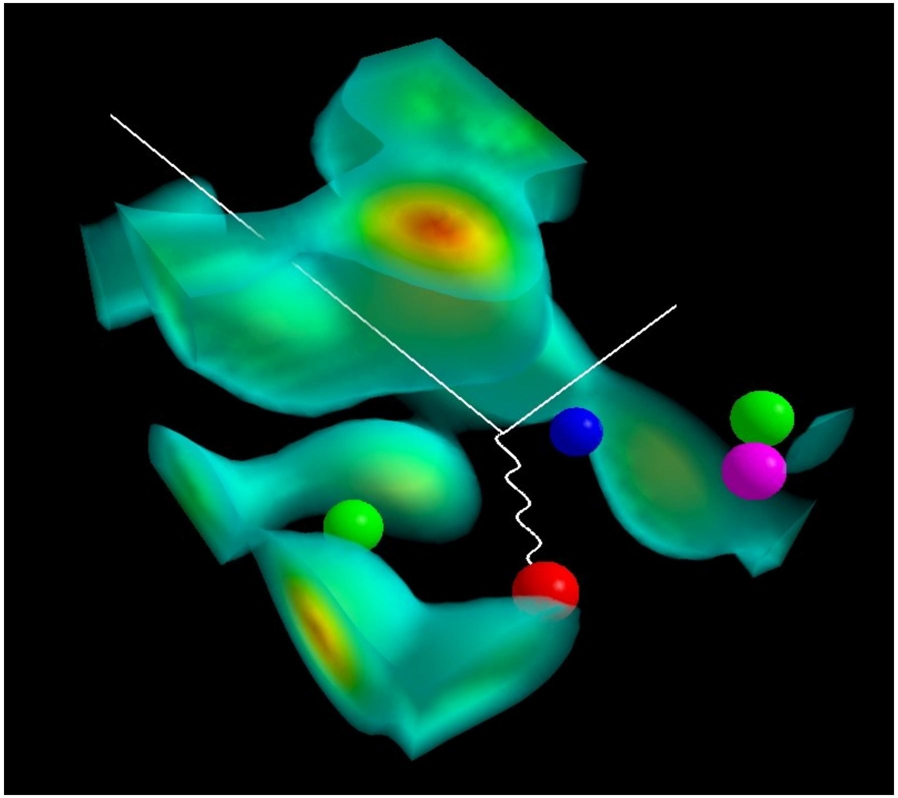
New Developments in Low Energy QCD



Anthony W. Thomas

International Conference on Exotic Atoms and Related Subjects
Stefan-Meyer-Institute for Subatomic Physics, Wien
15th September 2021

Outline

I. New Insight into the Quark Model
- The Λ(1405) IS a Kbar-N bound state
- The Roper IS generated by πN-σN-πΔ rescattering
- The Quark Model is not so bad!

II. Kaonic H and D

III. Nuclei from Quarks
- 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

Spectroscopy

- how do excited states emerge from QCD ?
- what are the fundamental degrees of freedom ?
- Lattice QCD provides extremely valuable information

Resonances are very complicated − and the lattice is not

- **Everything is stable – an eigenstate of the QCD Hamiltonian**

- **Whereas real resonances decay like crazy.....**

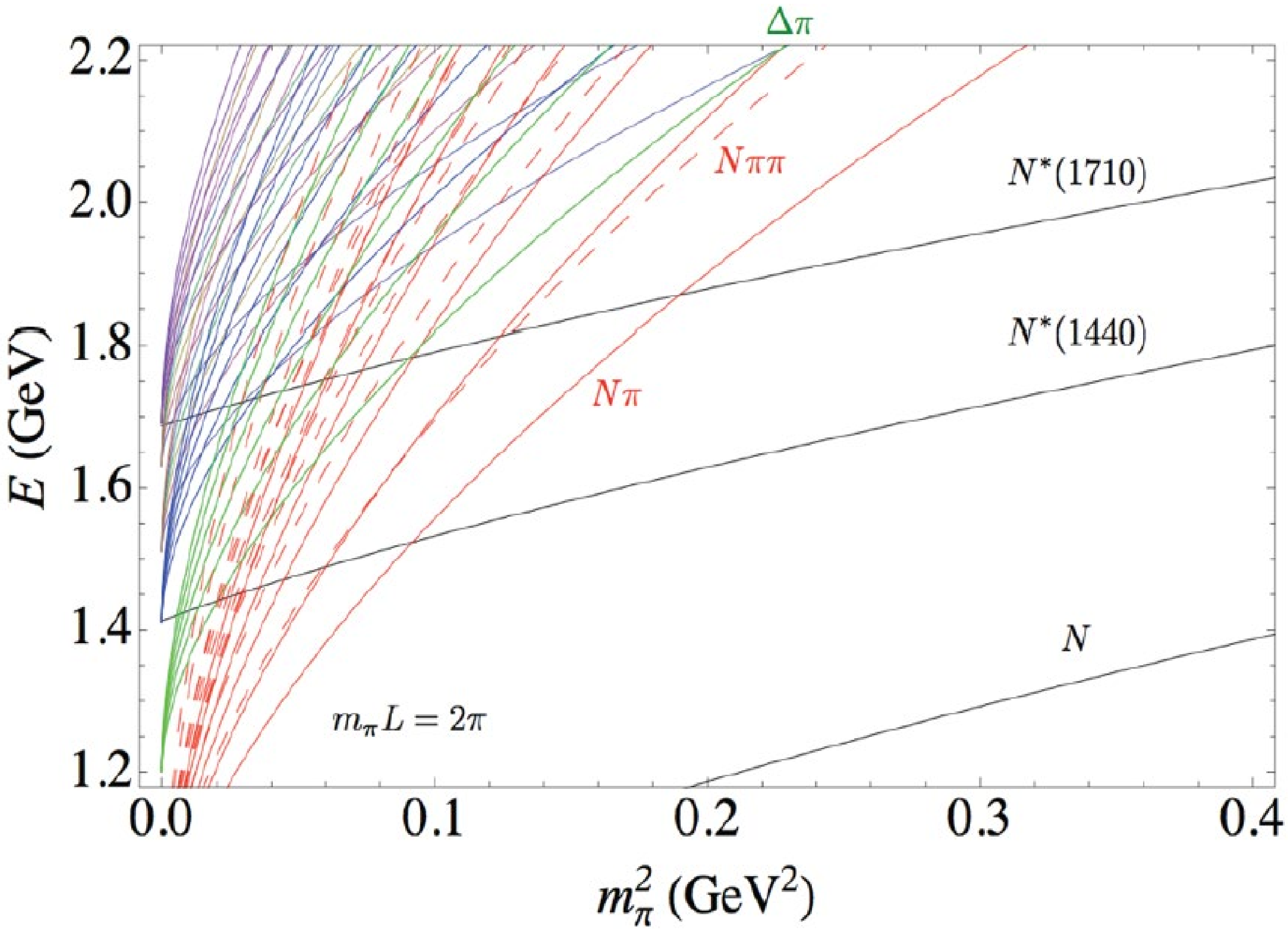
- **Lüscher has a method to derive phase shifts at discrete energies when there is one open channel**

- **That approach has been generalized to coupled channels by Hansen and Sharpe (Phys.Rev. D86 (2012) 016007) and Lellouch and Lüscher (Comm.Math.Phys., 219 (2011) 31) BUT it becomes very complicated**

Interesting cases have many open channels

– at least at realistic quark masses

In General: Multiple open channels



and then there is: σN, ωN, ρN etc....

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The Λ(1405)

- **50 years after speculation by Dalitz *et al*., we have unambiguous evidence that it is a Kbar-N bound state!**

- **Rather than the Lüscher method we apply Hamiltonian Effective Field Theory**
  - **shown to be equivalent for phase shifts***
  - **BUT also provides information on eigenstates**

- **Carry out a Hamiltonian analysis of lattice data**

- **Examine the strange magnetic form factor of Λ(1405)**

* Wu et al., Phys. Rev. C 90 (2014) 5, 055206

First calculation after QCD incorporating chiral symmetry

PHYSICAL REVIEW D VOLUME 31, NUMBER 5 1 MARCH 1985

S-wave meson-nucleon scattering in an SU(3) cloudy bag model

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(Received 8 June 1984)

The cloudy bag model (CBM) is extended to incorporate chiral SU(3)×SU(3) symmetry, in order to describe S-wave KN and $\bar{K}N$ scattering. In spite of the large mass of the kaon, the model yields reasonable results once the physical masses of the mesons are used. We use that version of the CBM in which the mesons couple to the quarks with an axial-vector coupling throughout the bag volume. This version also has a meson-quark contact interaction with the same spin-flavor structure as the exchange of the octet of vector mesons. The present model strongly supports the contention that the $\Lambda^*(1405)$ is a $\bar{K}N$ bound state.

