Hadrons in the Nuclear Medium

Unpolarized Quasielastic Electron Scattering

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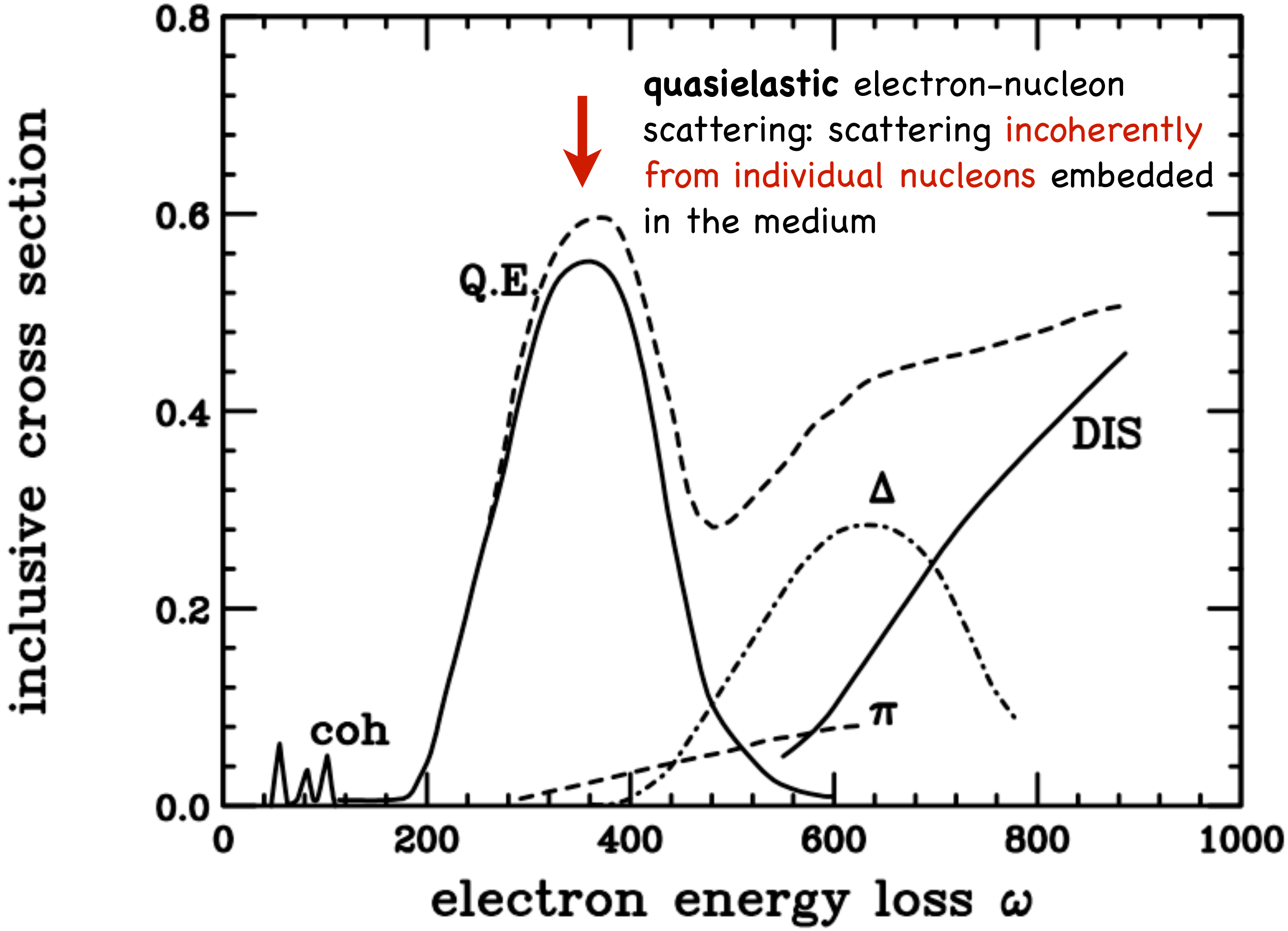
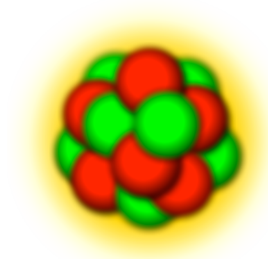
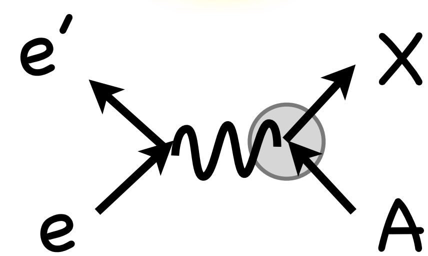
26th Annual Hampton University Graduate Studies Program
Jefferson Lab, Newport News, Virginia
May 31 - June 17, 2011

