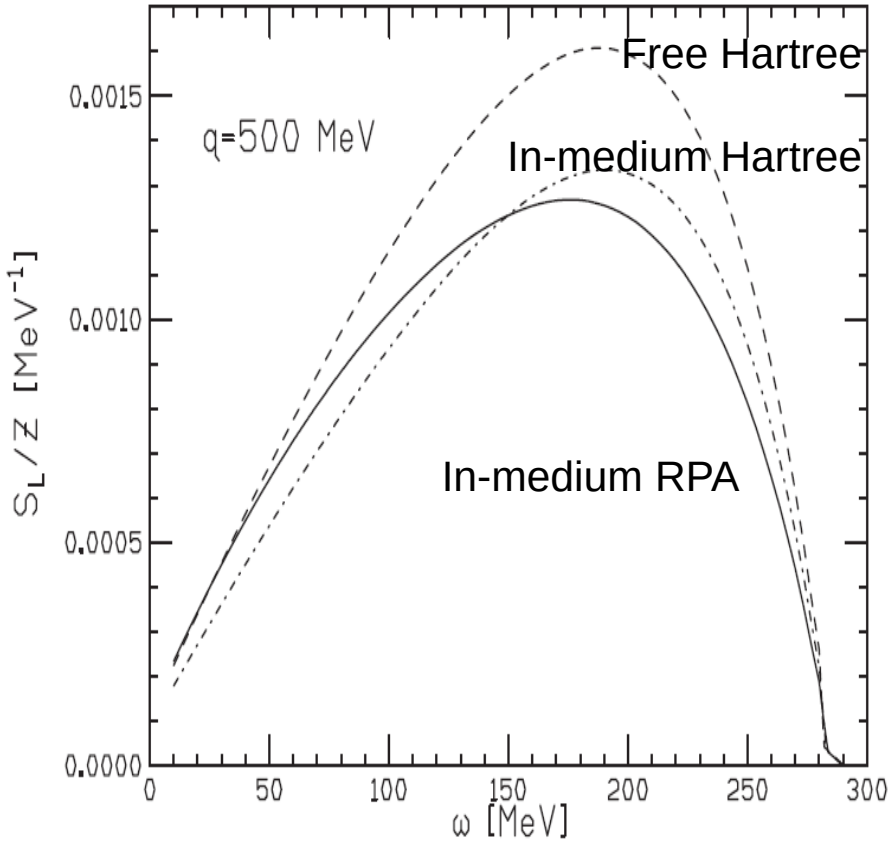
**Strauch et al., EPJ Web of Conf. 36 (2012) 00016**