Reached a similar conclusion

But now we can use QCD itself

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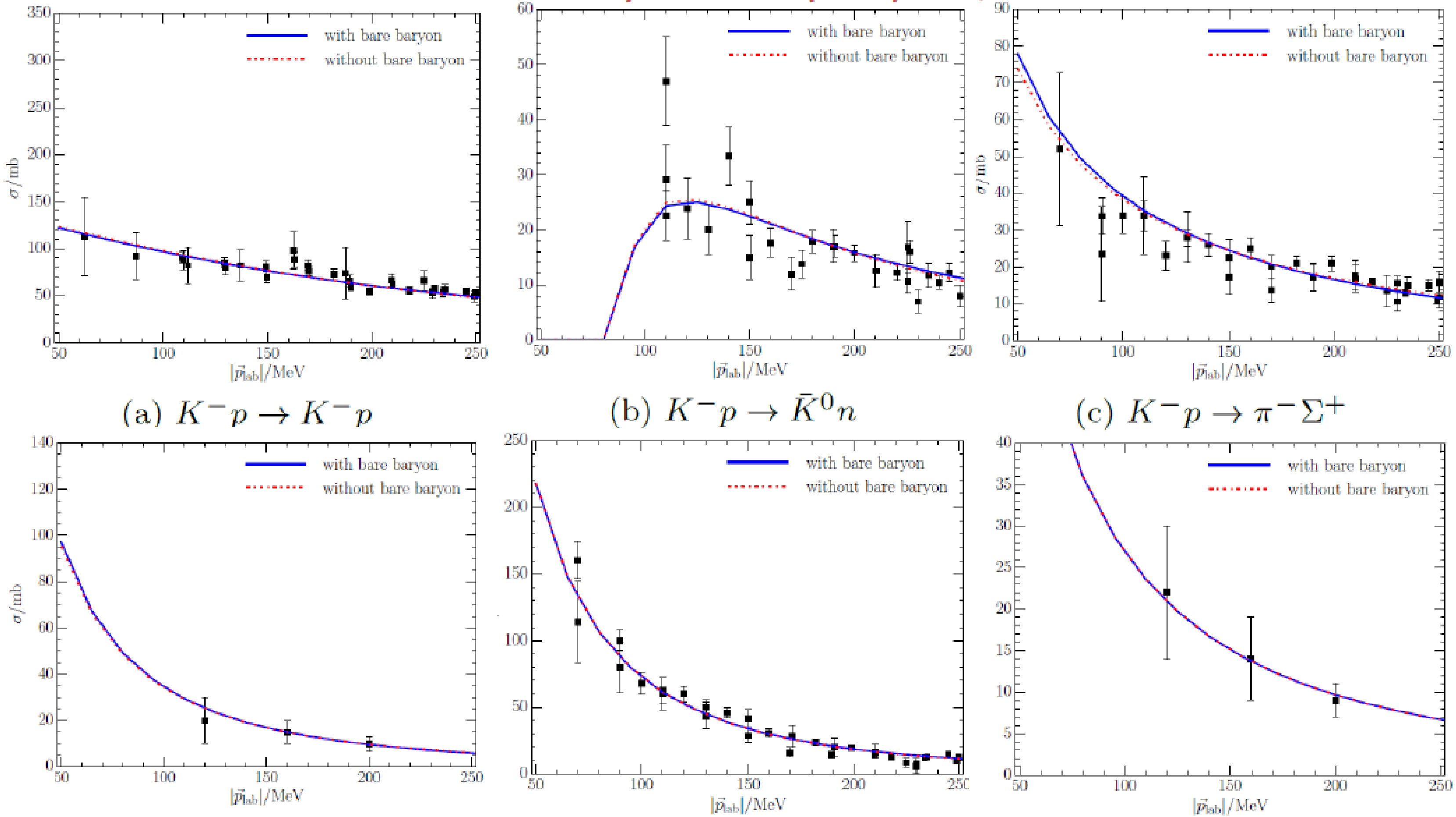
Hamiltonian fits existing data

Zhan-wei Liu etc. Phys.Rev. D95 (2017) no.1, 014506



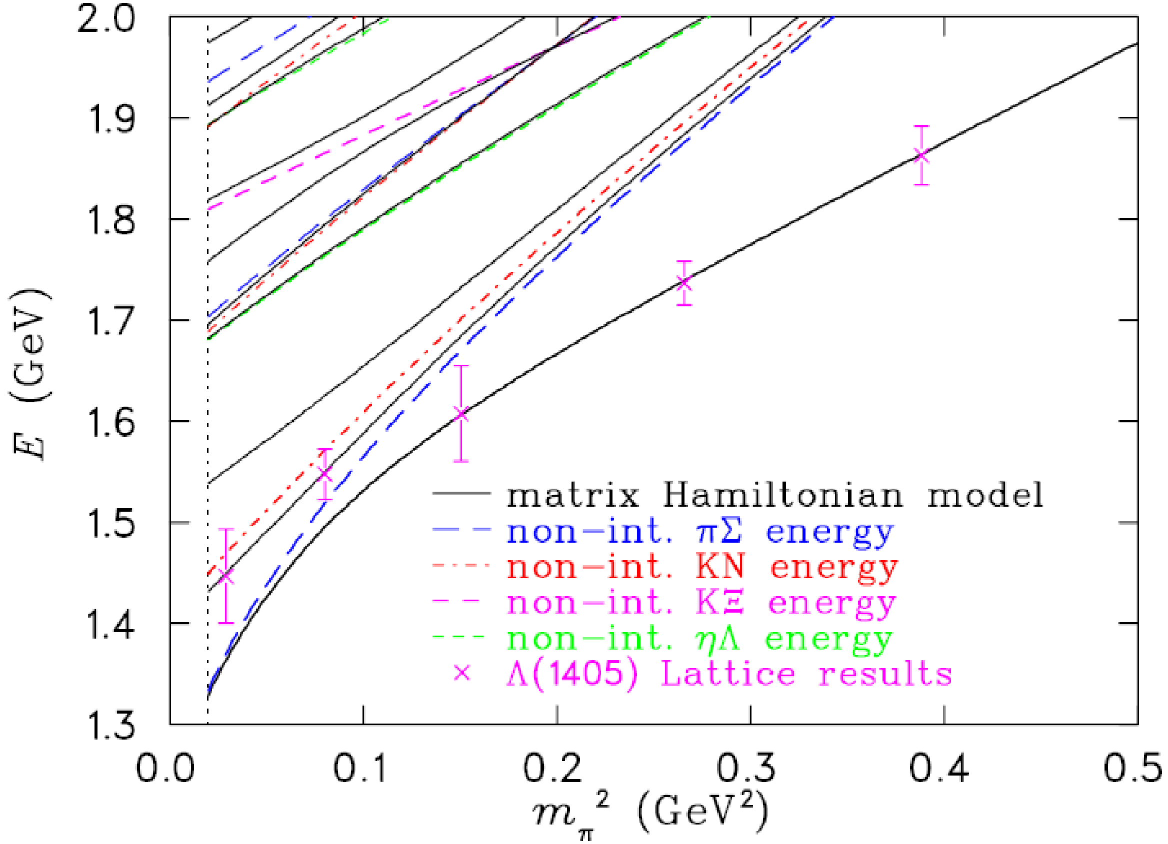
(a) $K^-p \to K^-p$ (b) $K^-p \to \bar{K}^0 n$ (c) $K^-p \to \pi^-\Sigma^+$

(d) $K^-p \to \pi^0\Sigma^0$ (e) $K^-p \to \pi^+\Sigma^-$ (f) $K^-p \to \pi^0\Lambda$

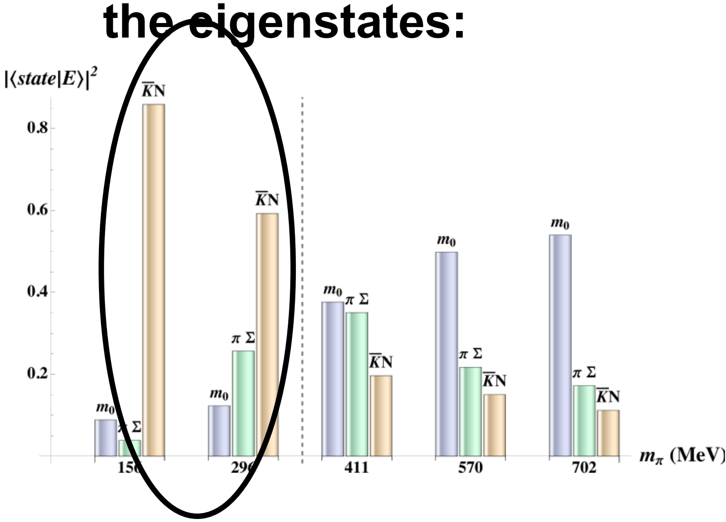
Include πΣ, KbarN, ηΛ and KΞ channels
Similar work by Valencia, Bonn, Jlab and other groups

Low lying negative parity state : Λ(1405)

Clear evidence that it is a Kbar-N bound state



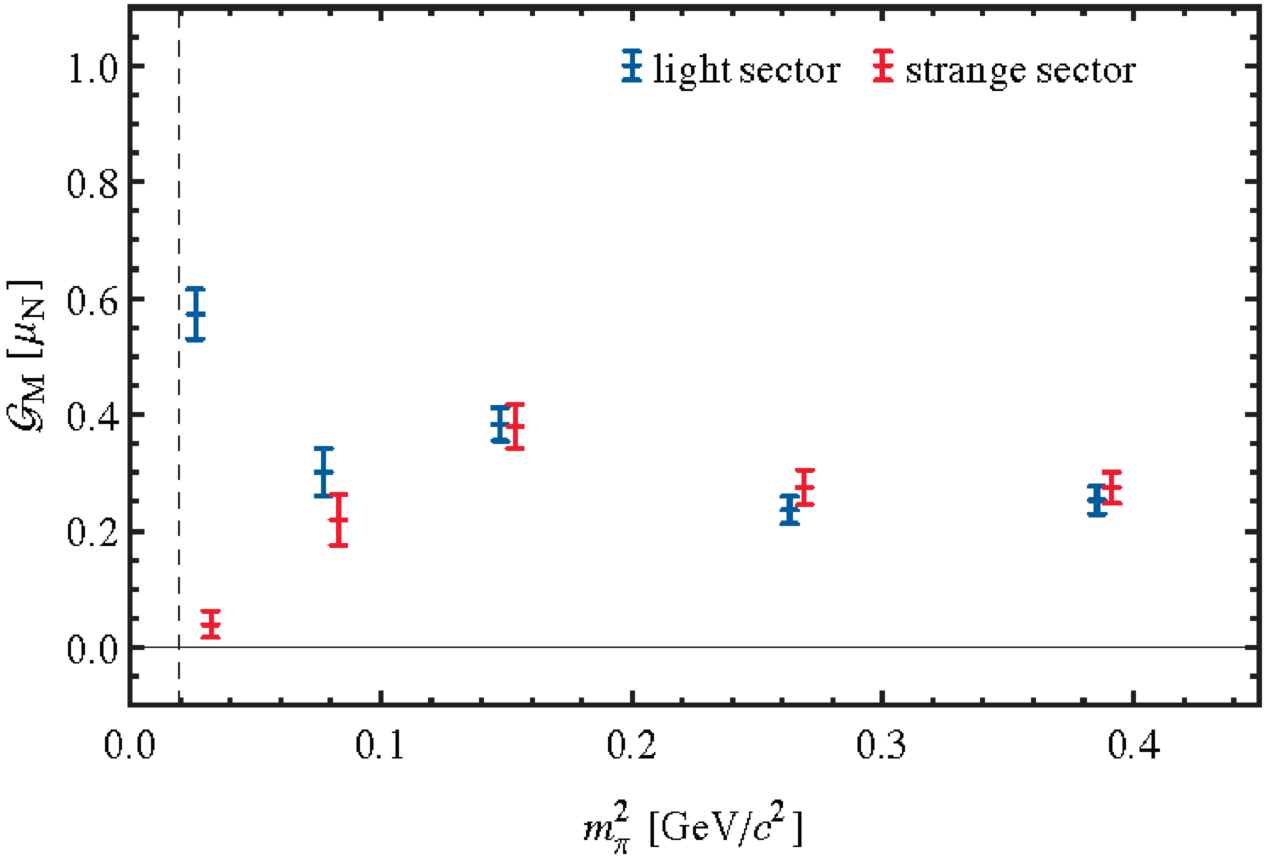
Hamiltonian approach allows one to examine the eigenstates:



Hall, Leinweber, Menadue, Young, AWT – Phys. Rev. Lett. 114 (2015) 13

Lattice Magnetic Form Factor Calculations

- **Calculation of the individual quark contributions to the magnetic form factor confirms that it is a Kbar-N bound state**



Only an L=0 Kbar-N state gives vanishing strange moment

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Hall *et al.*, Phys. Rev. *D* 95 (2017) 5, 054510

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Note that Lattice QCD allows us

to study hadron structure IN QCD as a

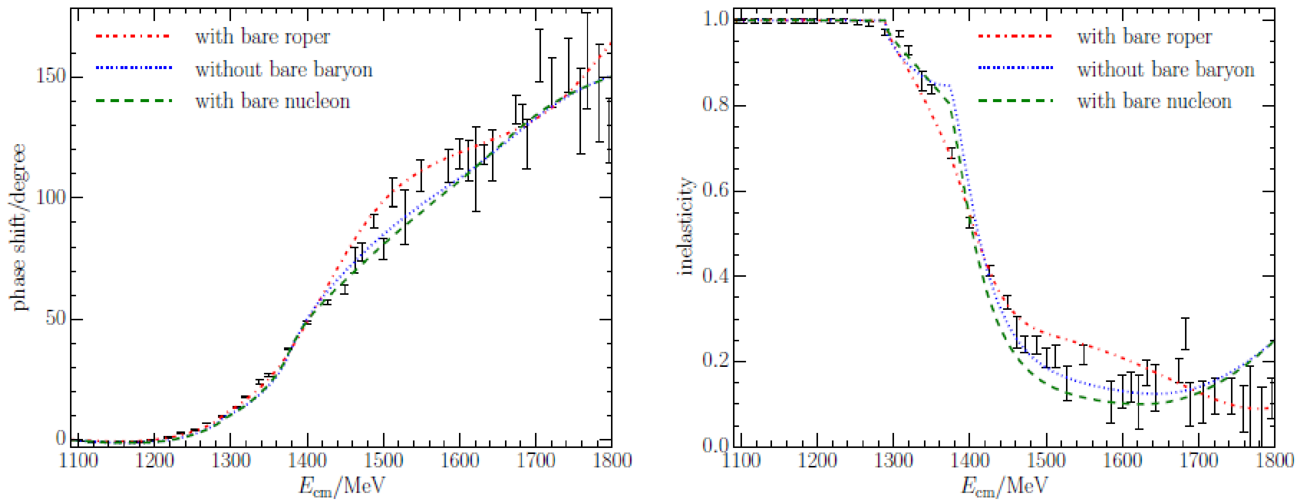
function of quark mass – a powerful tool

Roper Resonance

Again this has <u>long been a challenge for the quark model</u>, as it is the 1st positive parity excited state and lies <u>below</u> the N(1535), the 1st negative parity state

Bare Roper Case: $m_0 = 2.03$ GeV

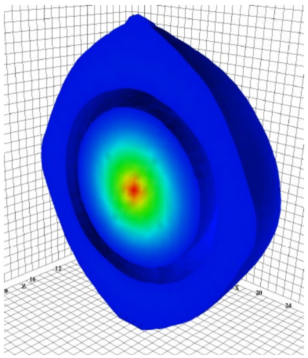
- Consider πN, $\pi\Delta$ and σN channels, dressing a bare state.
- Fit to phase shift and inelasticity

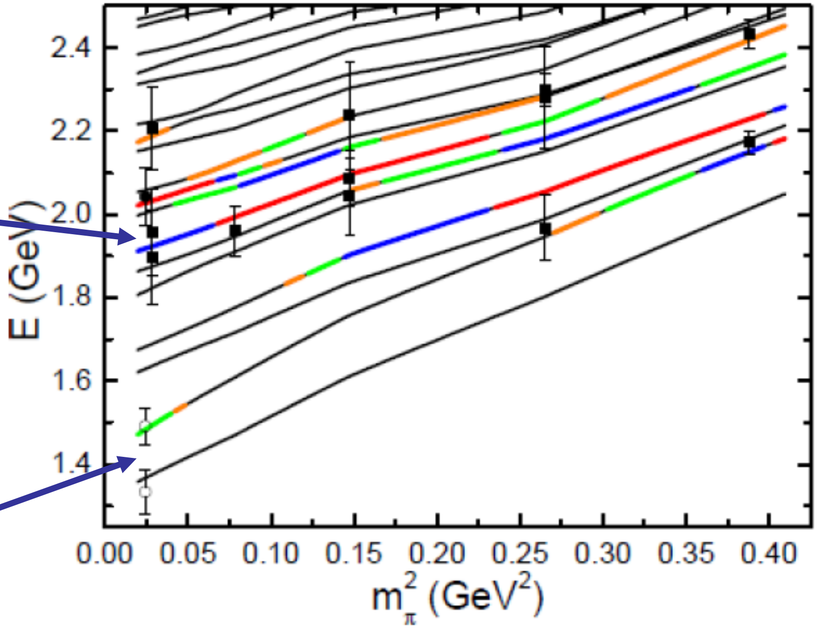


- Fit yields a pole at 1380 $- i\,87$ MeV.
- Compare PDG estimate $1365 \pm 15 - i\,95 \pm 15$ MeV.

Comparison of HEFT Results with Lattice Energy Levels

- **Blue indicates high "bare state" (i.e. 3-quark) content. This matches the lowest state found with a 3-quark interpolating field**





- **Lattice calculations of Lang et al., Phys. Rev. D 95, 014510 (2017), using baryon-meson interpolating fields, especially Nσ**

- **Matched by Hamiltonian levels but with little or no 3-quark content**

The first scenario with a bare state for P11 around the pole at 2.0 GeV can fit both Lattice data and experimental data well, it indicates that N*(1440) seems a molecule state, and first radial excitation of nucleon should be around 2.0 GeV.

Wu et al., Phys. Rev. D 97 (2018) 9, 094509

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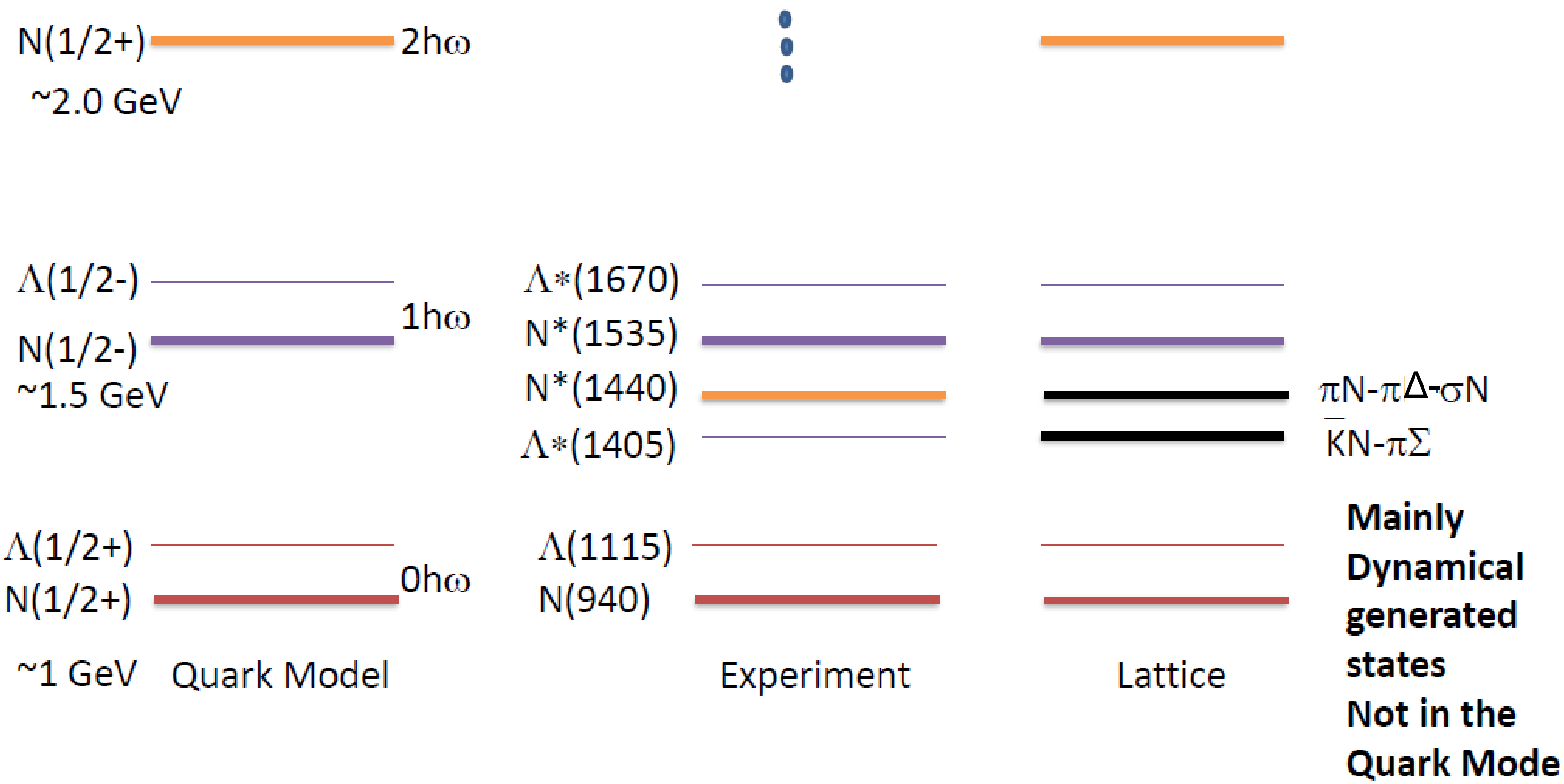
Clear conclusion is that the Roper is dynamically generated by coupling to the Nσ and Δπ channels

Once the nature of key states becomes clear

the quark model makes sense



Test Λ(1405) Solution in Kaonic Atoms

Using the Hamiltonian discussed earlier (with Λ(1405) a Kbar-N bound state) compare with the kaonic hydrogen binding found by the SIDDHARTA experiment*

$$\epsilon_{1S}^{p} = 283 \pm 36(\text{stat}) \pm 6(\text{sys}) \text{ eV},$$
$$\Gamma_{1S}^{p} = 541 \pm 89(\text{stat}) \pm 22(\text{sys}) \text{ eV}$$

The result is excellent agreement with the calculation:

$$a_{K^-n} = 0.27 + 0.52\,i \text{ fm}, \qquad a_{\bar{K}^0 n} = -0.75 + 0.80\,i \text{ fm},$$
$$a_{\bar{K}^0 n \to K^- p} = 1.02 - 0.28\,i \text{ fm}.$$

which yields (Liu *et al.*, Phys. Lett. B808 (2020) 135652)