Electron Scattering from a Nuclear Target



Benhar, Day, and Sick, Rev. Mod. Phys. **80**, 189 (2008)



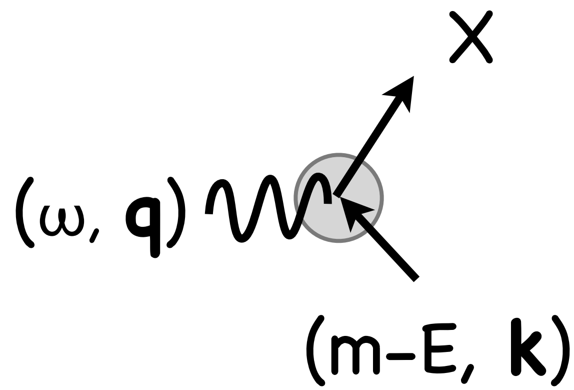


$$q = k_e - k_{e'} \equiv (\omega, \mathbf{q})$$

$$\frac{d^2\sigma}{d\Omega_{e'} dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[W_2(|\mathbf{q}|, \omega) + 2W_1(|\mathbf{q}|, \omega) \tan^2 \frac{\theta}{2} \right]$$

y-Scaling

- The inclusive cross section is a function of two independent variables, q and ω. Scaling refers to the dependence of the cross section on a single variable y(ω, q).
- Energy and momentum conservation (IA)



$$\omega + m - E = \sqrt{(\vec{k} + \vec{q})^2 + m^2} + E_{\mathrm{recoil}}$$

- For sufficiently large q (neglecting E, E_{recoil}, $k_{\perp}{}^2$)

$$(\omega + m)^2 = k_{||}^2 + 2k_{||}\,|\vec{q}\,| + |\vec{q}\,|^2 - m^2$$

- $k_{||}$ = y(ω, q); q and ω are no longer independent variables.

O. Benhar, D. Day, I. Sick, Rev. Mod. Phys. **80**, 189 (2008)

y-Scaling (II)

- Under certain approximations, the cross section can be written as:

$$\frac{d^2\sigma}{d\Omega_e d\omega} \approx \bar{\sigma}_e(q,y) \cdot F(y)$$

quantity related to the elementary electron nucleon cross section

F(y) = probability to find in the nucleus a nucleon of momentum component y parallel to **q**

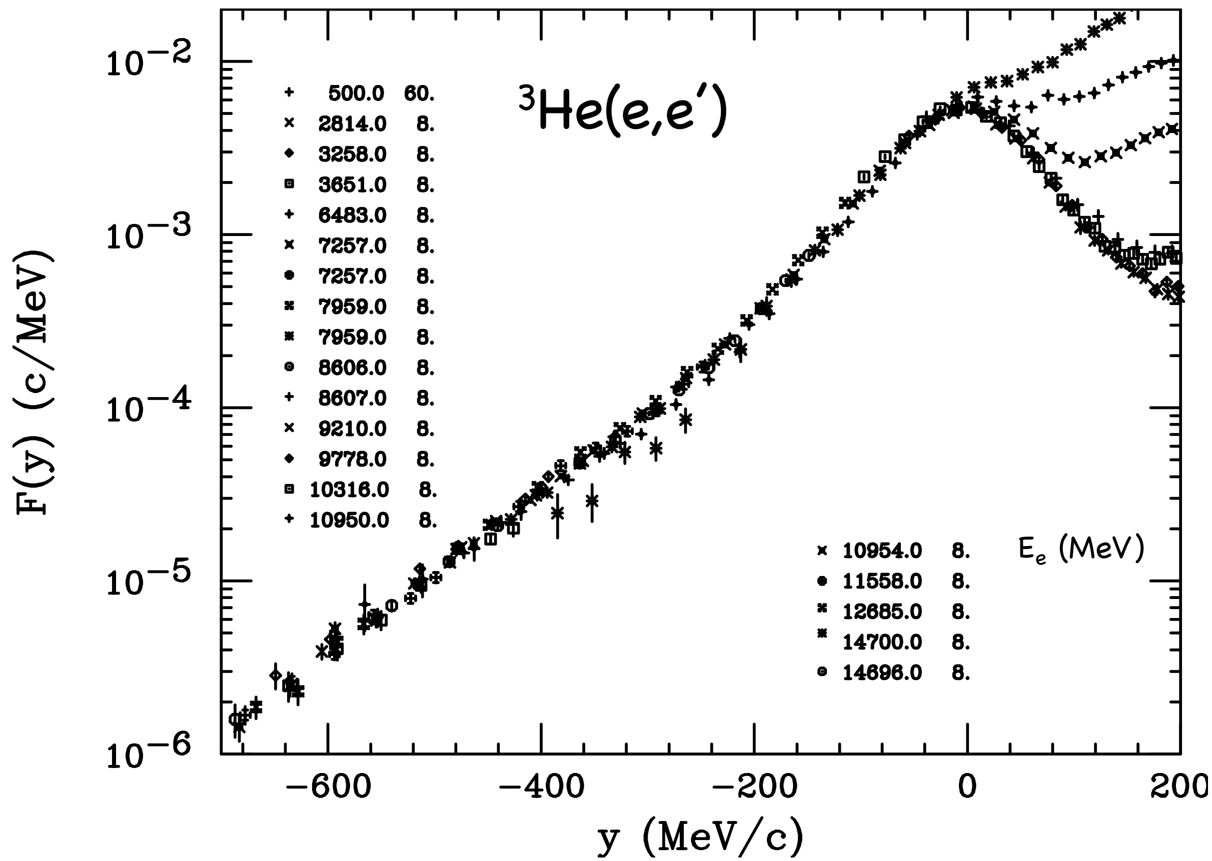
- y-scaling in quasi-elastic electron-nucleus scattering reveals the nucleon momentum distribution in the nucleus.