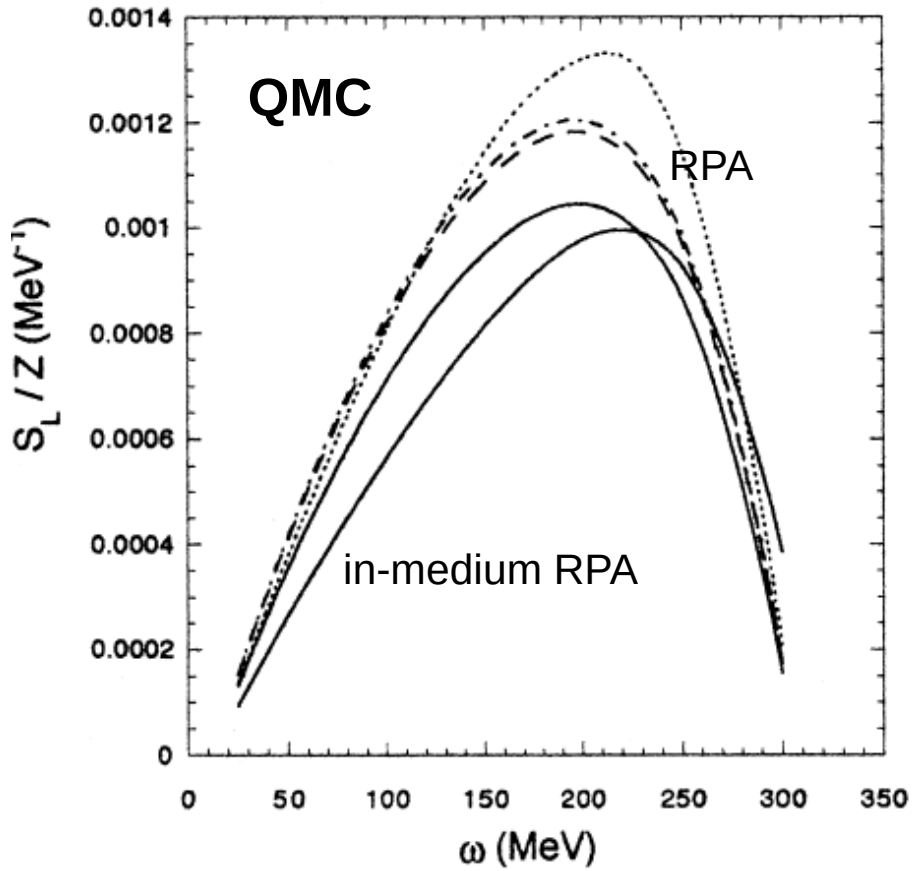

**QMC medium effect predicted more than a decade years before the experiment**
**(D.H. Lu et al., Phys. Lett. B 417 (1998) 217)**