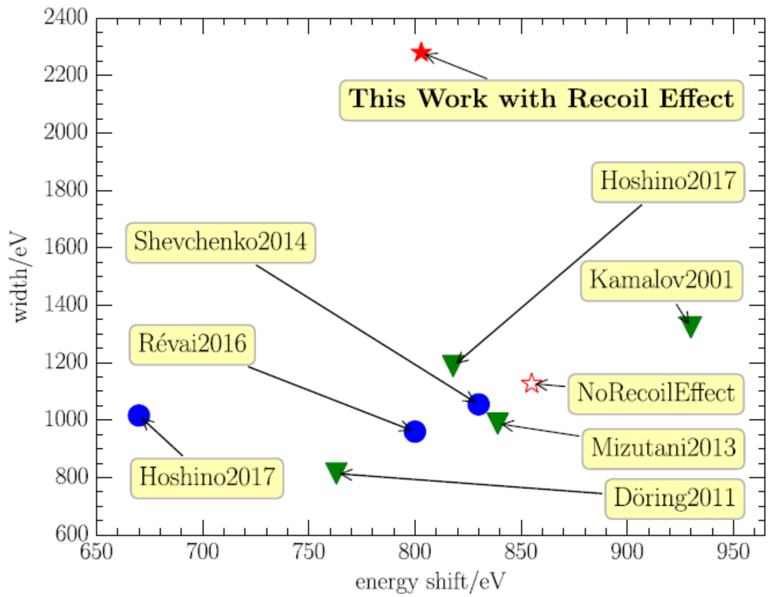
$$\epsilon_{1S}^{p} = 307 \text{ eV}, \qquad \Gamma_{1S}^{p} = 533 \text{ eV}$$

* **Bazzi *et al.*, Nucl. Phys. A881 (2012) 88**

Kaonic Deuterium

This was also applied to kaonic deuterium using an approximate solution of the Faddeev equations

Result was a surprisingly large width



Z.-W. Liu et al. / Physics Letters B 808 (2020) 135652

Result challenged by Barnea and collaborators…
Await results from experiments of Zmeskal, Pochodzalla *et al*. at J-PARC and Frascati

A new paradigm for nuclear structure

– what is the atomic nucleus?

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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!!**

Just one example of very large scalar mean-fields

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 C42 (1990) 1965

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., 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)

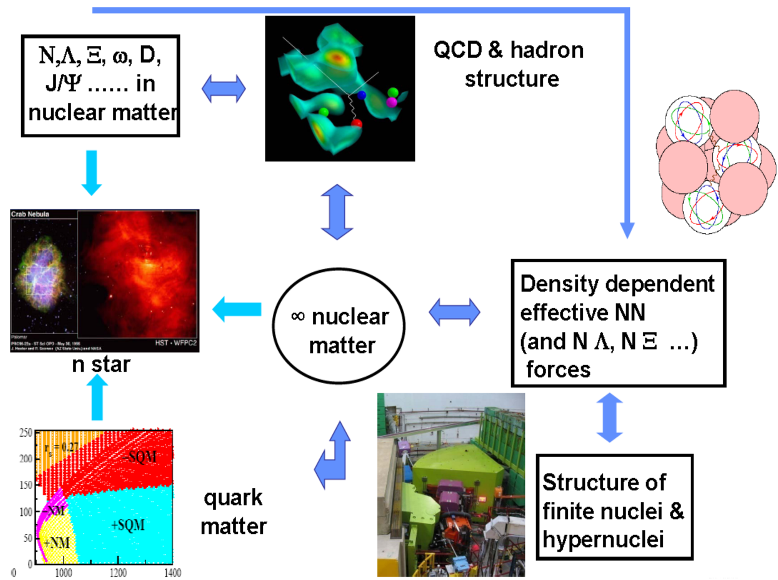
- **Start with quark model (MIT bag/NJL...) for all hadrons**

- **Introduce a relativistic Lagrangian with σ, ω and ρ mesons coupling to non-strange quarks**

- **Hence, initially <u>only 4 parameters</u>**

  $(m_\sigma, g^{\sigma,\omega,\rho}_q)$

  – determine by fitting to:
  ρ_0, E/A and symmetry energy
  – same in dense matter & finite nuclei



- **Must solve <u>self-consistently</u> for the internal structure of baryons in-medium ≡ 3-body forces with NO new parameters**

Application to nuclear structure

QMC π3

- **Just 5 parameters***: m_σ , quark couplings to σ, ω and ρ and λ_3 - the strength of σ^3 term

- Tensor term included:

$$H^J_{\sigma,\omega,\rho} = \left(\frac{G_\sigma(1-d\,v_0)^2}{4m_\sigma^2} - \frac{G_\omega}{4m_\omega^2}\right)\sum_m \vec{J}_m^2 - \frac{G_\rho}{4m_\rho^2}\sum_{m,m'} S_{m,m'}\vec{J}_m\cdot\vec{J}_{m'},$$

and

$$H^J_S = -\frac{G_\sigma - G_\omega}{16M^2}\sum_m \vec{J}_m^2 + \frac{G_\rho}{16M^2}\sum_{mm'} S_{m,m'}\vec{J}_m\cdot\vec{J}_{m'}.$$

with

$$\vec{J}_m = i\sum_{i\in F_m}\sum_{\sigma\sigma'}\vec{\sigma}_{\sigma'\sigma}\times[\vec{\nabla}\phi^i(\vec{r},\sigma,m)]\phi^{i*}(\vec{r},\sigma',m),\quad \vec{J} = \vec{J}_p + \vec{J}_n,$$

- Pairing interaction (simple BCS) derived in the model

$$V^{\mathrm{QMC}}_{\mathrm{pair}} = -\left(\frac{G_\sigma}{1+d'G_\sigma\rho(\vec{r})} - G_\omega - \frac{G_\rho}{4}\right)\delta(\vec{r}-\vec{r}\,')$$

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*cf. Over 20 in FRDM and typically 16 (11+5) in Skyrme forces

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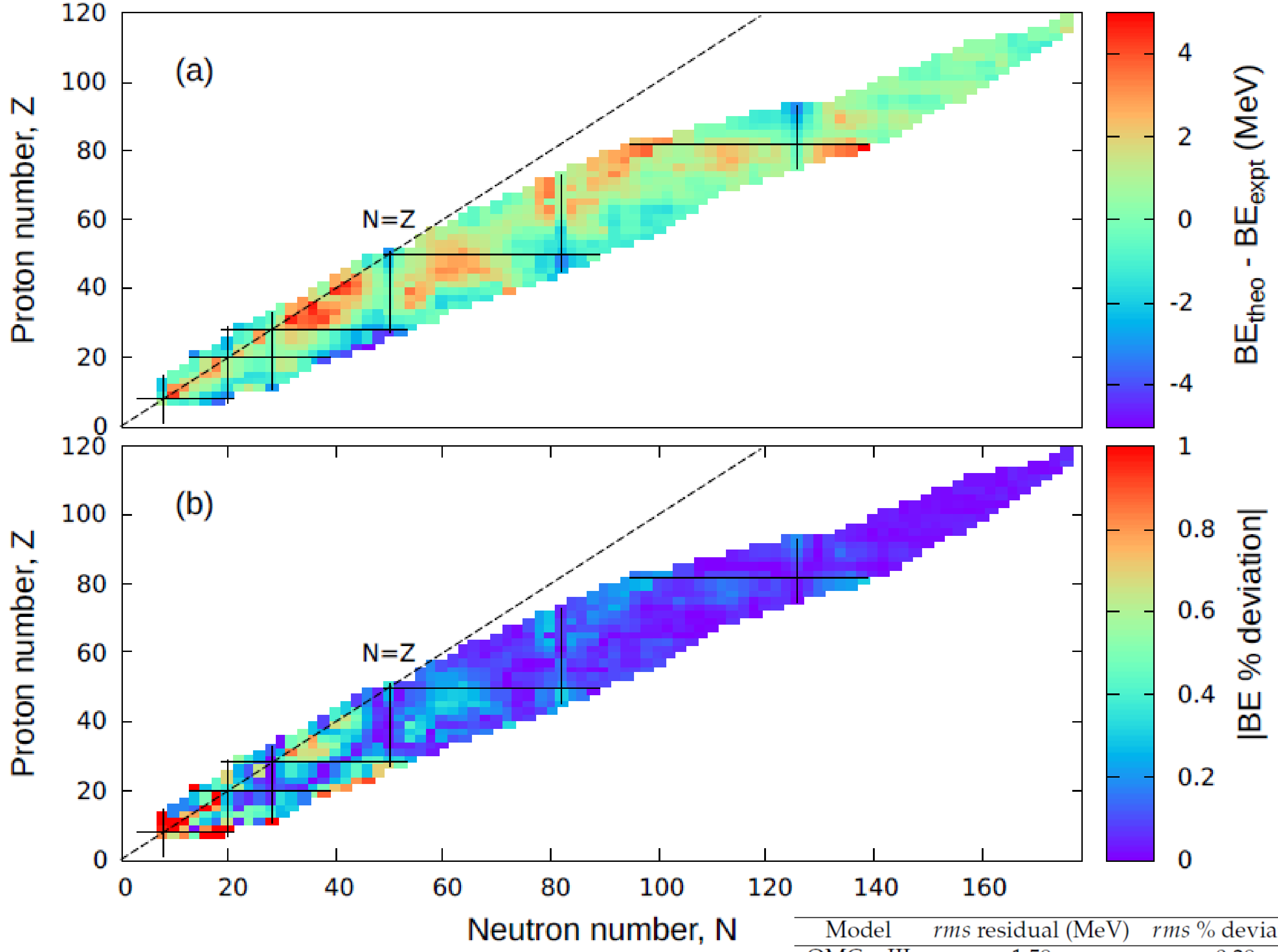
Binding Energies – All Known Even-Even Nuclei



Model	*rms* residual (MeV)	*rms* % deviation
QMCπ-III	1.59	0.29
QMCπ-II	2.34	0.39
QMCπ-I	2.78	0.50
QMC-I	3.84	0.69
SV-min	3.64	0.38
UNEDF1	2.06	0.55
DD-MEδ	2.41	0.42
FRDM	0.89	0.18