D.H. Lu, et al., Nucl. Phys. A **634**, 443 (1998);
O. Benhar, D. Day, I. Sick, Rev. Mod. Phys. **80**, 189 (2008)

y-Scaling (III)

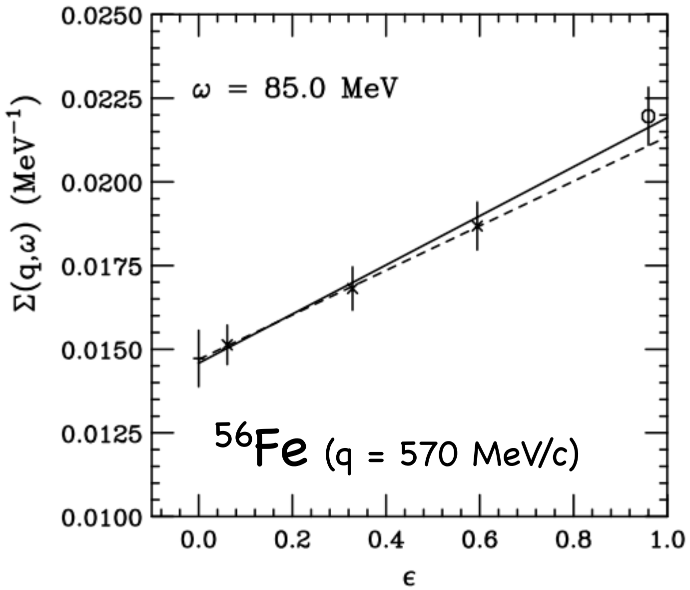
- Deviation of the cross-section from scattering from free nucleons scales to a function of a single variable y, the longitudinal momentum distribution.
- y-scaling property sensitive to change of nucleon radius
- Limits: $Q^2 > 1\ (\mathrm{GeV/c})^2$: $\Delta G_M < 3\%$

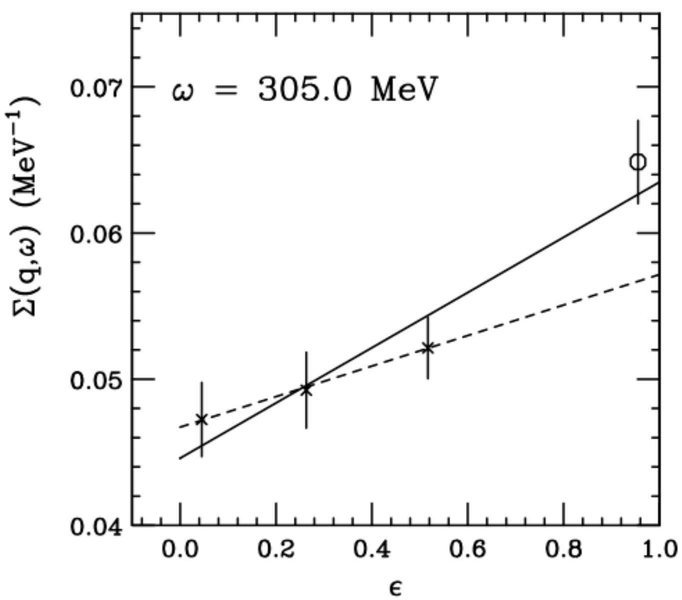
$$F(y) = \frac{\sigma(q,\omega)}{Z\sigma_{ep} + N\sigma_{en}} \cdot \frac{d\omega}{dy}$$



I. Sick, D. Day and J.S. McCarthy, Phys. Rev. Lett. **45**, 871 (1980);
Limit on radius from I. Sick, in: H. Klapdor (Ed.), Proc. Int. Conf. on Weak and Electromagnetic Interactions in Nuclei, Springer-Verlag, Berlin, 1986, p. 415