# Longitudinal response function

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




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



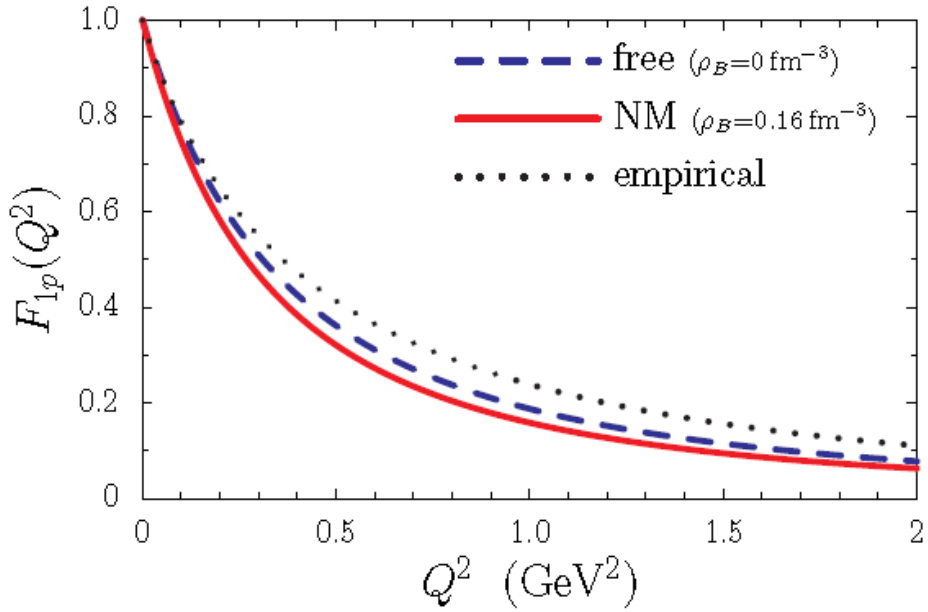

Horikawa and Bentz, nucl-th/0506021

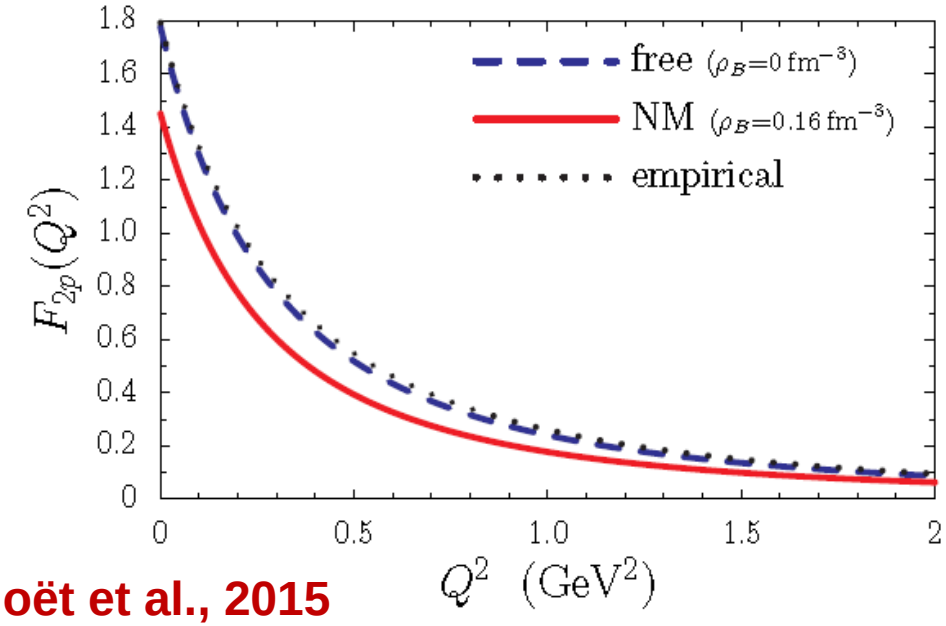
# Recent Calculations Motivated by:

## 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



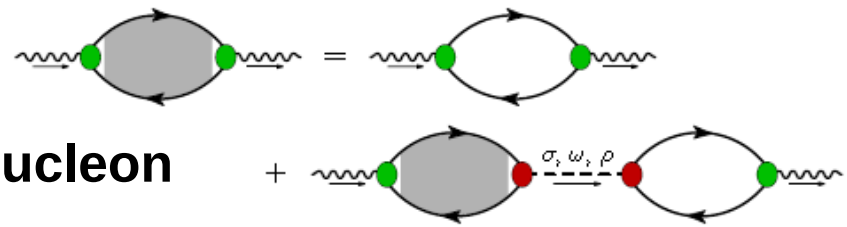

**Free nucleon form factors Bentz *et al.* Phys Rec C90, 045202 (2014)**

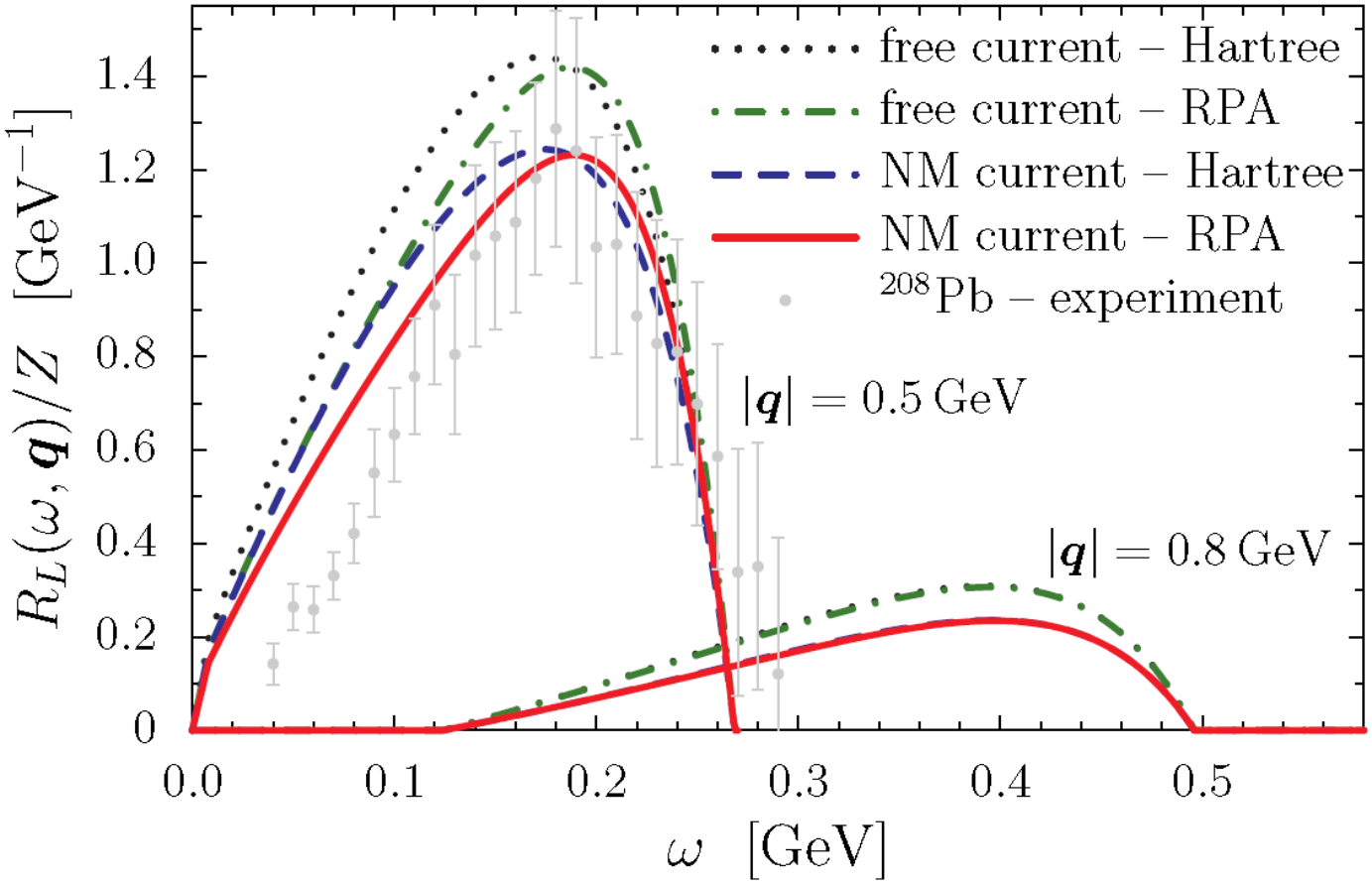
**Cloët et al., 2015**

# Response Function

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

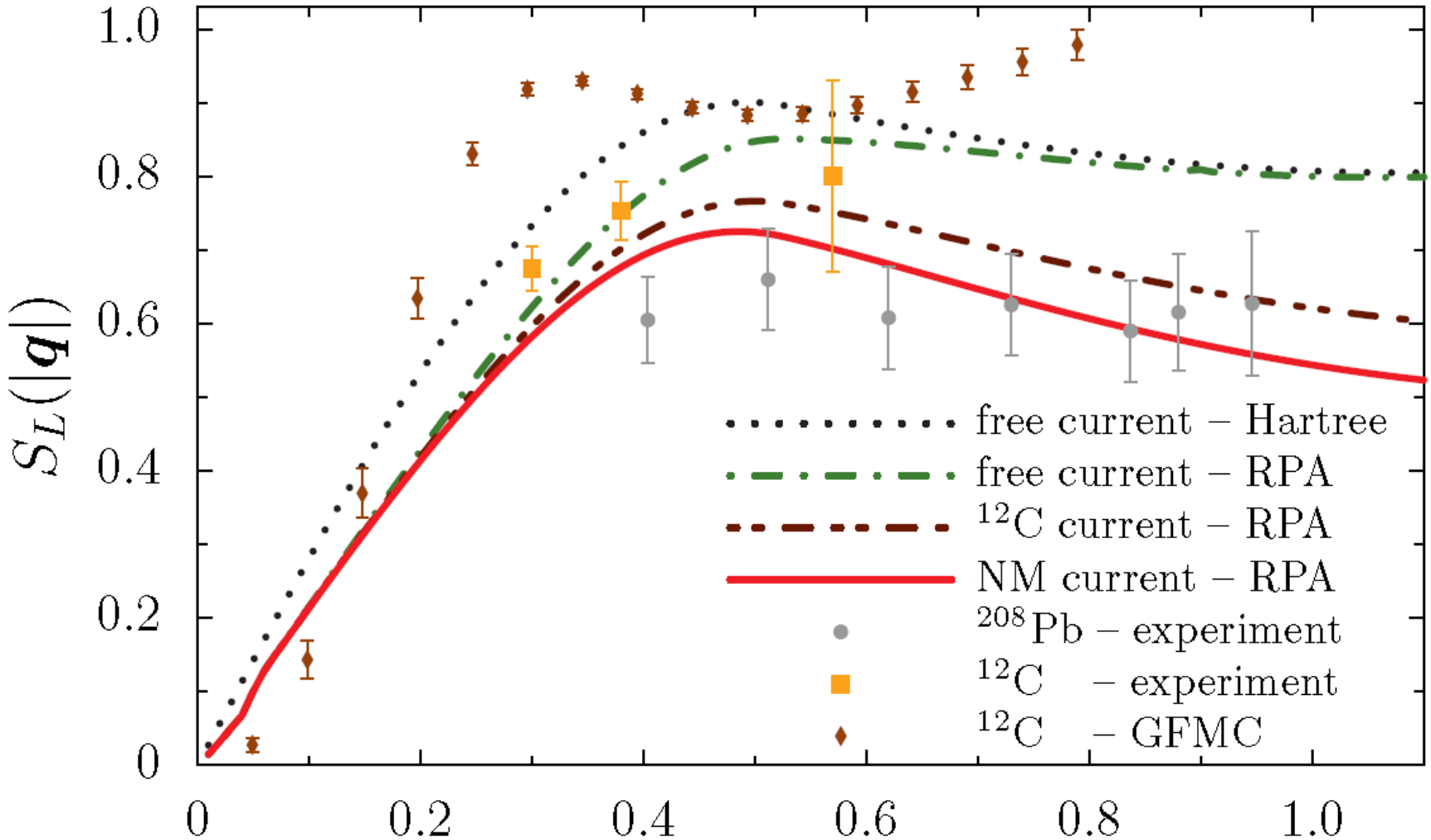
**RPA correlations repulsive**
**Significant reduction in Response Function from modification of bound-nucleon**




**Cloët, Bentz & Thomas ( arXiv: this week)**

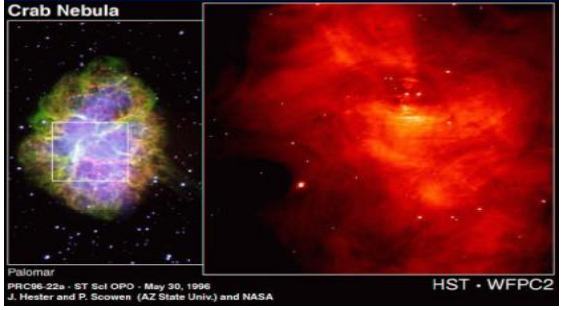
# Comparison with Unmodified Nucleon & Data




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

**Data: Morgenstern & Meziani**
**Calculations: Cloët, Bentz & Thomas (arXiv: this week)**

# Summary




- Relativity is essential
- Intermediate attraction in NN force is STRONG 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 0.5% 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)
- Await new data:
  - Response Functions & Coulomb sum rule (soon)
  - Isovector EMC effect; spin EMC etc....

# Special Mentions……

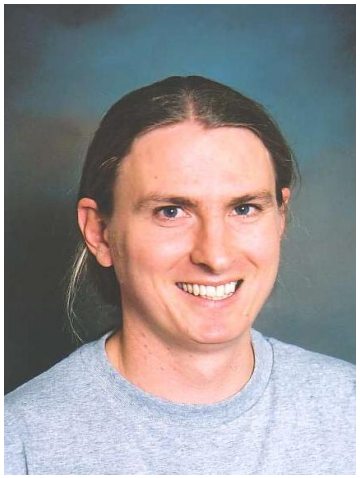

Guichon

Stone

Saito

Tsushima

Bentz



Cloët


We look forward to welcoming delegates to
Adelaide, Australia for INPC 2016
September 11-16 2016
http://www.physics.adelaide.edu.au/cssm/workshops/inpc2016/
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

# 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**