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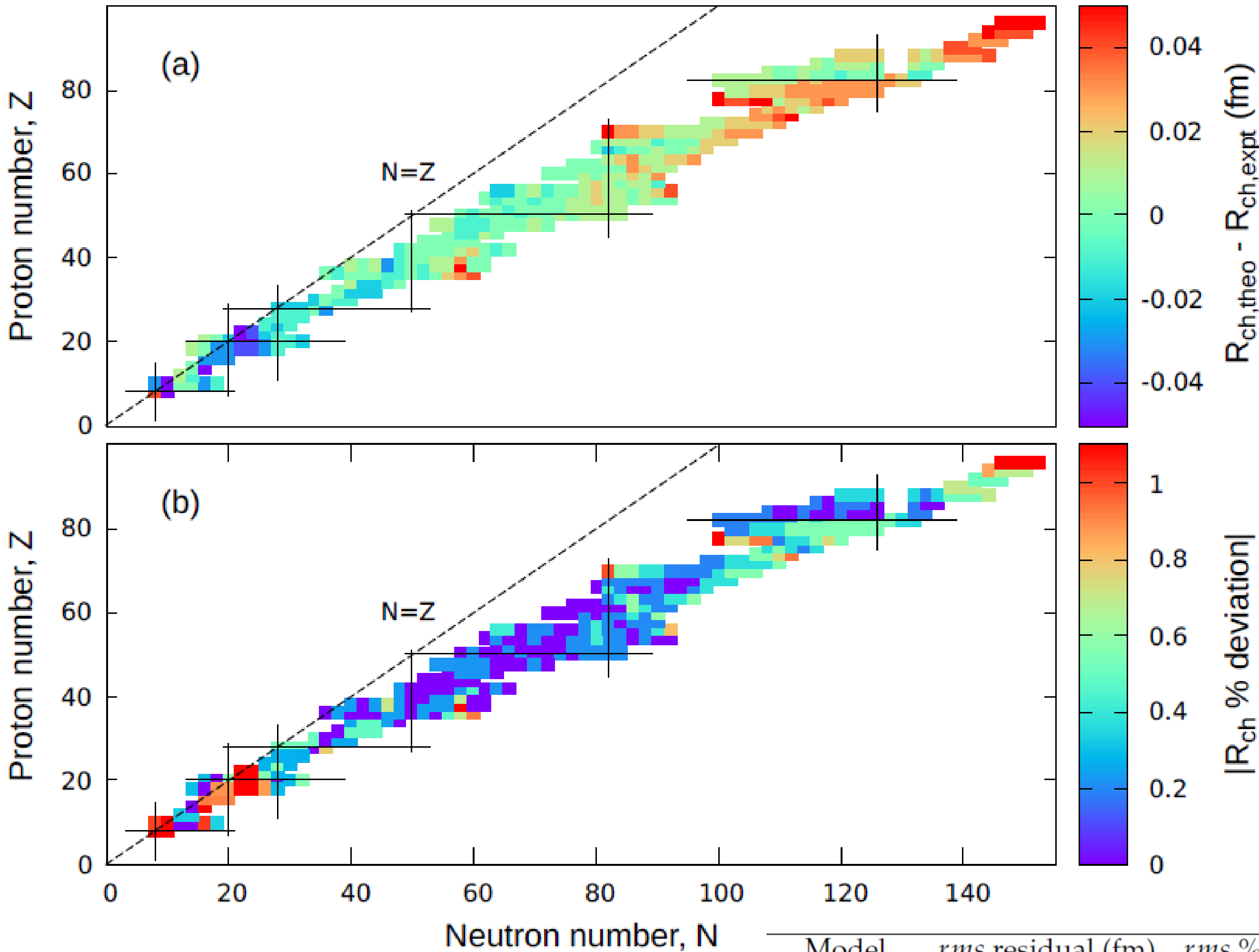
Charge Radii



Model	*rms* residual (fm)	*rms* % deviation
QMCπ-III	0.024	0.50
QMCπ-II	0.029	0.66
QMCπ-I	0.028	0.65
QMC-I	0.030	0.66
SV-min	0.024	0.61
UNEDF1	0.029	0.65
DD-MEδ	0.035	0.78

Separation energies: Drip Lines

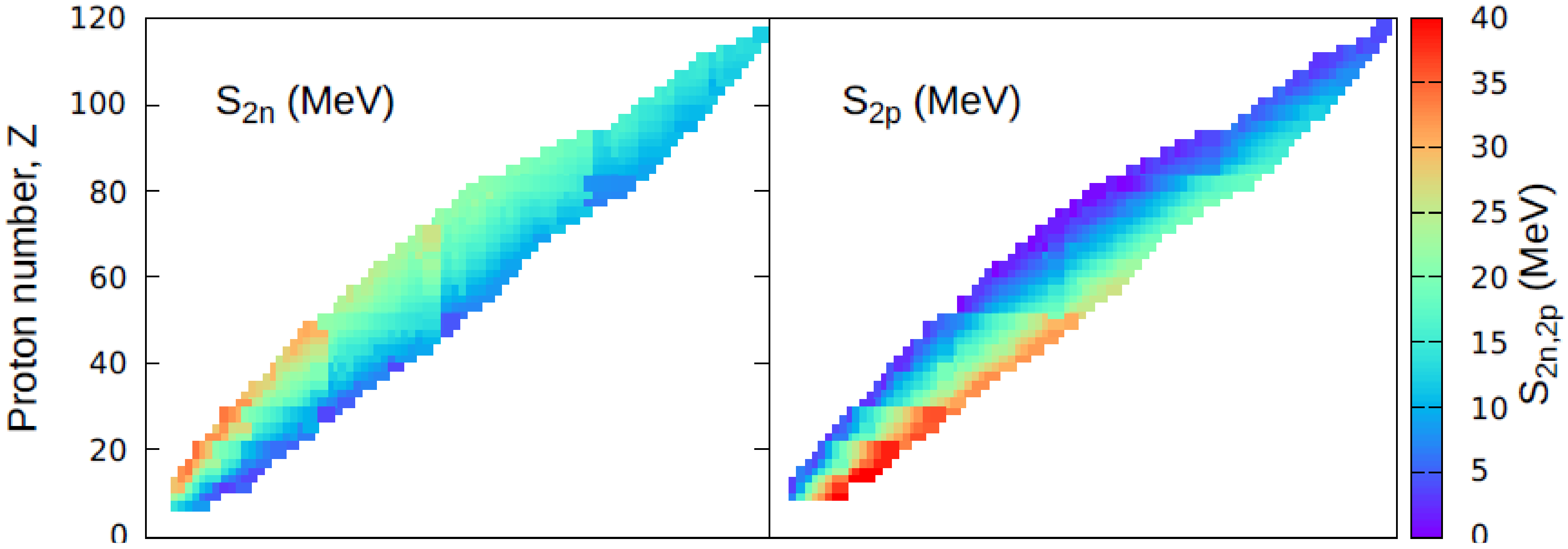


TABLE 7.3: Comparison of *rms* residuals for separation energies (in MeV) from QMC and from other nuclear models.

Model	S_{2n}	S_{2p}	δ_{2n}	δ_{2p}	Q_α
QMCπ-III	0.97	0.95	1.24	1.28	1.07
QMCπ-II	1.03	1.08	1.20	1.25	1.19
SV-min	0.77	0.82	0.87	1.00	0.79
UNEDF1	0.74	0.82	0.85	0.90	0.80
DD-MEδ	1.01	1.05	1.12	1.11	1.30
FRDM	0.50	0.55	0.61	0.75	0.61

Deformation

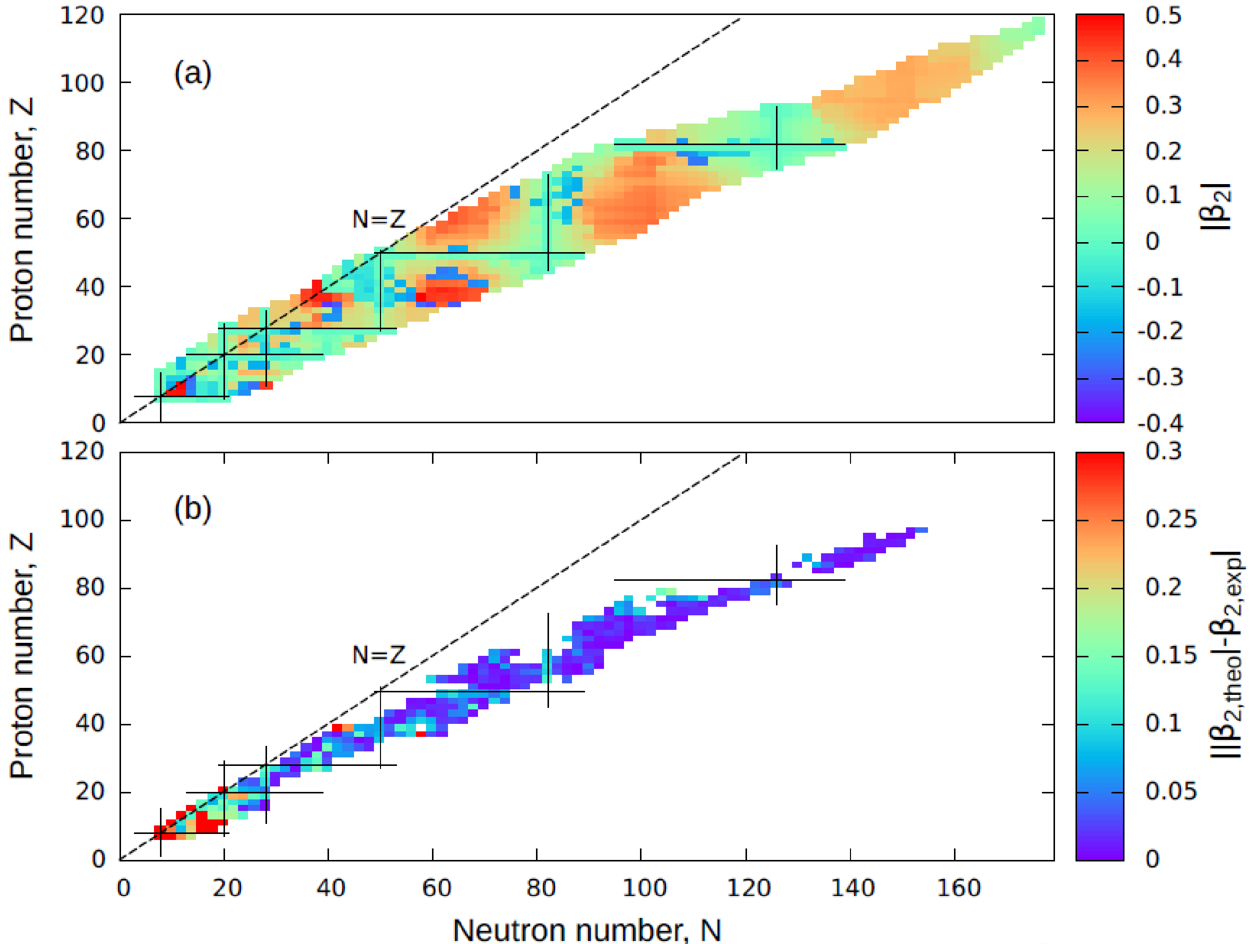


TABLE 7.4: Comparison of β_2 *rms* residuals and *rms* % deviations from QMCπ-III and from other nuclear models. There are a total of 324 even-even nuclei with available data for β_2 included for comparison.