Quasielastic A(e,e') Scattering





J. Jourdan, Nucl. Phys. A **603**, 117 (1996)

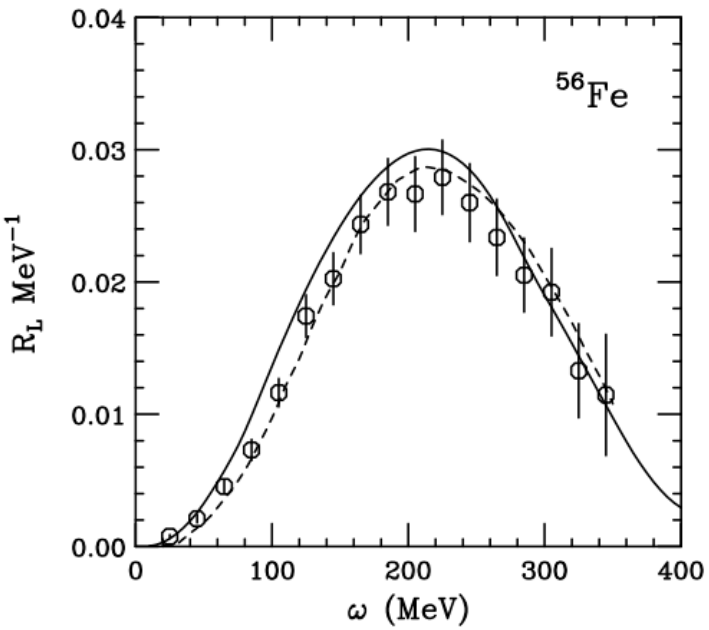
Rosenbluth technique

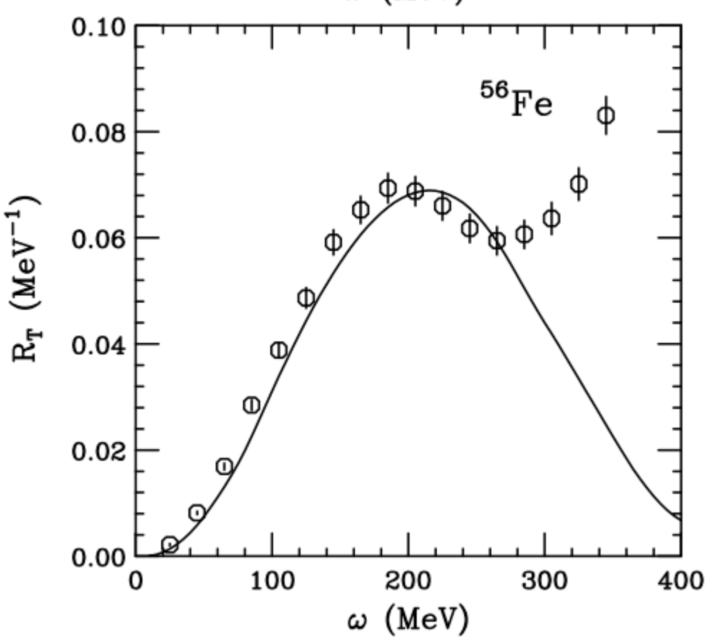
$$\frac{d\sigma}{d\Omega d\omega}\frac{\epsilon}{\sigma_M}\frac{q^4}{Q^4} = \Sigma$$

$$\boxed{\Sigma = \epsilon\, R_L(q,\omega) + \frac{q^2}{2Q^2}\, R_T(q,\omega)}$$

- Requires measurement at fixed q and varying ε
- Rosenbluth technique is only applicable in PW born approximation
- Important corrections due to Coulomb distortions of the electron waves

Coulomb Sum Rule





- L/T Separation
  - Transverse response: contributions from meson exchange currents and Δ excitation
  - Longitudinal response: Coulomb Sum Rule

- Coulomb Sum Rule

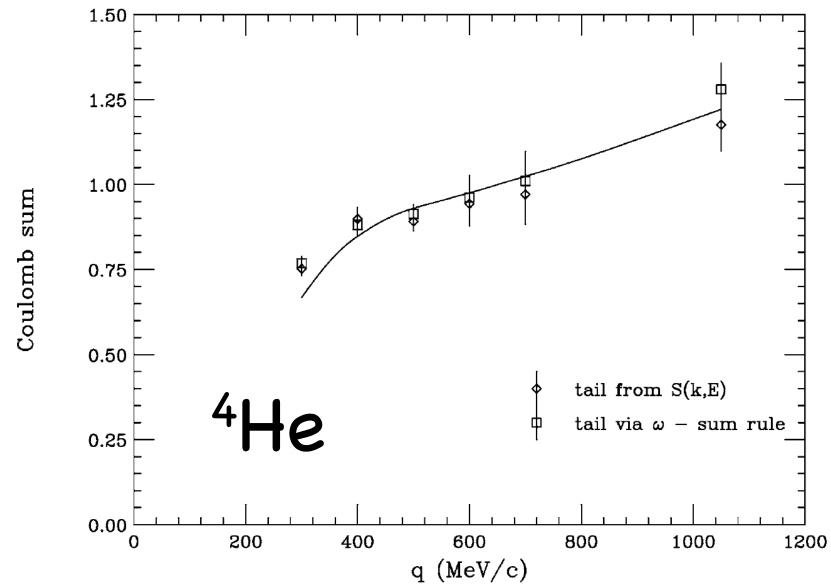
$$\boxed{S_L(q) = \frac{1}{Z}\int_{\omega^+}^{\infty} \frac{R_L(q,\omega)}{\tilde{G}_E^2}\, d\omega \quad \to 1}$$