Model	*rms* residual	*rms* % deviation
QMCπ-III	0.11	28
SV-min	0.16	59
UNEDF1	0.15	53
DD-MEδ	0.14	40
FRDM	0.11	30

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The Superheavy Region
First study:

PHYSICAL REVIEW C **100**, 044302 (2019)

Physics of even-even superheavy nuclei with $96 < Z < 110$ in the quark-meson-coupling model

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Updated and expanded here (Martinez *et al*., to be published)

Binding Energies

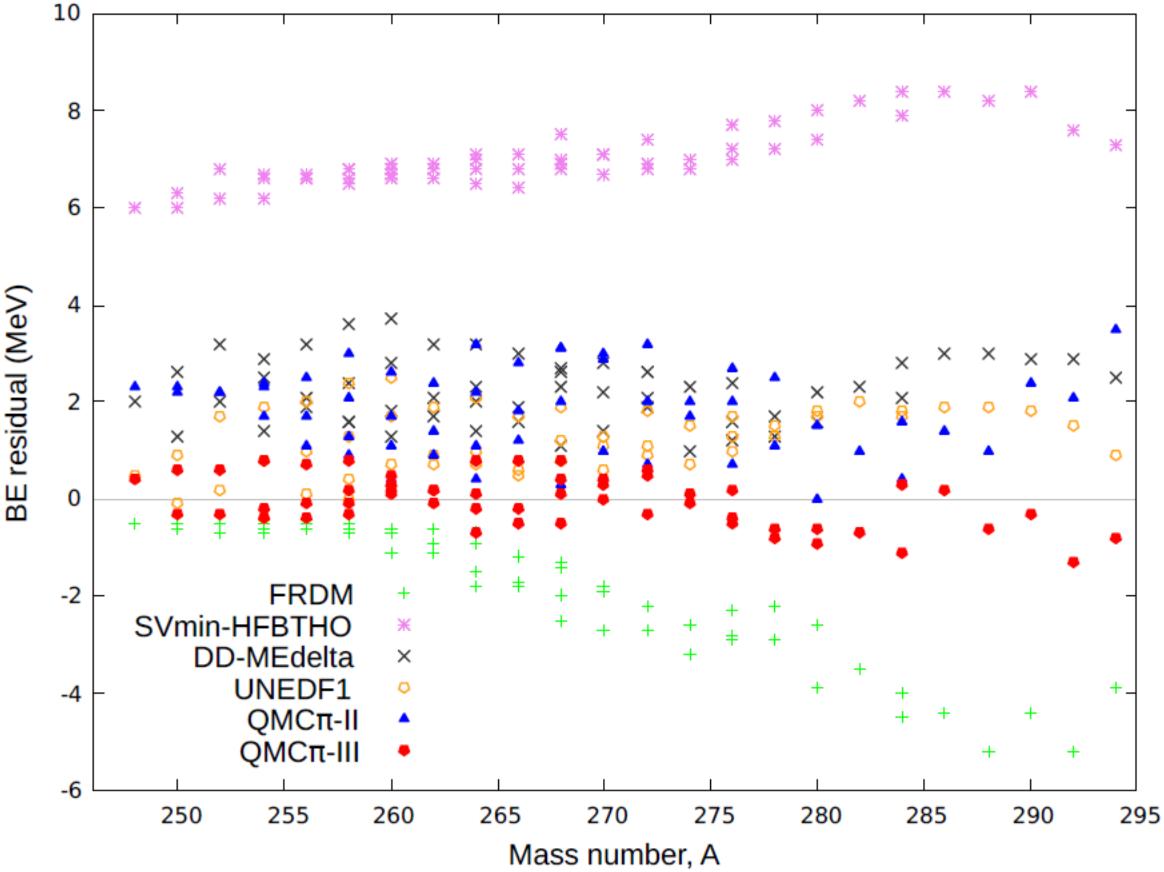

TABLE 6.1: Comparison of *rms* percent deviations and *rms* residuals from QMC and from other nuclear models for SHE with available data.

	rms % deviation	*rms* residual (MeV)
QMCπ-III	0.03	0.52
QMCπ-II [54]	0.11	2.04
QMCπ-I [53]	0.12	2.42
QMC-I [8]	0.08	1.50
FRDM [23]	0.11	2.25
SV-min [24]	0.36	6.99
UNEDF1 [28]	0.07	1.31
DD-MEδ [66]	0.12	2.28

Outstanding agreement

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Summary: Finite Nuclei

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

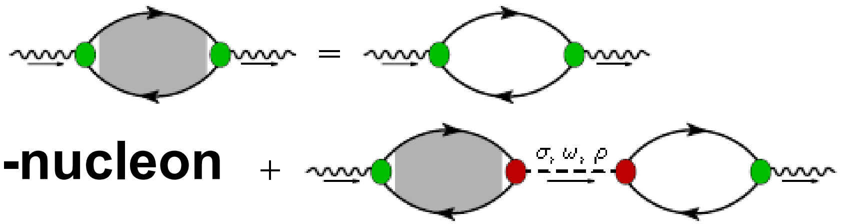
Modified Electromagnetic Form Factors In-Medium

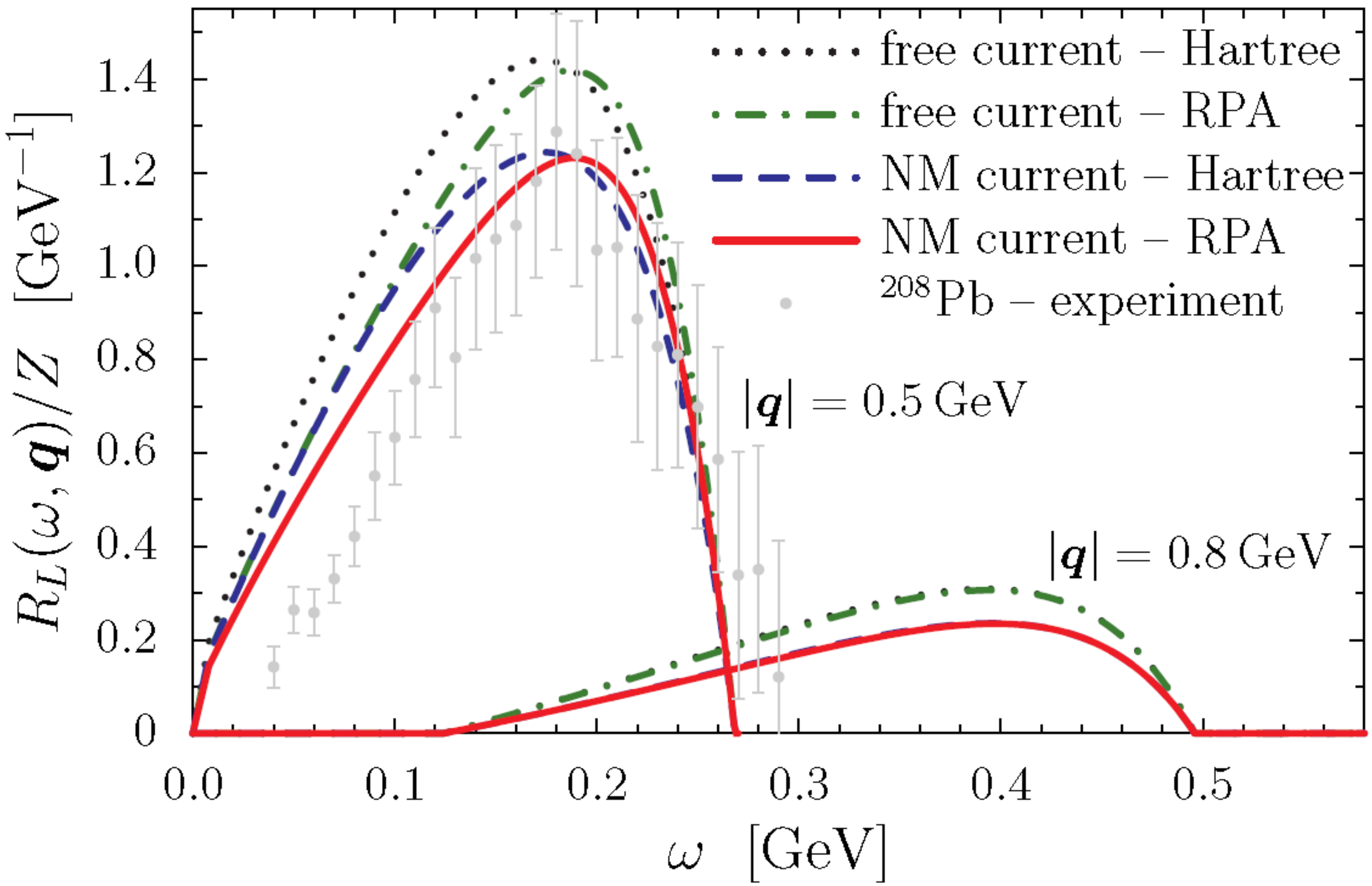
Response Function

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

RPA correlations repulsive

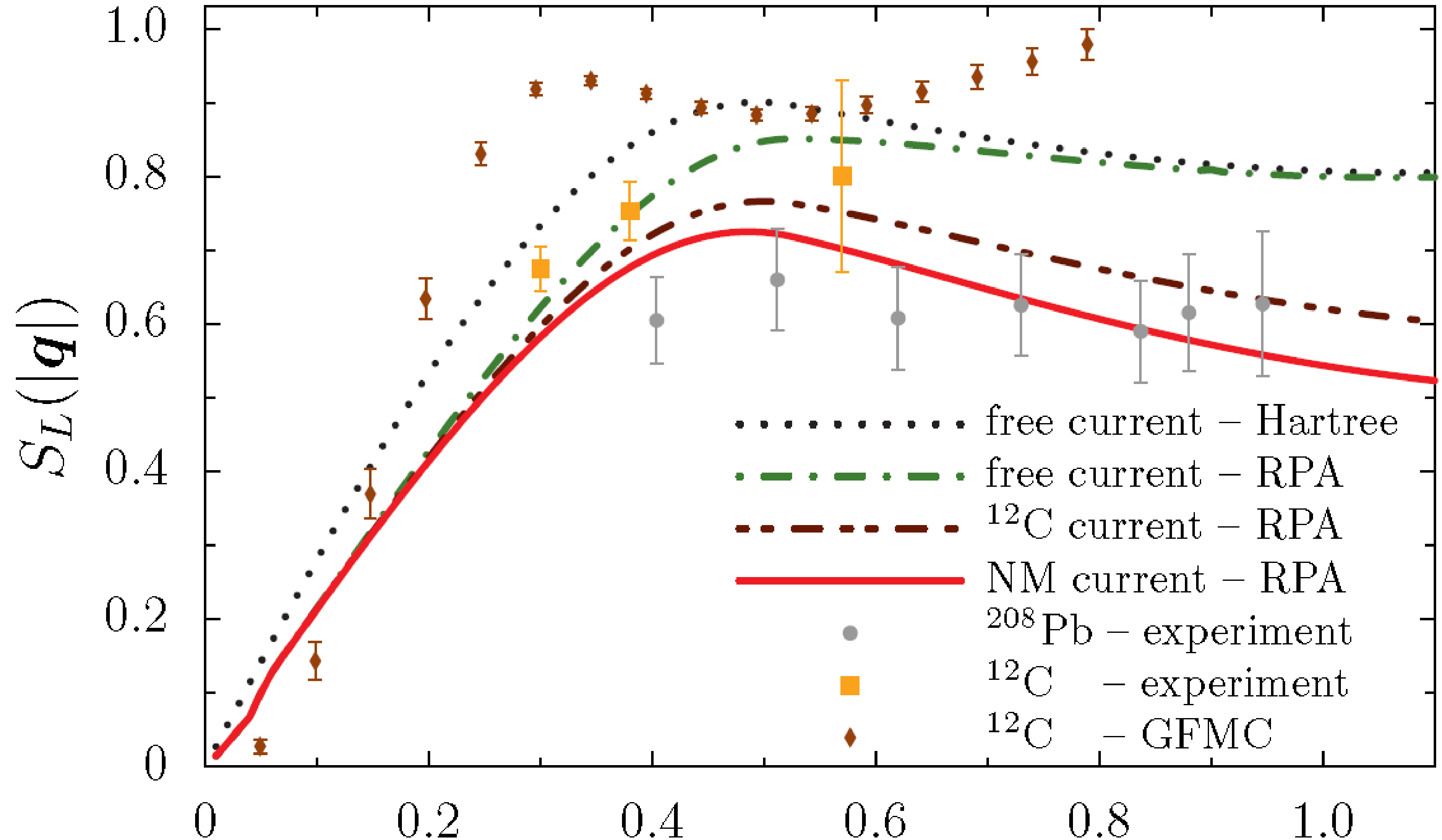
Significant reduction in Response Function from the modification of bound-nucleon





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

Comparison with Unmodified Nucleon & Data



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

Data: Morgenstern & Meziani

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

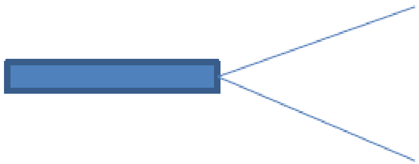
Summary

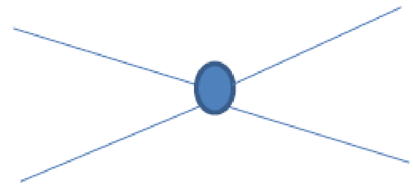
- New techniques applied to lattice QCD provide hitherto unimagined insights into hadron structure
- The quark model has new life
- Exotic atoms, e.g. Kbar and hyperon, provide valuable information
- There is much more to nuclear structure than EFT can give (powerful though it is)
- Hadron structure changes in nuclear matter: leading to a new paradigm for nuclear structure
- Experimental tests underway

N(1535) is a 3-quark state

Zhan-wei Liu etc. Phys.Rev.Lett. 116 (2016) no.8, 082004

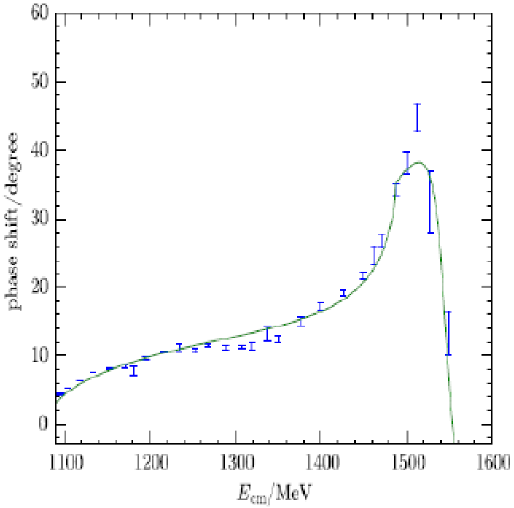
- 2 Channels: πN and ηN

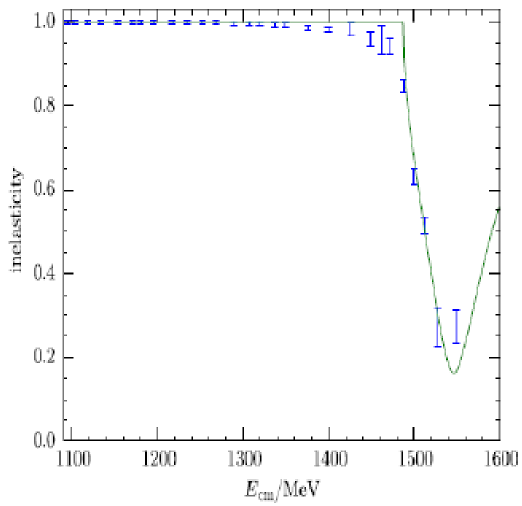




$$G_{iN}^2(k) = \left(3g_{N_0^* iN}^2/4\pi^2 f^2\right)\omega_i(k)u^2(k)$$

$$\frac{3g_{\pi N}^S \tilde{u}(k)\tilde{u}(k')}{4\pi^2 f^2}$$





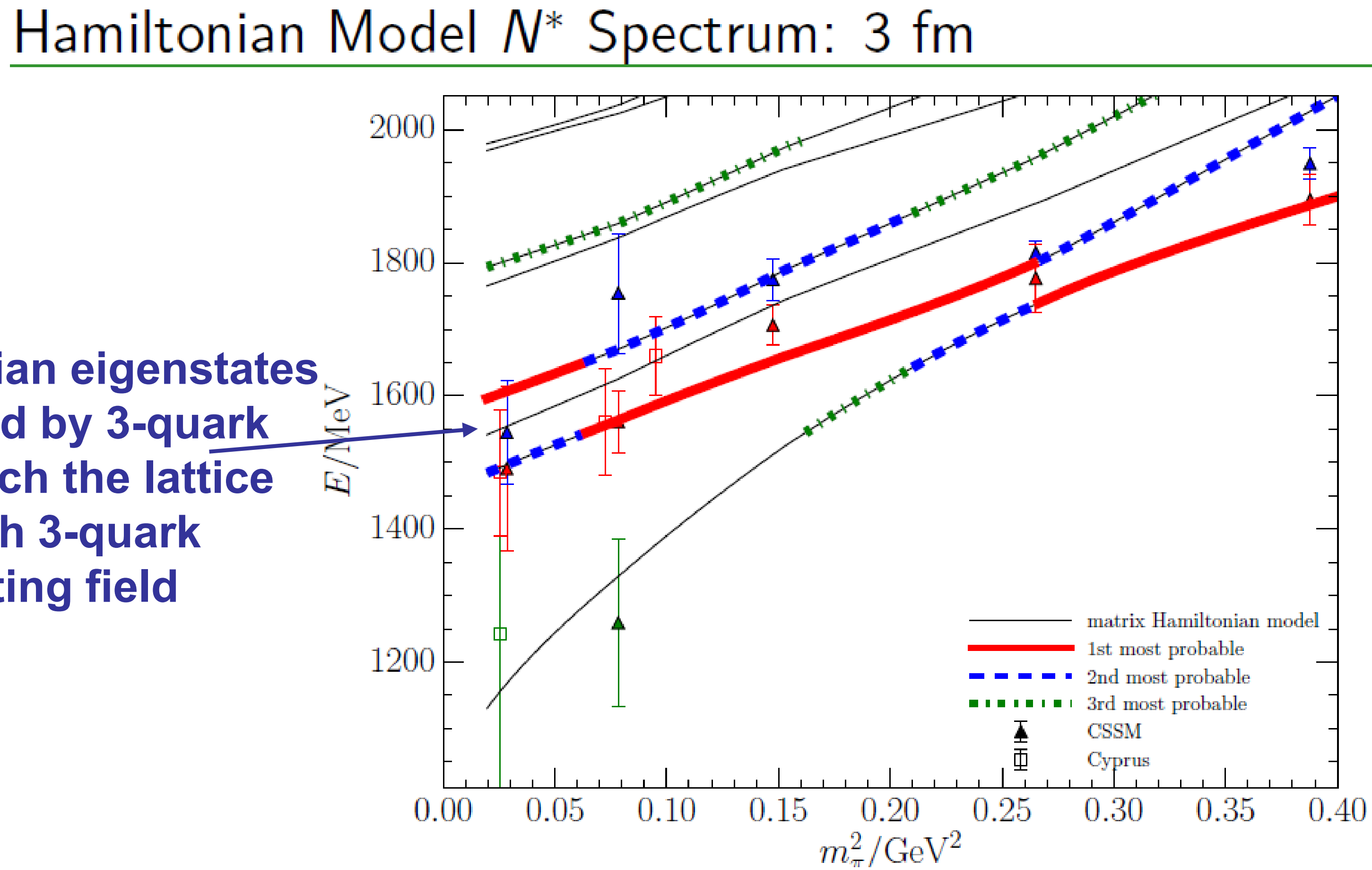
$$g_{\pi N}^S = -0.0608 \pm 0.0004$$
$$m_0 = 1601 \pm 14 \text{ MeV}$$
$$g_{N_0^*\pi N} = 0.186 \pm 0.006$$
$$g_{N_0^*\eta N} = 0.185 \pm 0.017,$$

$$\chi^2_{\text{DOF}} = 6.8$$

$$1531 \pm 29 - i88 \pm 2 \text{ MeV}$$

Liu *et al.*, PRL 116 (2016) 082004

N(1535) is a 3-quark state



Hamiltonian eigenstates dominated by 3-quark state match the lattice result with 3-quark interpolating field

Liu *et al.*, PRL 116 (2016) 082004

Special Mentions……


Guichon

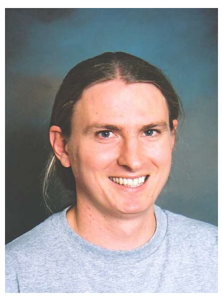

Tsushima


Saito


Stone


Krein


Matevosyan


Cloët


Whittenbury


Simenel


Bentz


Martinez


Motta


Antic


Kalaitzis

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Latest papers

- **QMC π3;**
  Martinez et al., Phys Rev C102 (2020) 034304

- **Review:**
  Guichon *et al.*, PPNP 100 (2018) 262

- **SHE:**
  Stone *et al.*, arXiv: 1901.06064

- **Systematic application to finite nuclei:**
  Stone *et al.*, Phys Rev Lett 116 (2016) 092501