  - non-relativistic regime
  - short-range correlations between nucleons and the effect of Pauli blocking is neglected

Coulomb Sum Rule: Results

- Experimental findings controversial
  - No quenching in the data observed [1]
  - Quenching of S_L is experimentally established [2]
- Good agreement between theory and experiment for ^{4}He when using free-nucleon form factors [3]
- Limits: $Q^2 \leq 0.5$ (GeV/c)^2: $\Delta G_E < 15\%$ or even $< 5\%$
- New data expected from JLab E05-110
  [Choi, Chen, and Meziani]

Analysis	S_L in ^{56}Fe
Jourdan	0.91 ± 0.12
Morgenstern, Meziani	0.73 ± 0.12



[1] J. Jourdan, Nucl. Phys. A 603, 117 (1996)
[2] J. Morgenstern, Z.-E. Meziani, Phys. Lett. B 515, 269 (2001)
[3] J. Carlson, J. Jourdan, R. Schiavilla, and I. Sick, Phys. Lett. B 553, 191 (2003)

Hadrons in the Nuclear Medium

Some Modern
Models of In-Medium Nucleons

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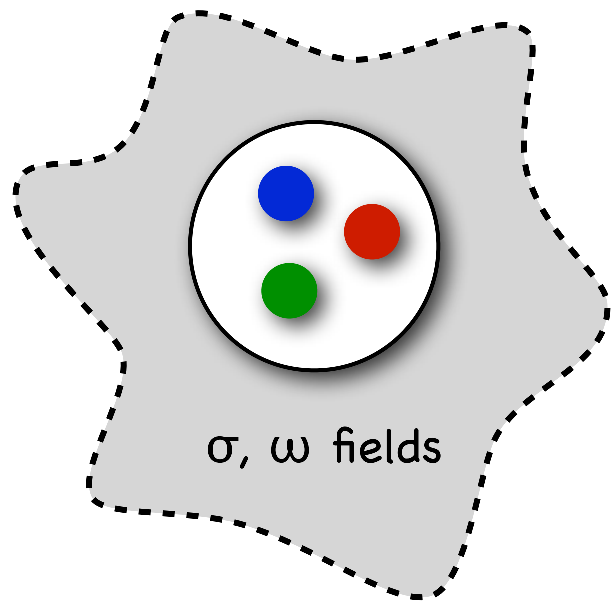
Quark-Meson Coupling Model (QMC)

- Lagrangian density for the QMC model (symmetric nuclear matter)

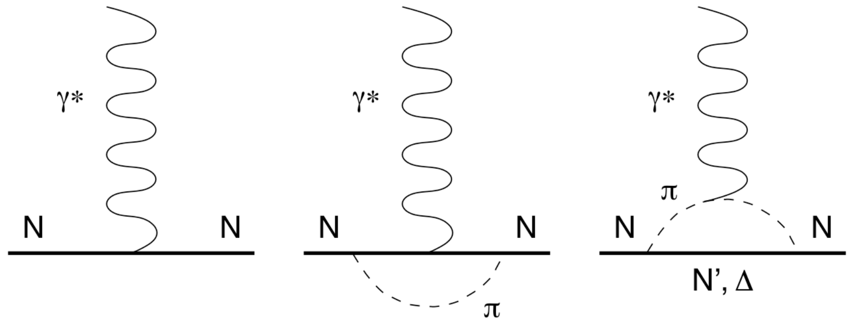
$$L_q = \underbrace{\bar{q}(i\gamma^\mu \delta_\mu - m_q)q\theta_V - B_0\theta_V}_{\text{quarks in a MIT bag}} + \underbrace{g_\sigma^q \bar{q}q\sigma - g_\omega^q \bar{q}\gamma_\mu q\omega^\mu - \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{2}m_\omega^2\omega^2}_{\text{scalar and vector meson fields couple directly to the quarks}}$$

- Solve equations self-consistently:
  - The meson fields are given by the nucleon densities in the nucleus
  - The nucleon structure is determined by the quarks coupling to the mesons
- Modification of internal structure of bound nucleons

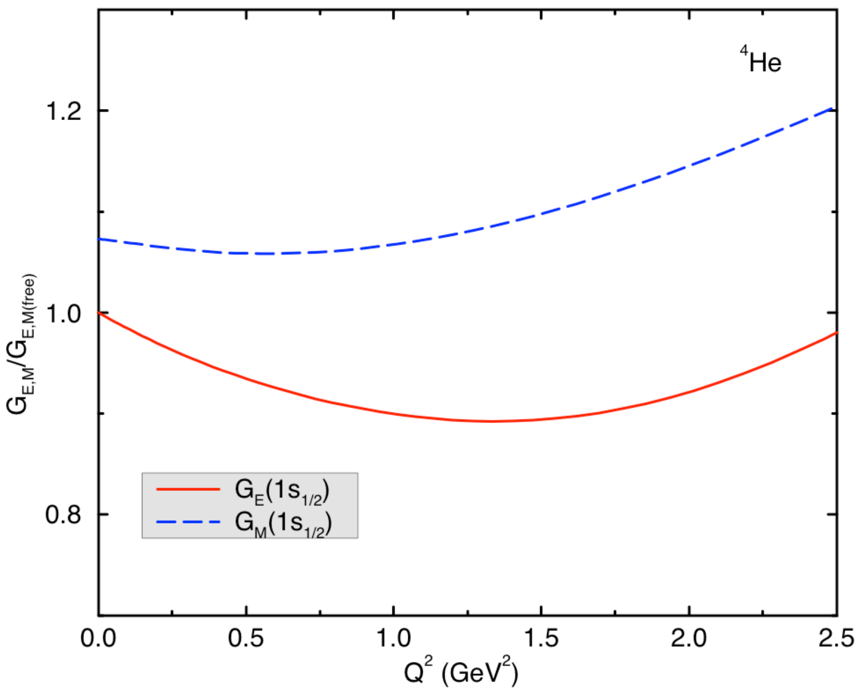


D.H. Lu, et al., Nucl. Phys. A **634**, 443 (1998); K. Saito et al., Prog. Part. Nucl. Phys. **58**, 1 (2007)

QMC In-Medium Form Factors



intermediate baryon restricted to N or Δ



- Structure of the nucleon described by valence quarks in a bag (Cloudy-bag model).
- At low Q^2: Charge form factor much more sensitive to the nuclear medium than the magnetic one
- Electromagnetic rms radii and magnetic moment of the bound proton are increased

D.H. Lu, A.W. Thomas, K. Tsushima, A.G. Williams, K. Saito, Phys. Lett. B **417**, 217 (1998); D.H. Lu et al., Phys. Rev. C **60**, 068201 (1999)

Chiral Solitons in Nuclei

- Three constituent quarks interact with pions.
- The central mechanism to explain the EMC effect is that the nuclear medium provides an attractive scalar interaction that modifies the nucleon wave function.
- Quark scalar and pseudoscalar densities

quark scalar density	condensate	valence contribution	contribution from the medium

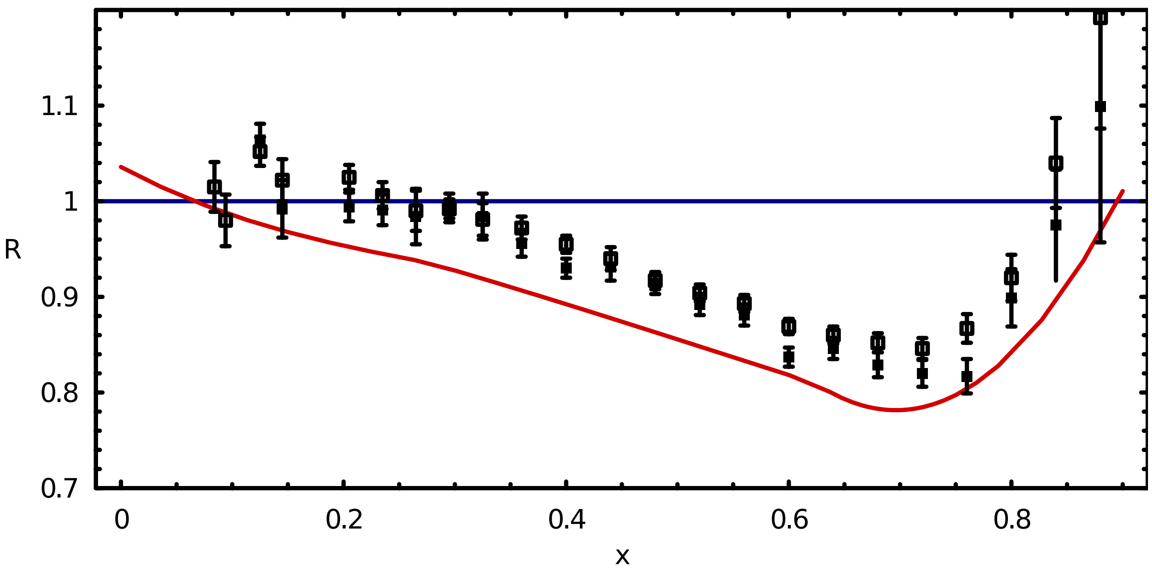
$$\rho_s^q(r) \simeq \langle\bar{\psi}\psi\rangle_0 + \rho_s^v(r) + \tilde{c}_s \int d^3r' \rho_s^N(r')\rho_s^v(r-r')$$

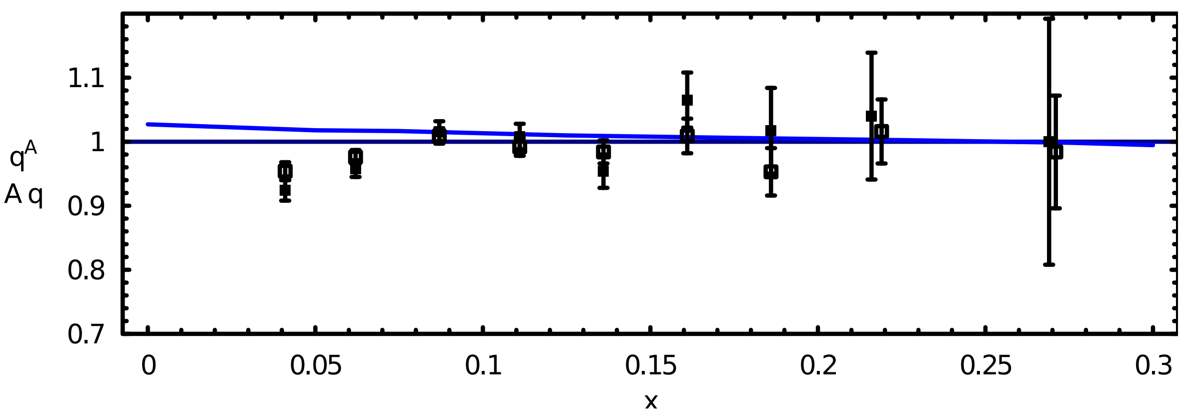
$$\rho_{ps}^q(r) \simeq \rho_{ps}^v(r)$$

- Chiral-soliton model provides the quark and antiquark substructure of the proton, embedded in nuclear matter.
- Two free parameters: $\langle\Psi\Psi\rangle_0$ and g_v; effective condensate falls 30% at nuclear density.

J.R. Smith and G.A. Miller, Phys. Rev. Lett. **91**, 212301 (2003)

Chiral Solitons in Nuclei

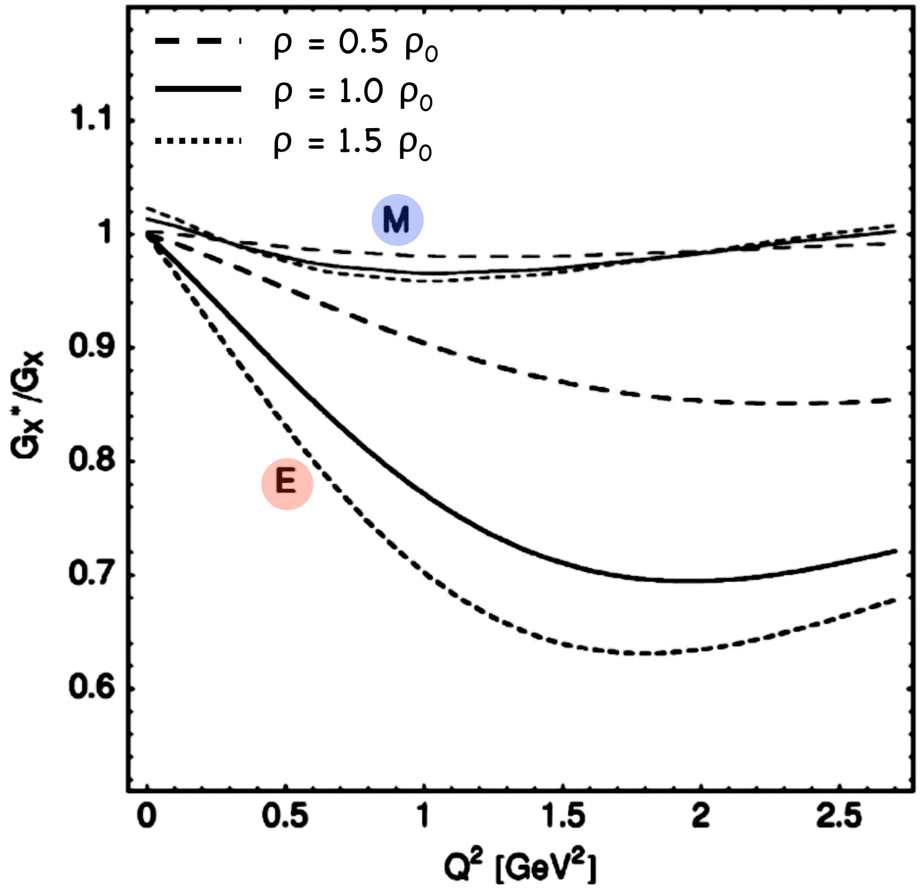




- The CQS model consistent with free nucleon properties, nuclear saturation properties, EMC effect, Drell-Yan experiments
- Medium induced increase of nucleon radius = 2.4%; consistent with A(e,e′p) limit of < 6%.

J.R. Smith and G.A. Miller, Phys. Rev. Lett. **91**, 212301 (2003)

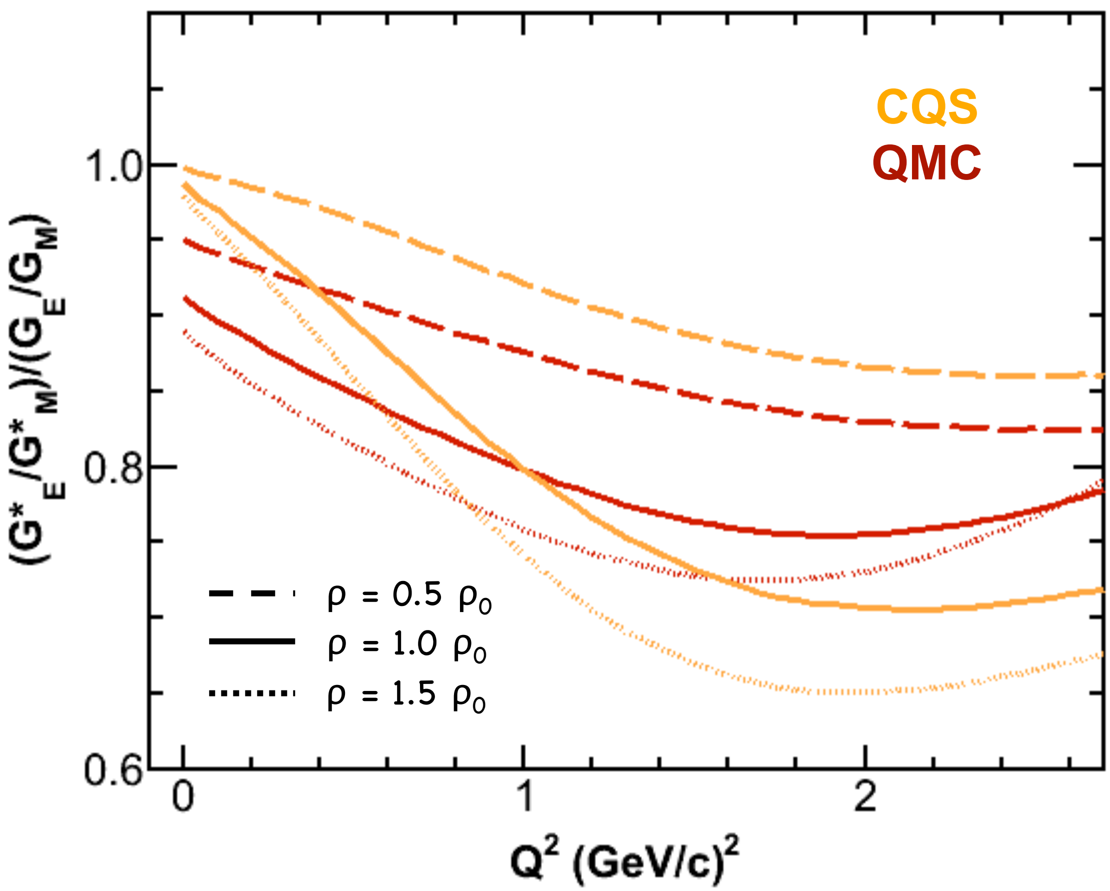
Chiral Quark Soliton Model (CQS)



- Density-dependent medium modifications:
  - significant for G_E, only moderate for G_M
  - no strong enhancement of the magnetic moment
- sea quarks almost completely unaffected (magnetic form factor)

CQS: J.R. Smith and G.A. Miller, Phys. Rev. C **70**, 065205 (2004)

In-Medium Form Factors



- Changes in the internal structure of bound nucleons result also in bound nucleon form factors.
- Observable effects predicted:

  Chiral Quark Soliton (CQS), Quark Meson Coupling (QMC), Skyrme, Nambu-Jona-Lasinio (NJL), GPD Models.
- Model Predictions:
  - are density and Q^2 dependent,
  - show similar behavior,
  - consistent with experimental data (within large uncertainties).

CQS: J.R. Smith and G.A. Miller, Phys. Rev. C **70**, 065205 (2004)
QMC: D.H. Lu et al., Phys. Lett. B 417, 217 (1998)
NJL: I.C. Cloet, W. Bentz, and A.W. Thomas (to be published)