Key papers on QMC

- **Many-body forces:**
  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)
  6. Guichon et al., Prog. Part. Nucl. Phys. 100 (2018) 262

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

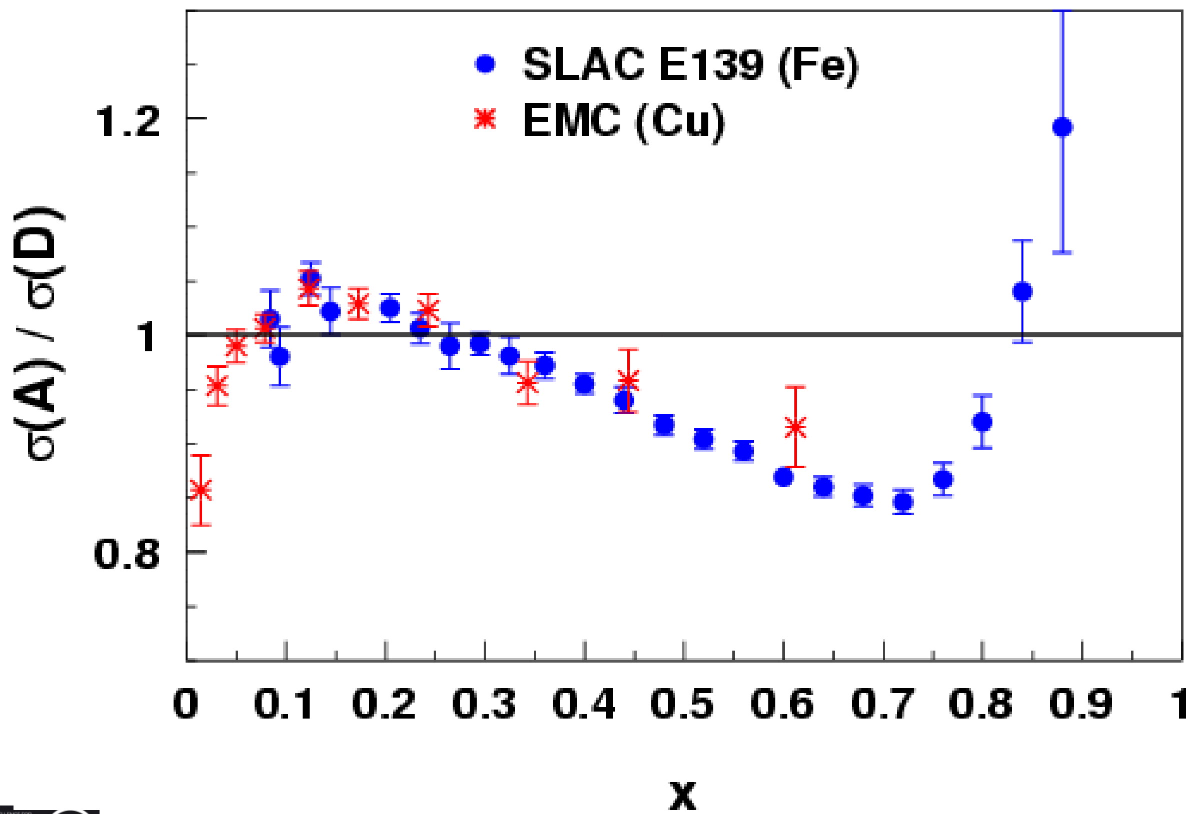
Nuclear DIS Structure Functions: The EMC Effect

To address questions like this one MUST start with a theory that quantitatively describes nuclear structure and allows calculation of structure functions

– very, very few examples.....

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)

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF 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 Bentz, 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

EMC Effect for Finite Nuclei

(There is also a spin dependent EMC effect - as large as unpolarized)

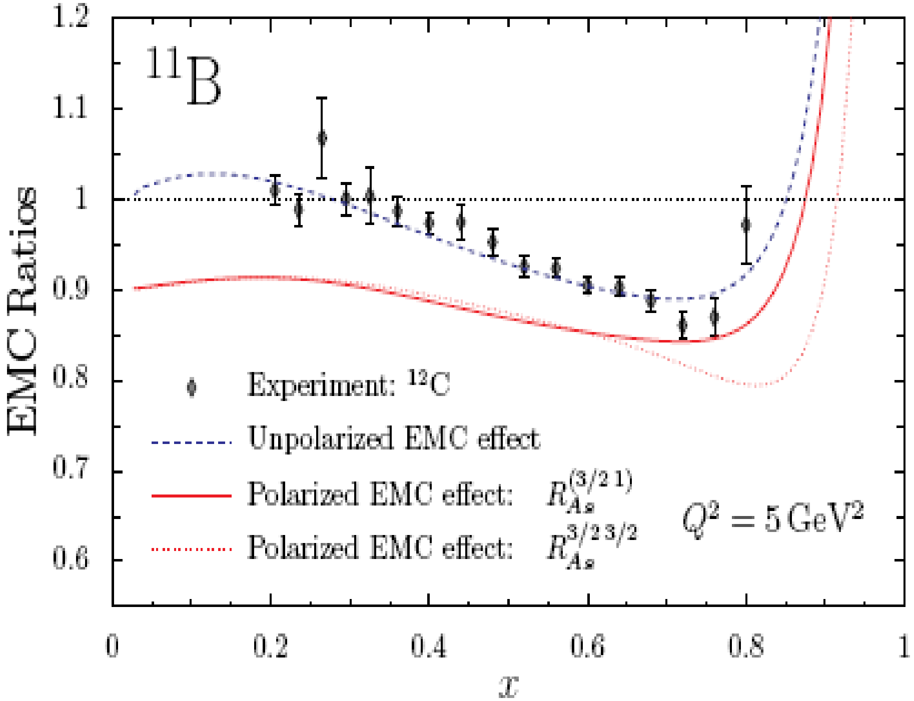

FIG. 7: The EMC and polarized EMC effect in ^{11}B. The empirical data is from Ref. [31].

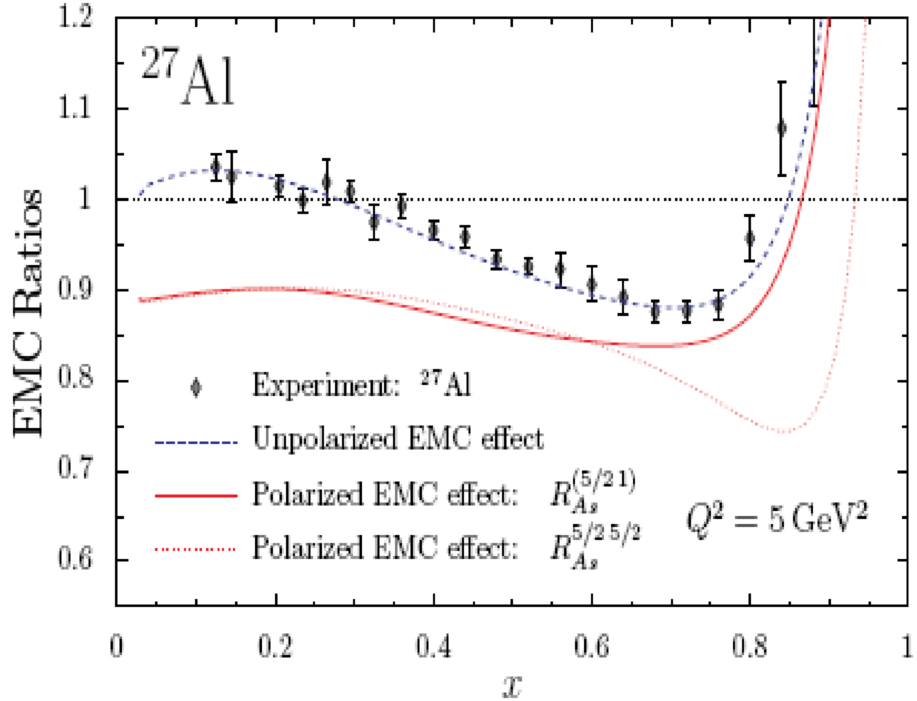

FIG. 9: The EMC and polarized EMC effect in ^{27}Al. The empirical data is from Ref. [31].

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Cloët, Bentz &Thomas, Phys. Lett. B642 (2006) 210

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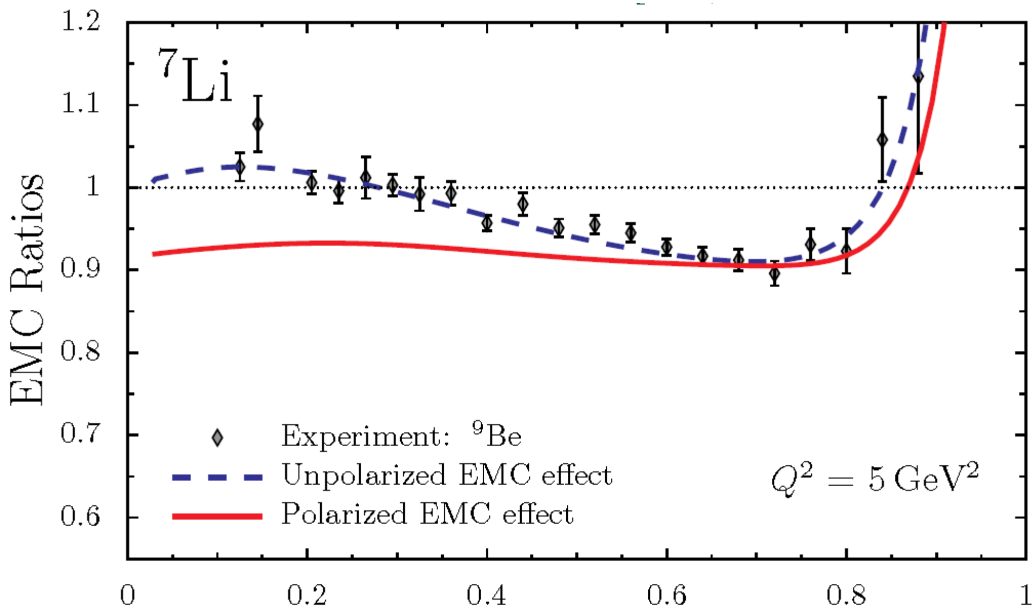
Approved JLab Experiment

- 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: $P_p = 0.86$ & $P_n = 0.04$)



Spin EMC measurement is critical as the proposed explanation in terms of SRC through the tensor force gives NO spin EMC effect (arXiv:1809.06622)

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DARK MATTER

SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER