Experimental Signatures for Medium Modifications

Steffen Strauch

The George Washington University

The Physics of Nuclei with 12 GeV Electrons Workshop

Jefferson Lab, November 1–5, 2004

Outline

- Introduction
- Experimental searches for medium effects
  - Meson medium modifications
  - Nucleon medium modifications
- Probing high-density configurations at higher energies
- Summary

Conventional Nuclear Physics *vs.* QCD

- Conventional nuclear physics:
  Nuclei are effectively and well described as
  - point like protons and neutrons
  - interaction through meson exchange
  - Nuclear mass: $M_A \approx [NM_n + ZM_p](1 - 0.01)$
- Underlying theory: QCD
  - Nucleons and mesons are not the fundamental entities
  - In the chiral limit, phase transition to quark-gluon plasma
- Connection: agreement between Skyrme force and effective interaction corresponding to the quark meson coupling model. Talk by P. Guichon.

P.A.M. Guichon and A.W. Thomas, nucl-th/0402064

Hadrons in the Nuclear Medium

- Nonperturbative QCD

	chiral condensate
chiral symmetry spontaneously broken in the ground state	$\langle \bar{q}q \rangle \neq 0$
chirally restored phase ($T \geq 150$ MeV)	$\langle \bar{q}q \rangle = 0$
at nuclear densities	reduced

- Hadronic properties should depend on value of the chiral condensate $\langle \bar{q}q \rangle$. Brown-Rho scaling:

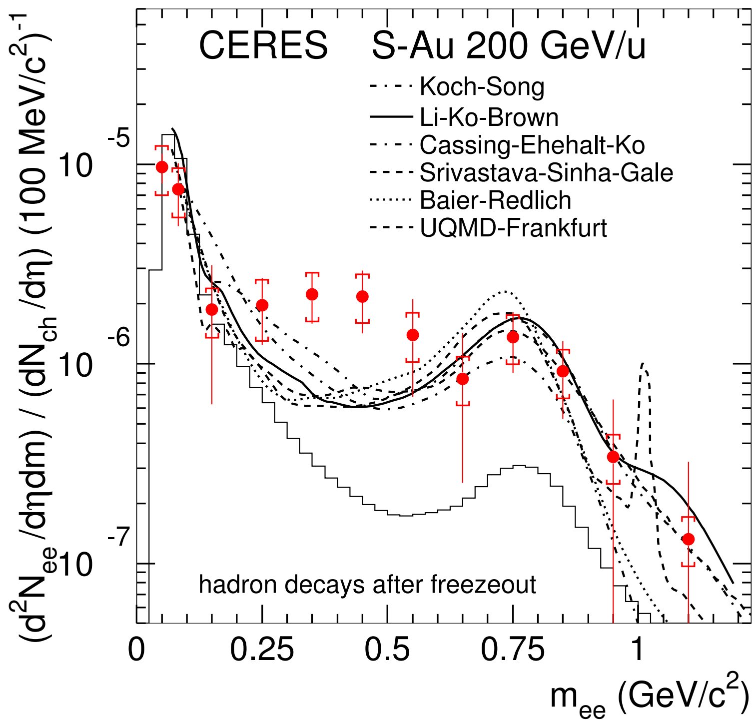
$$m_\sigma^*/m_\sigma \approx m_N^*/m_N \approx m_\rho^*/m_\rho \approx m_\omega^*/m_\omega < 1$$

- Talk by U .Mosel

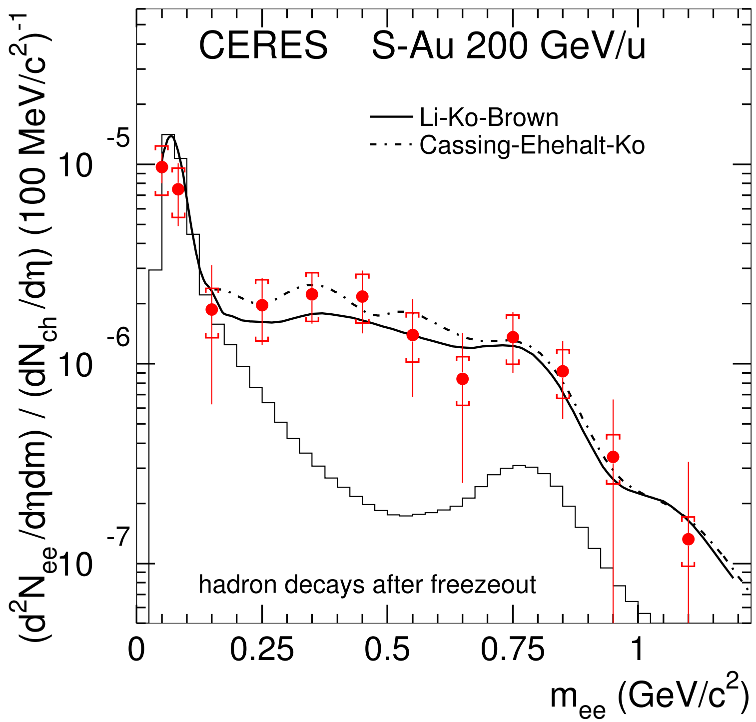
Ko, Koch, Li, Ann. Rev. Nucl. Part. Sci **47**, 505 (1997)
G.E. Brown, M. Rho, Phys. Rev. Lett **66**, 2720 (1991)

In-medium properties of Vector Mesons

- Dilepton invariant mass spectrum from Nucleus–Nucleus Collision



... without dropping vector-meson masses



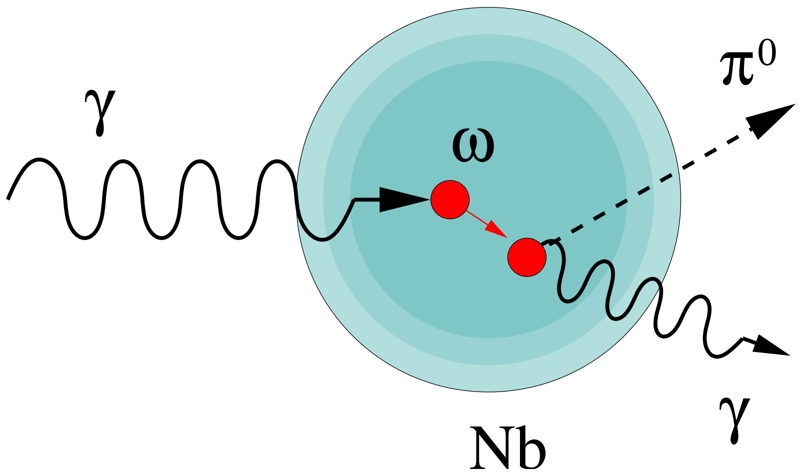
... with dropping vector-meson masses

- Comparison with transport calculations indicate lowering of ρ-meson mass in medium.
- “Cleaner” conditions: γA

Figures adapted from: A. Drees, Proc. Quark Matter 96, Nucl. Phys. **A610**, ed. P. Braun-Munzinger (1997); Ko, Koch, Li, Ann. Rev. Nucl. Part. Sci **47**, 505 (1997)

ω Photoproduction in Nuclei

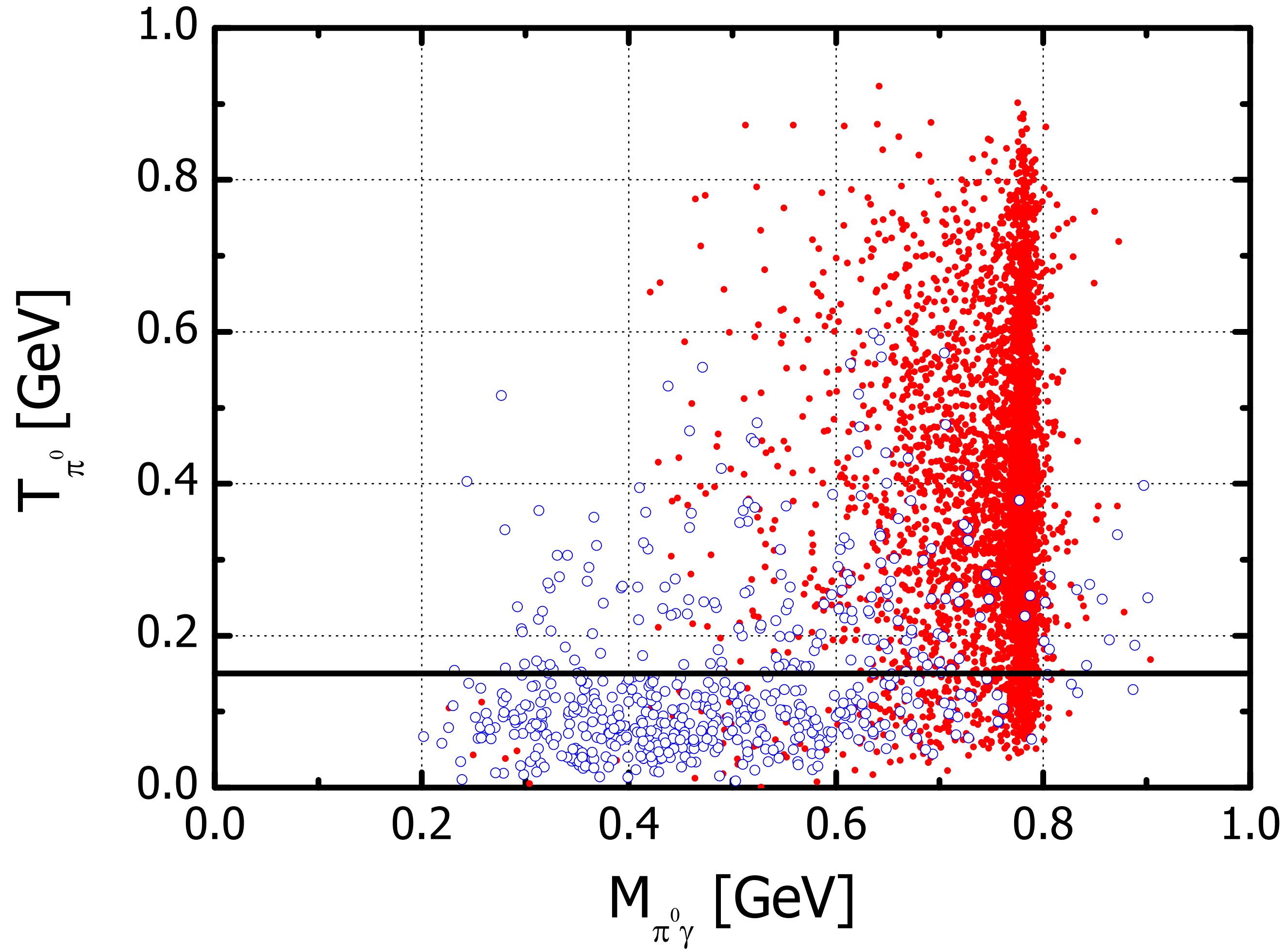
- TAPS / Crystal-Barrel Experiment at ELSA (Bonn)
  $E_\gamma = 0.8 - 2.5$ GeV



- Nb: dense and large
- ω meson: mass shift (-140 MeV to -15 MeV) expected; survives in medium with observable resonance structure
- Observable: $\pi^0\gamma$ invariant-mass spectrum
  - + Branching ratio 8.9%; no ρ-meson contribution
  - – FSI of π^0 in nucleus

Messchendorp, Sibirtsev, Cassing, Metag, Schadmand, Eur. Phys. J. A **11**, 95 (2001)

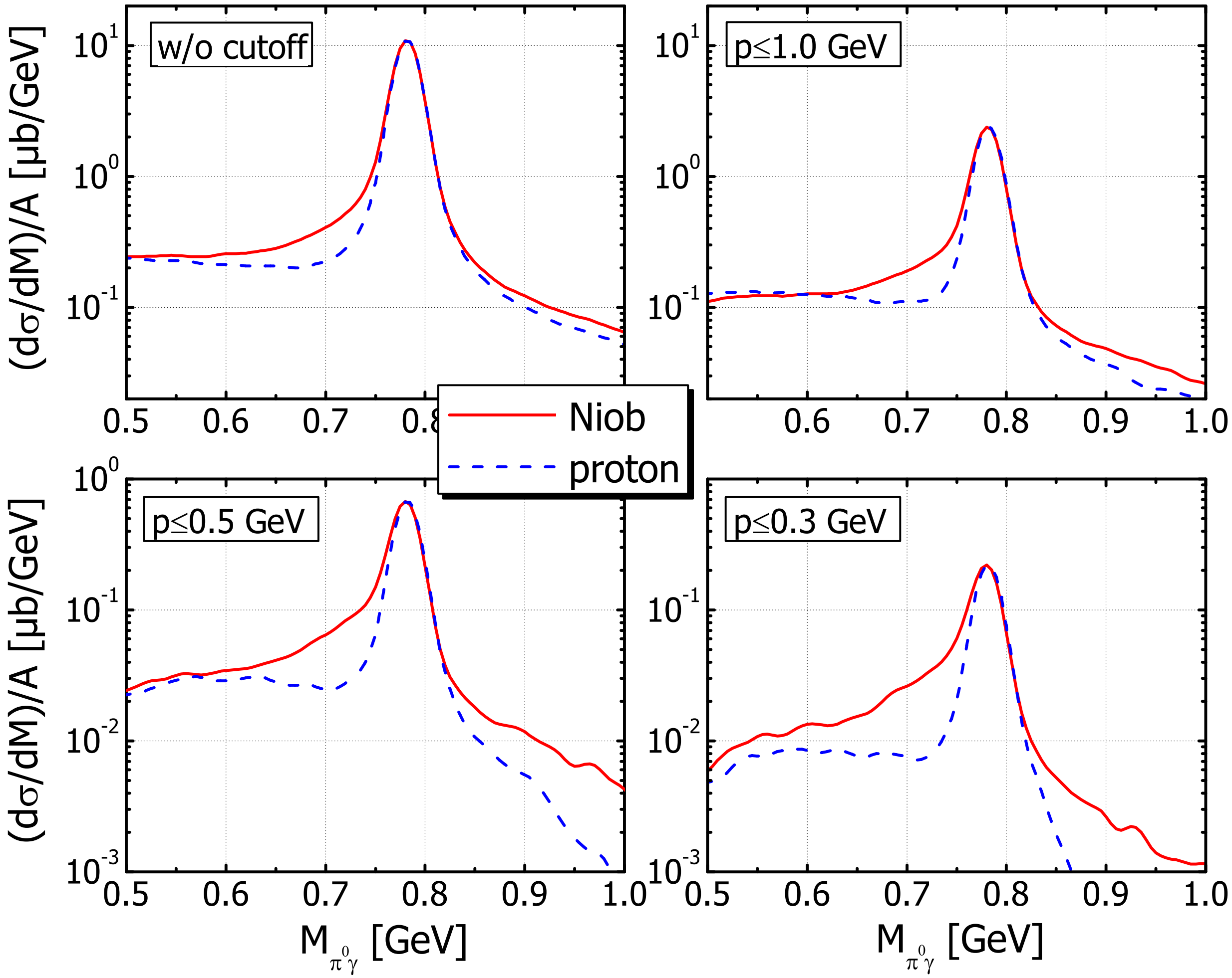
π^0-Kinetic-Energy Cutoff



- Reduction of π^0-rescattering background

Transport calculation. Figure from Pascal Mühlich, T. Falter and U. Mosel, in Proc. Intnl Workshop XXXII on Gross Properties of Nuclei and Nuclear Excitations, M. Buballa, *et al.* Eds., Hirschegg, Austria (2004)

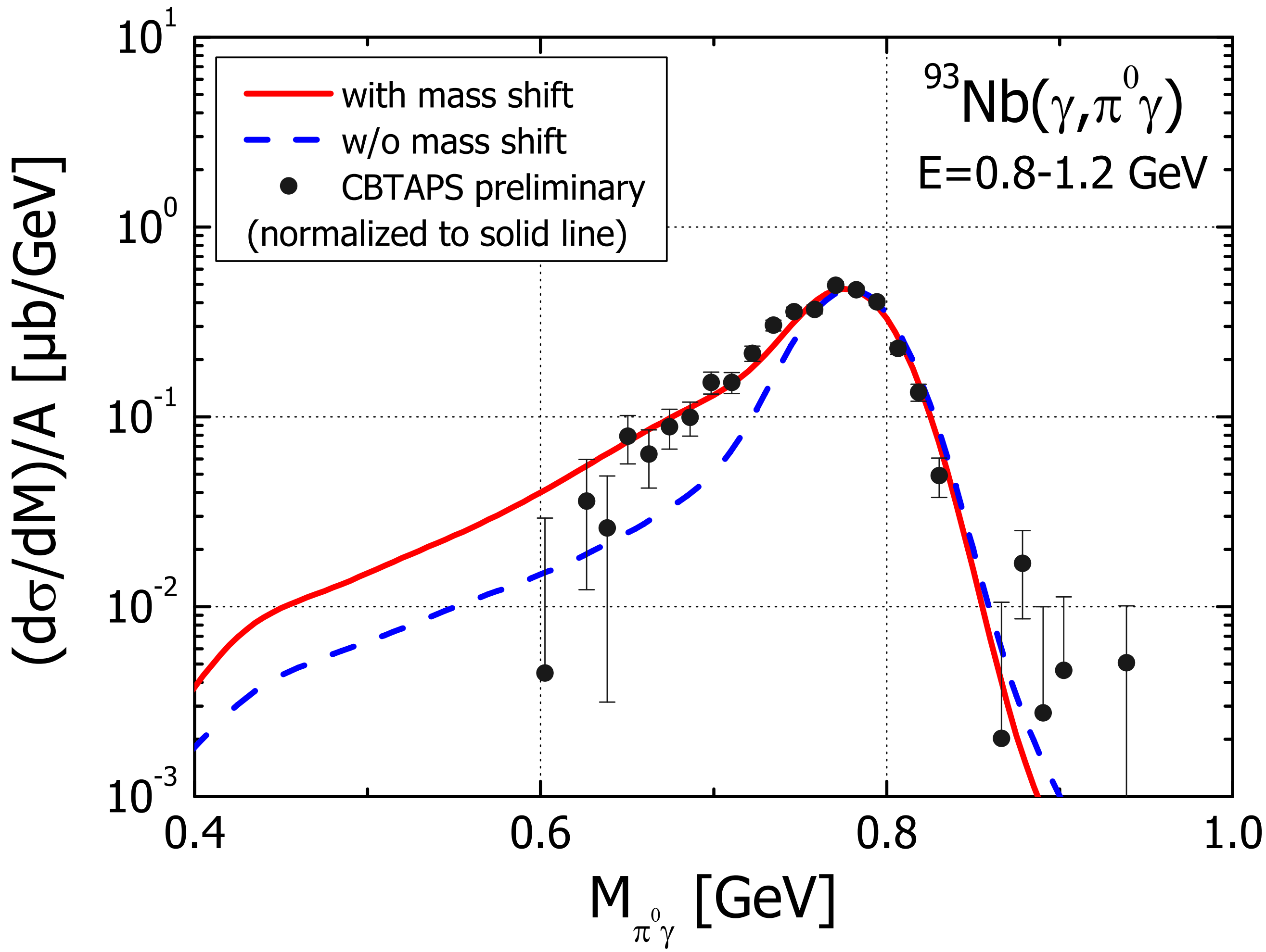
In-Medium Decays



- Enhancement of in-medium decays by minimizing the decay length
- ω-three-momentum cutoff

Figure from Pascal Mühlich, T. Falter and U. Mosel, in Proc. Intnl Workshop XXXII on Gross Properties of Nuclei and Nuclear Excitations, M. Buballa *et al.* Eds., Hirschegg, Austria (2004)

Preliminary Data from CBTAPS

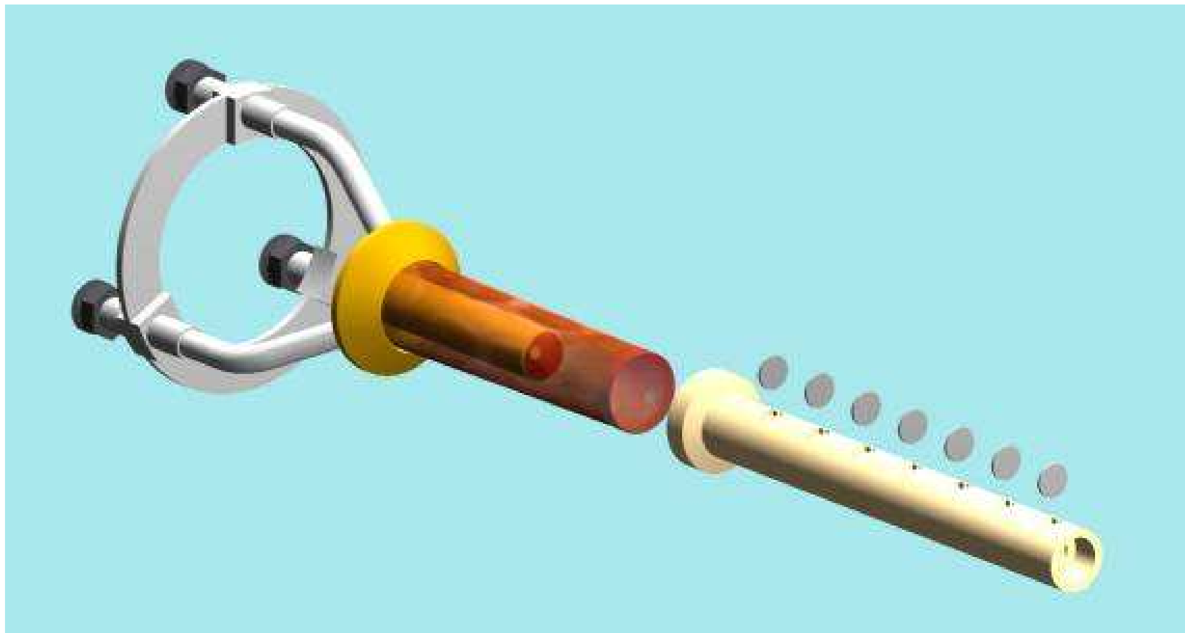


- Preliminary experimental data favor sizable modification of the ω spectral density in nuclei; $m^*_\omega = m^0_\omega(1 - 0.16\rho_N/\rho^0)$

Figure from Pascal Mühlich, T. Falter and U. Mosel,in Proc. Intnl Workshop XXXII on Gross Properties of Nuclei and Nuclear Excitations, M. Buballa *et al.*, Hirschegg, Austria (2004)

CLAS g7 Experiment

- Photoproduction of vector mesons (ρ, ω, and ϕ) off nuclei
- Targets: D_2, C, Ti, Fe, and Pb, Beam: E_e = 3 and 4 GeV

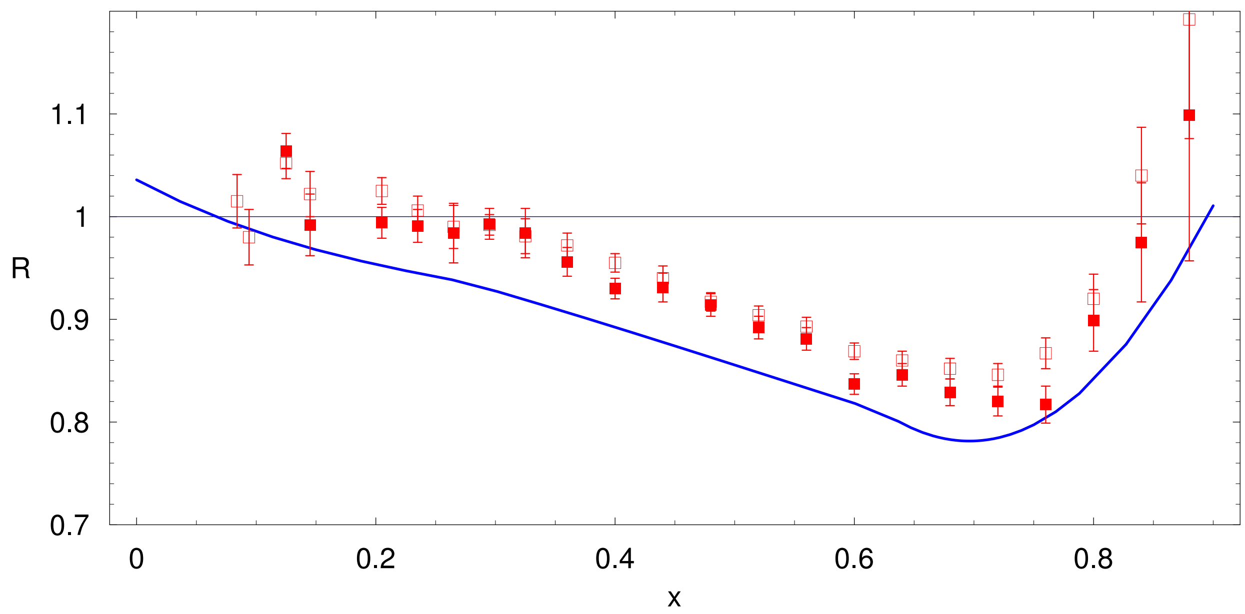


- Observable: e^+e^- invariant-mass spectrum
  - + no strong FSI
  - – small branching ratio, broad ρ-meson signal, background from Bethe-Heitler processes
- Data taken fall 2002; Data analysis underway (C. Tur, M. Wood)

JLab Experiment E 01-112, C. Djalali, M. Kossov, and D. Weygand, spokespeople

Interpretation of the EMC Effect

- $R(x, Q^2) = F_2^A / A F_2^N$: Depletion of the nuclear structure function $F_2^A(x)$ in the valence-quark regime $0.3 \leq x \leq 0.8$



- J. Smith and G. Miller: chiral quark-soliton model of the nucleon
  Conventional nuclear physics does not explain EMC effect
  $\longrightarrow$ Nucleon structure is modified

SLAC-E139 data for Iron and Gold;
Figure from Jason R. Smith and Gerald A. Miller, Phys. Rev. Lett. **91**, 212301 (2003)

Limits for Medium Modifications of Nucleon Form Factors

- y-scaling
  - $Q^2 > 1$ (GeV/c)^2: $\Delta G_M < 3\%$ [1]
- Coulomb Sum Rule, L–Response
  - No quenching in the data is observed [2]
  - Quenching of S_L is experimentally established [3]
  - $Q^2 \leq 0.5$ (GeV/c)^2: $\Delta G_E < 15\%$, or even $< 5\%$
- Exclusive $A(e, e'p)$ processes

[1] I. Sick, in: H. Klapdor (Ed.), Proc. Int. Conf. on Weak and Electromagnetic Interactions in Nuclei, Springer-Verlag, Berlin, 1986, p. 415

[2] J. Jourdan, Nucl. Phys. A **603**, 117 (1996), J. Carlson *et al.*, Phys. Lett. B **553**, 191 (2003)

[3] J. Morgenstern, Z.-E. Meziani, Phys. Lett. B **515**, 269 (2001)

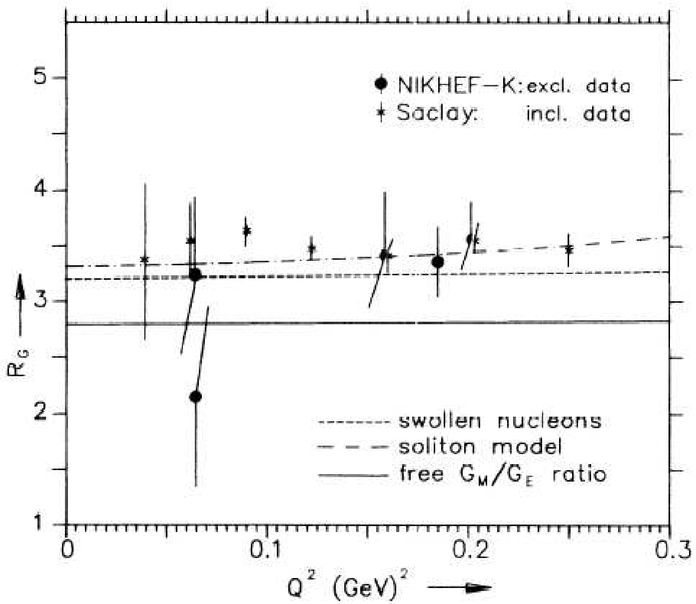
Form-Factor Ratio from LT Separation

$$R_G = \frac{G_M}{G_E} = \sqrt{\frac{W_T}{W_L}\frac{4m^2}{Q^2}}$$

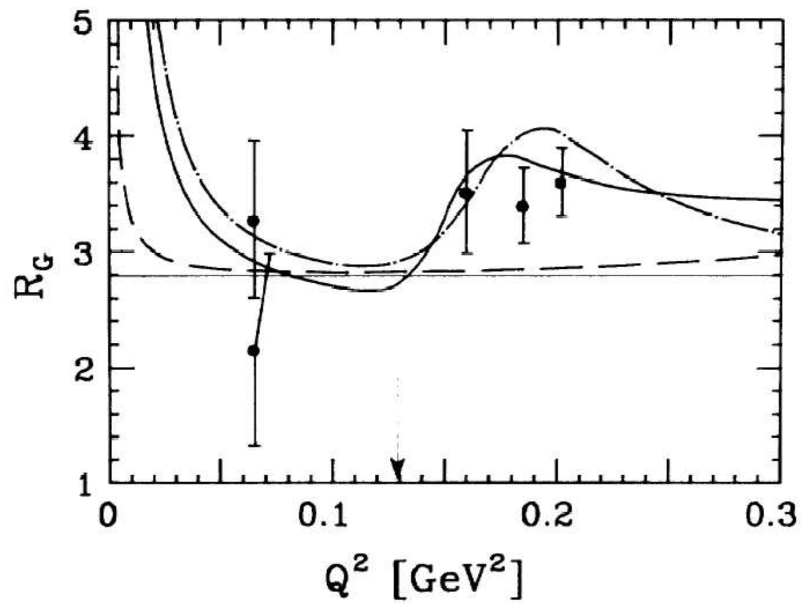
Nuclear medium effects ^{12}C(e,e'p) ?

Experimental evidence...?

... maybe not!



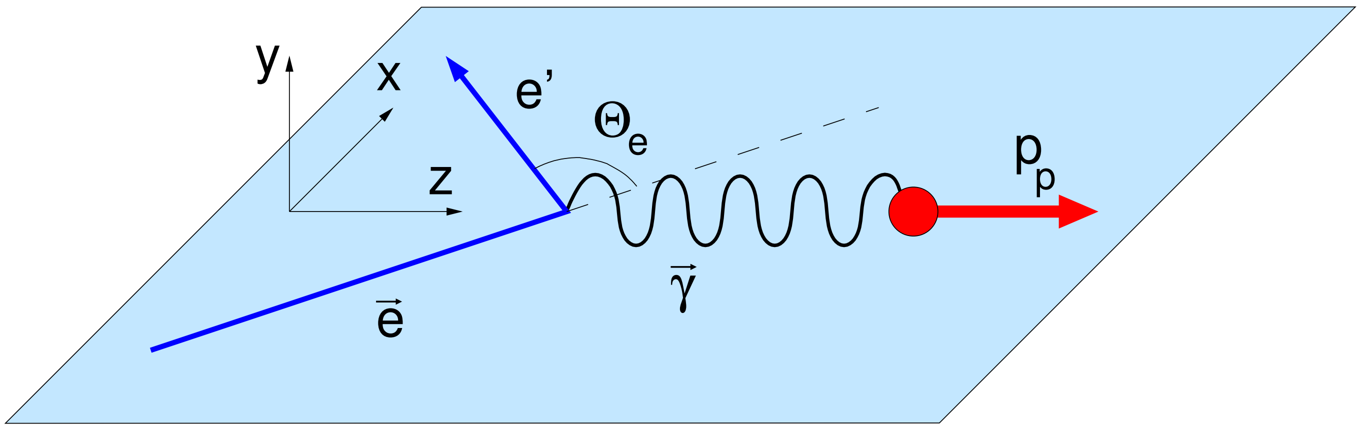
G. Van der Steenhoven *et al.*,
Phys. Rev. Lett. **57**, 182 (1986)



T.D. Cohen, J.W. Van Orden, A. Picklesimer,
Phys. Rev. Lett. **59**, 1267 (1987)

Polarization-Transfer Technique

- Proton recoil polarization in $(\vec{e}, e'\vec{p})$



- Free electron-nucleon scattering

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z} \cdot \frac{(E_i + E_f)}{2m} \tan\left(\frac{\theta_e}{2}\right)$$

- Bound nucleons $\longrightarrow$ evaluation within model

R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981).

Polarization Transfer in ^{4}He$(\vec{e}, e'\vec{p})^3$H

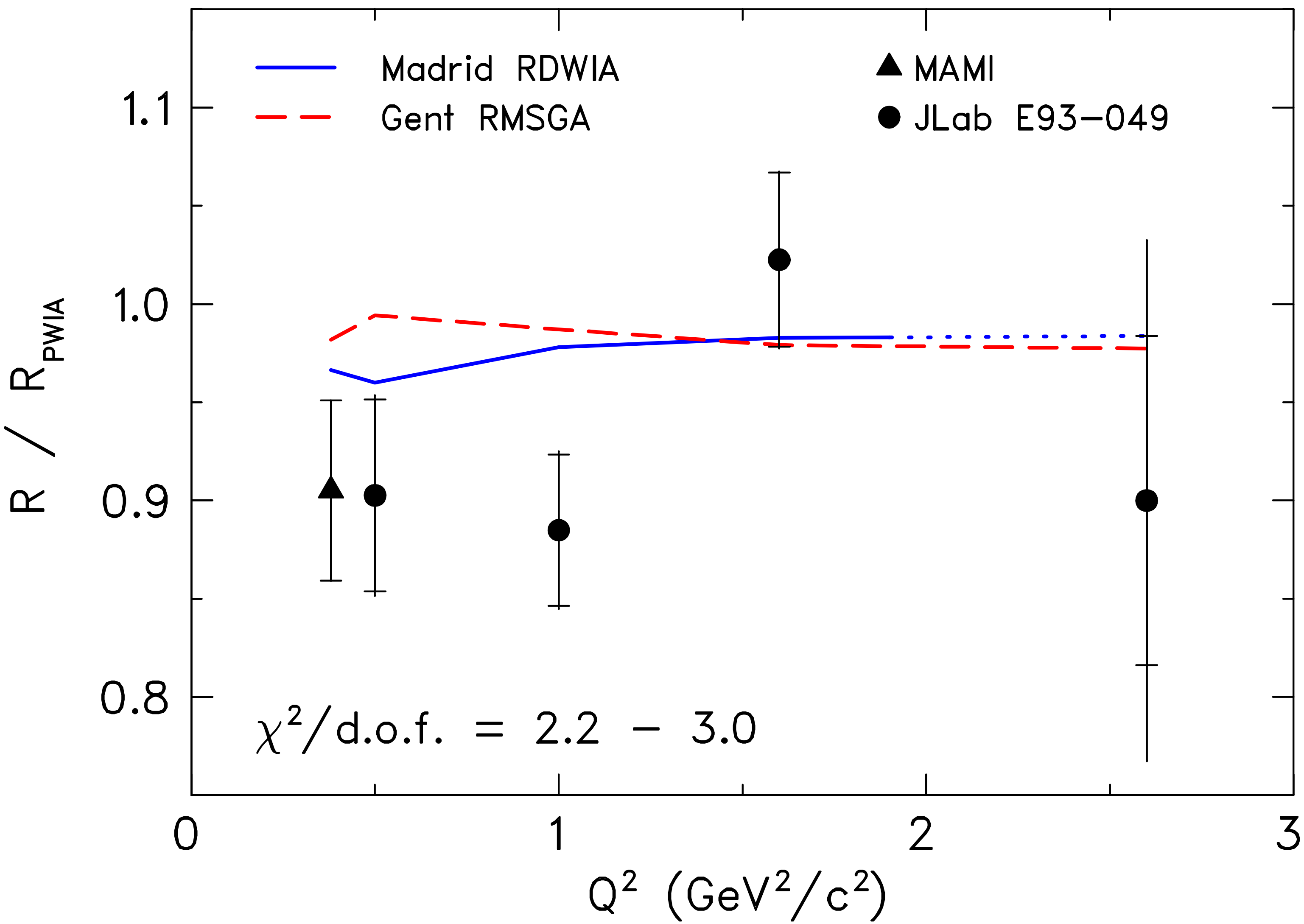
- Reaction mechanism effects in $A(\vec{e}, e'\vec{p})B$ predicted [1] to be minimal and small for
  - Quasielastic scattering
  - Low missing momentum
  - Symmetry about $\mathbf{p}_m = 0$
- Jefferson Lab Hall-A Experiment E93-049 [2]
  - ^{4}He target: dense yet simple nucleus; s-shell knockout; RDWIA and microscopic calculations possible
  - $Q^2 = 0.5$, 1.0, 1.6, and 2.6 (GeV/c)^2

[1] *e.g.*, J.M. Laget, Nucl. Phys. A **579**, 333 (1994), J.J. Kelly, Phys. Rev. C **59**, 3256 (1999)

A. Meucci, C. Guisti, and F.D. Pacati, Phys. Rev. C **66**, 034610 (2002).

[2] Jefferson Lab experiment E93-049, R. Ent and P. Ulmer, spokespersons; S. Strauch *et al.*, Phys. Rev. Lett. **91**, 052301 (2003)

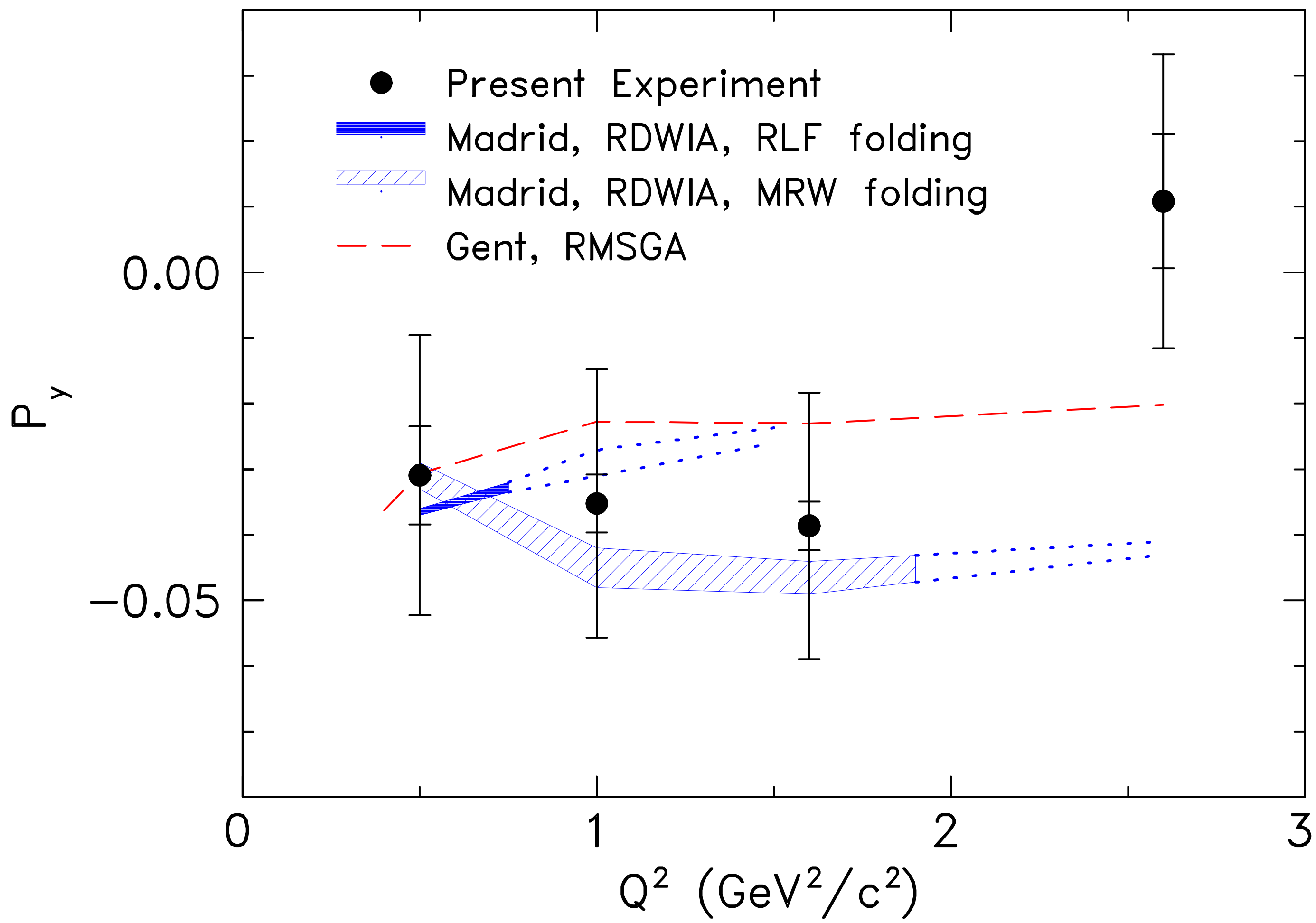
^{4}He$(\vec{e}, e'\vec{p})^3$H – Polarization-Transfer Ratio



Optical potential *vs.* Glauber approximation to describe FSI

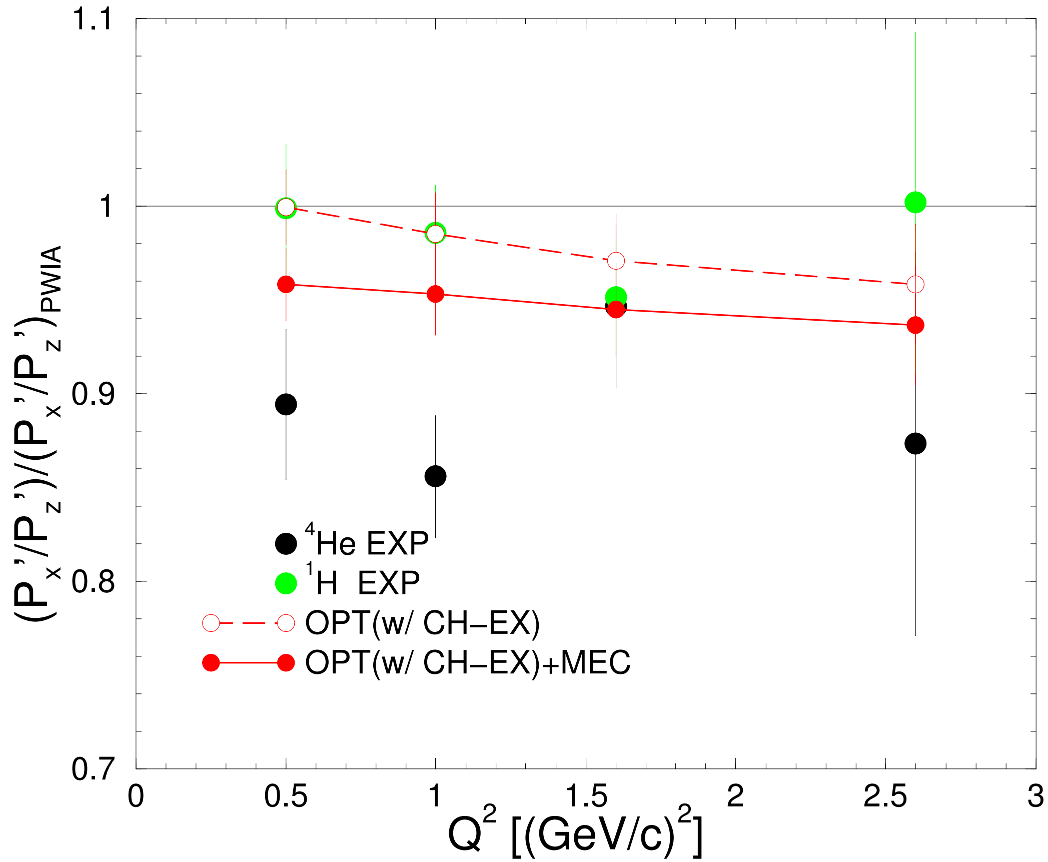
RDWIA: J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999); Relativistic Multiple-scattering Glauber Approximation (RMSGA): J. Ryckebusch *et al.*, Nucl. Phys. A **728**, 226 (2003)

^{4}He$(e, e'\vec{p})^{3}$H — Induced Polarization



- Final-state interactions consistent with data
- Need smaller systematic uncertainties of P_y

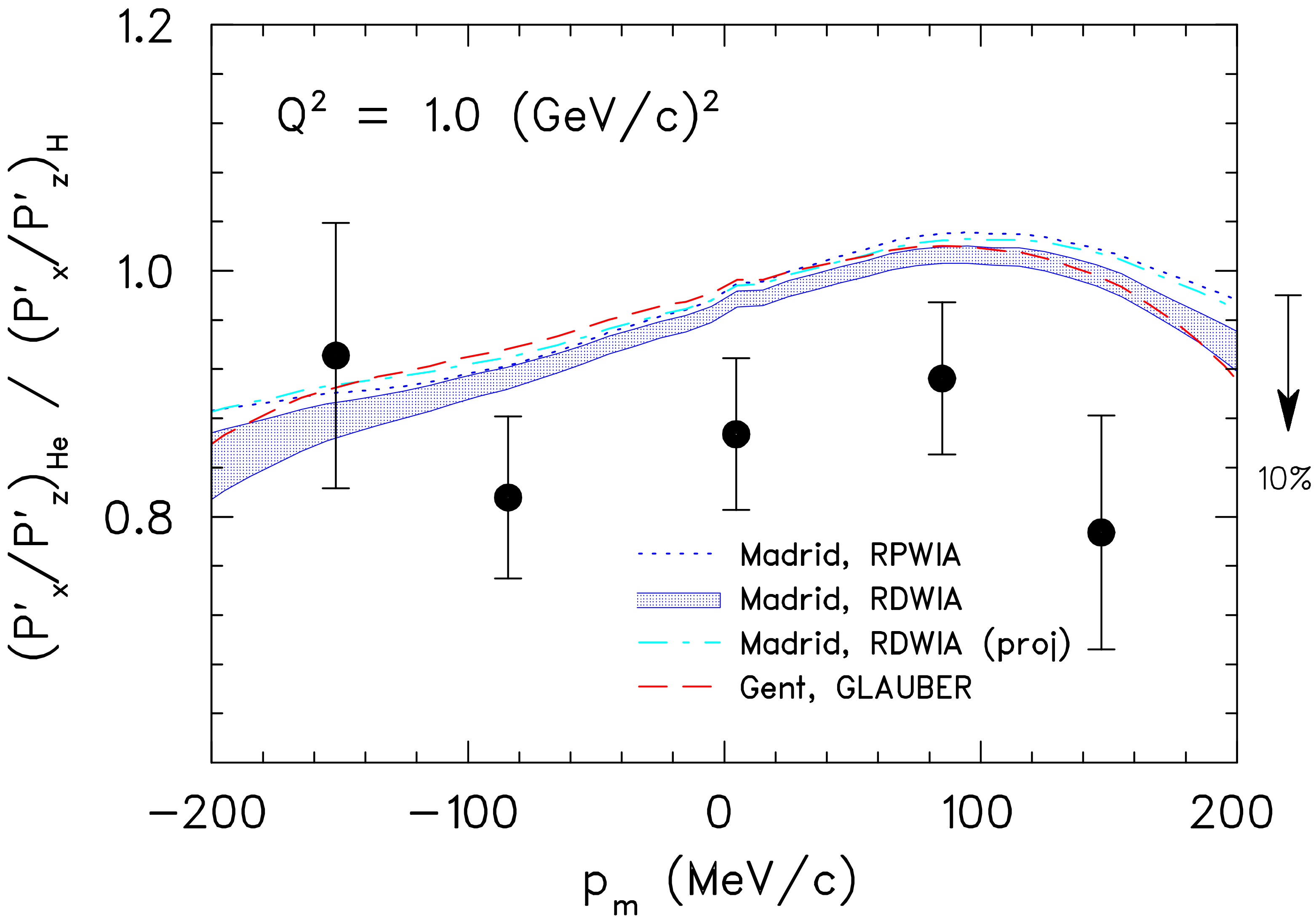
Prelim. Calculations by R. Schiavilla *et al.*



- Small effect of charge-exchange FSI and MEC on P'_x/P'_z.
- Sizeable effect from spin-dependent charge-exchange FSI on P'_x/P'_z ratio <u>and</u> P_y.

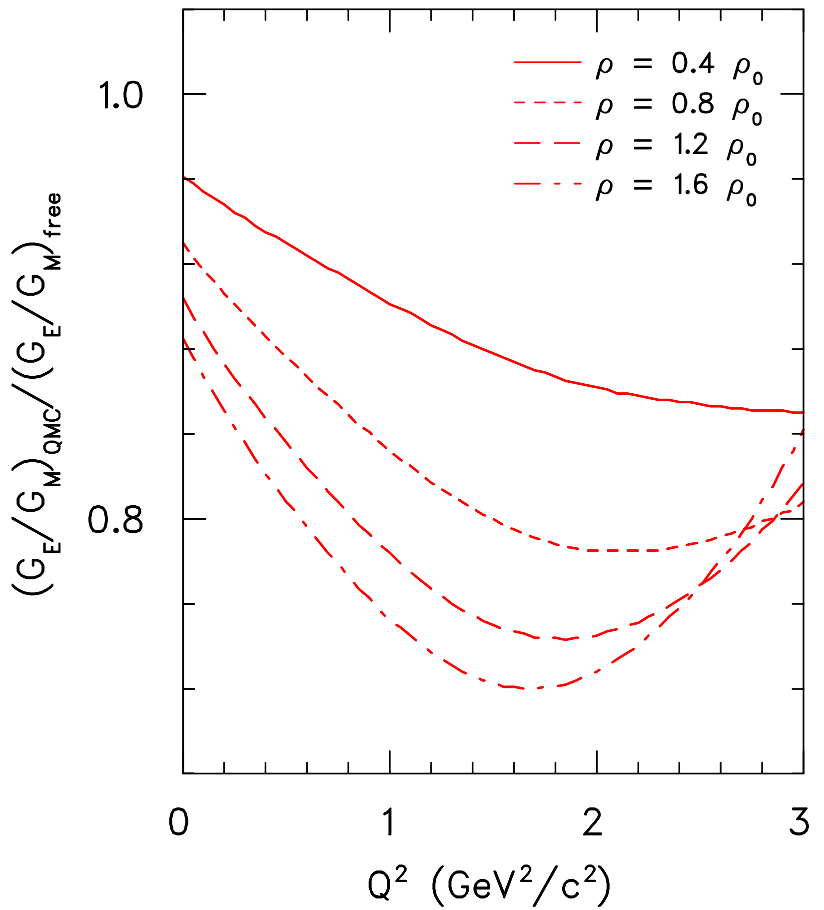
Figure curtesy of R. Schiavilla. Calculation not yet acceptance averaged.
Schiavilla, Benhar, Kievsky, Marcucci, and Viviani, in preparation.

Polarization-Transfer Ratio



J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999)
D. Debruyne *et al.*, Phys. Rev. C **62**, 024611 (2000), J. Ryckebusch *et al.*, Nucl. Phys. A **728**, 226 (2003)

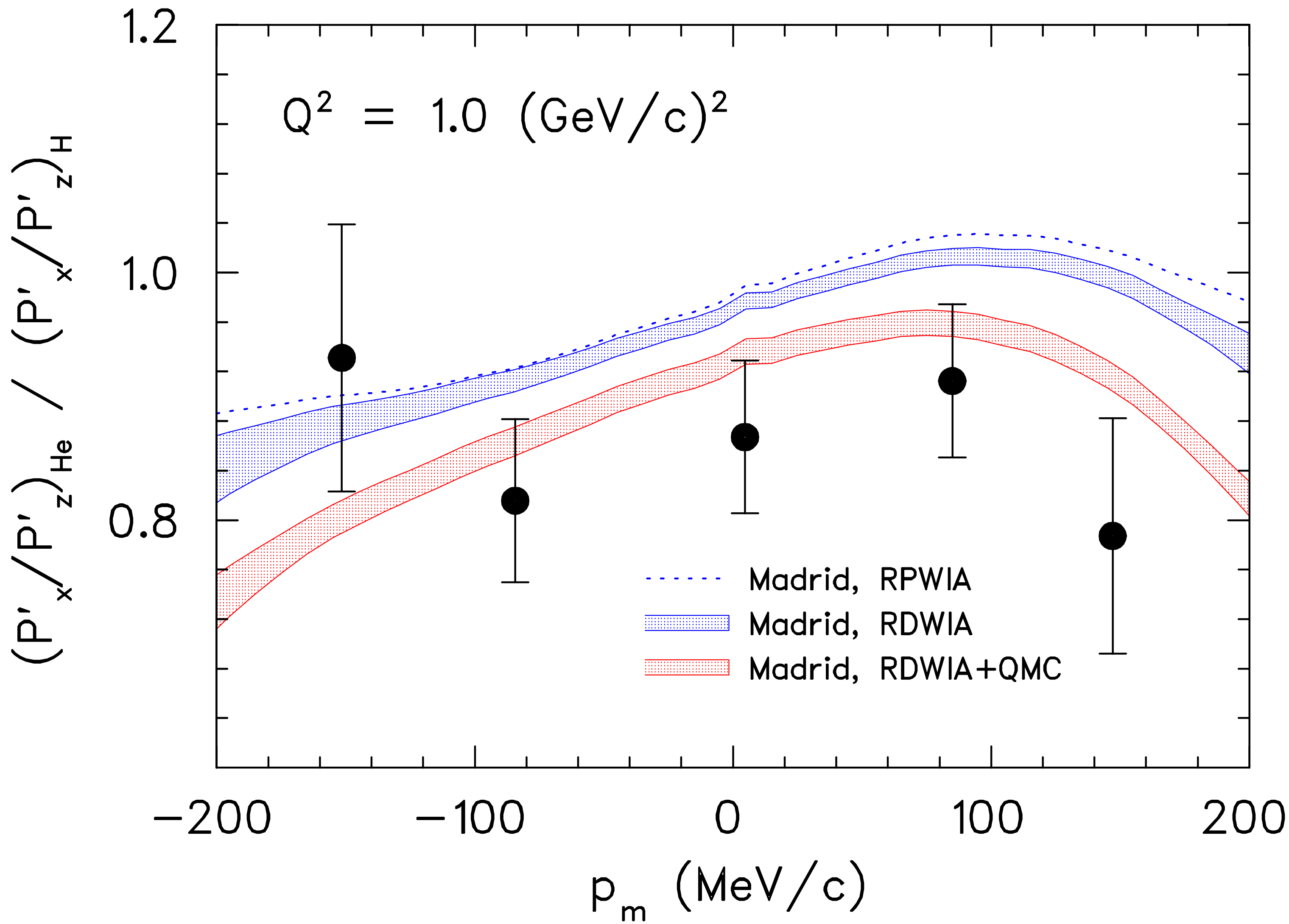
In-Medium Nucleon Form Factor



- Quark meson coupling model
- Chiral quark-soliton model
- Modified Skyrme model
- Form factor suppressed as density increases
- Calculations in agreement with existing exp. limits on medium modifications

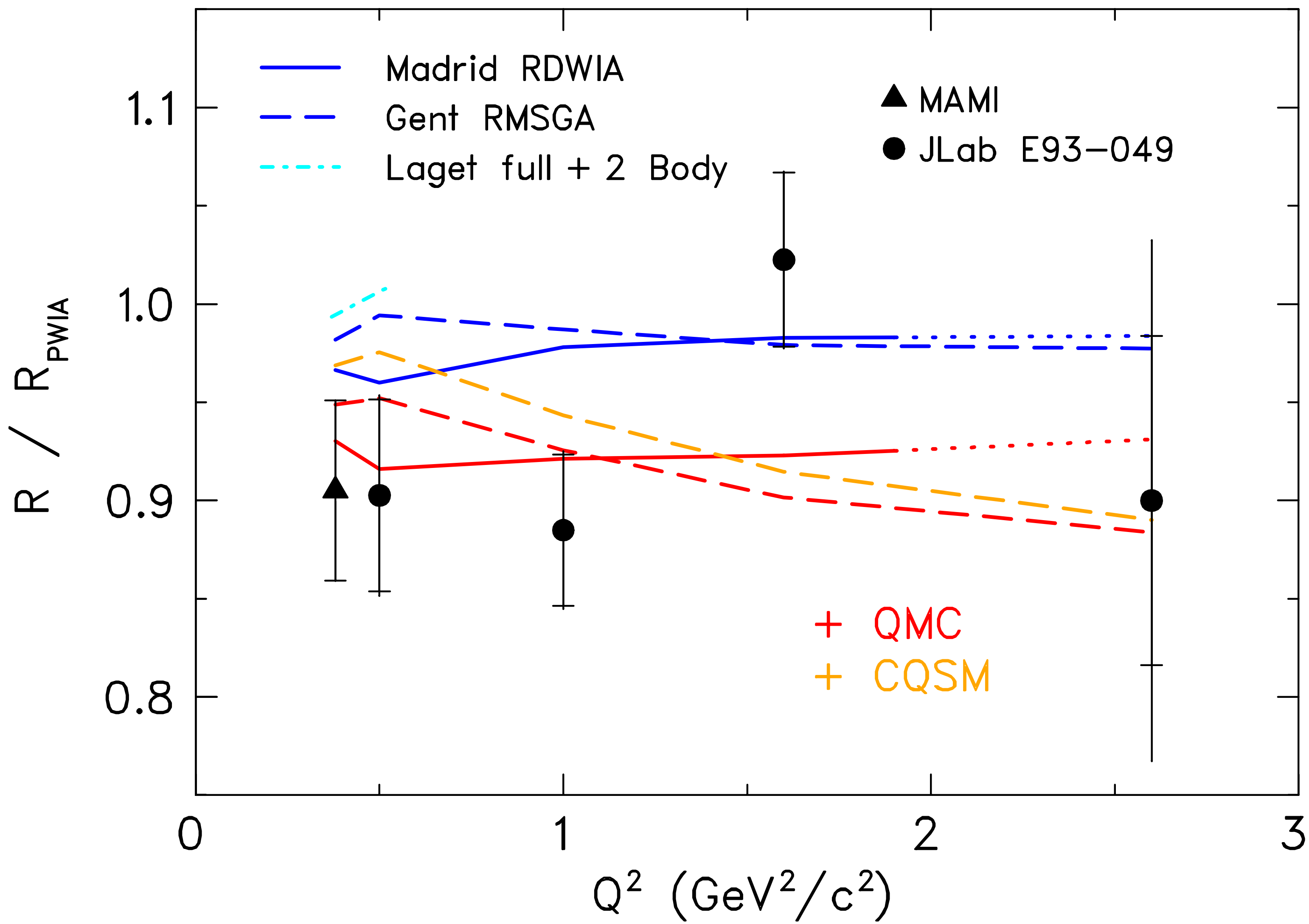
QMC: D.H. Lu *et al.*, Phys. Rev. C **60**, 068201 (1999)
Soliton: Jason R. Smith and Gerald A. Miller, Phys. Rev. Lett. **91**, 212301 (2003)
Skyrme: U. Yakhshiev, U. Meißner, A. Wirzba, Eur. Phys. J. A **16**, 569 (2003)

RDWIA including QMC Form Factors



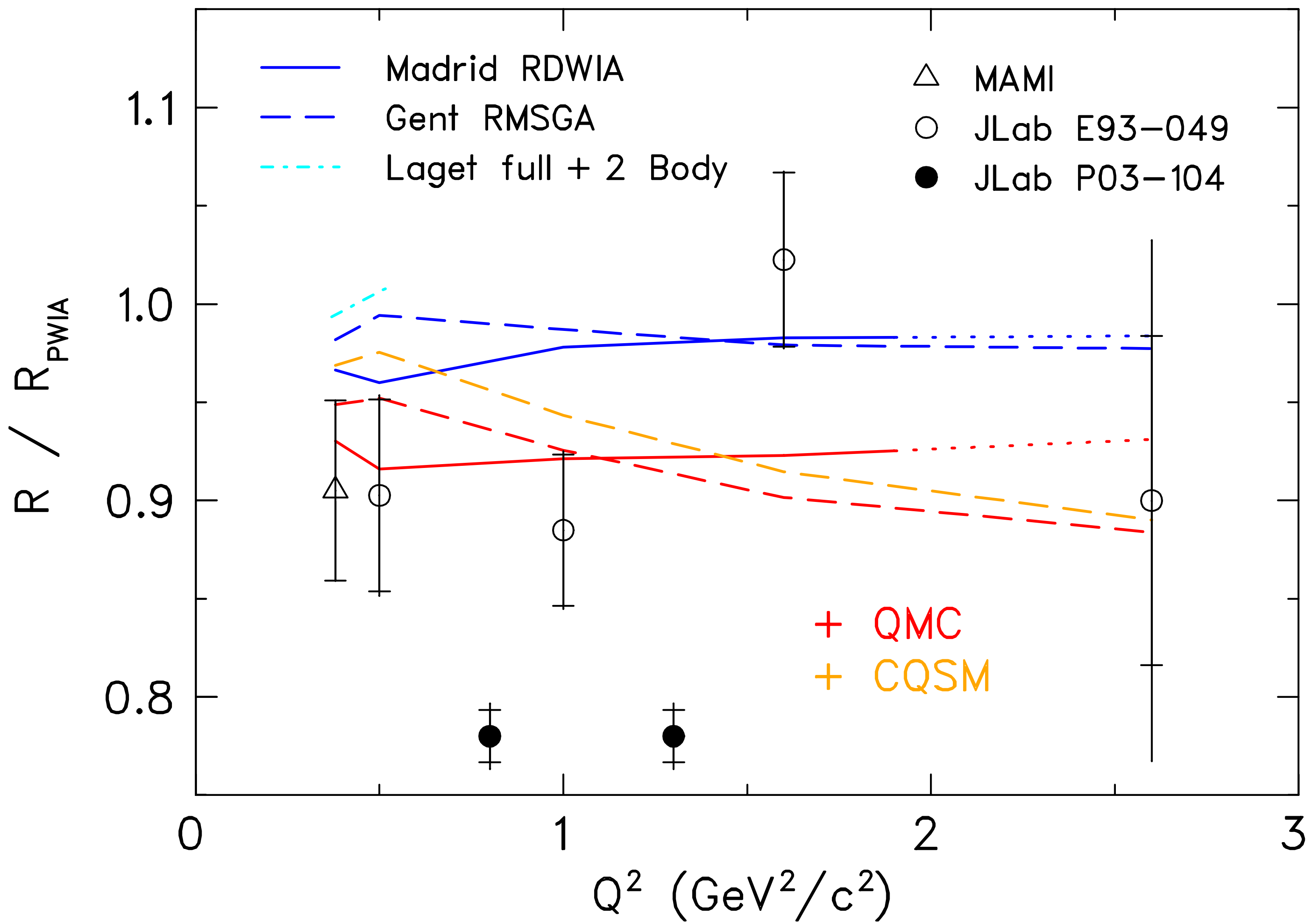
J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999)
D.H. Lu *et al.*, Phys. Rev. C **60**, 068201 (1999)

Polarization Double Ratio — Summary



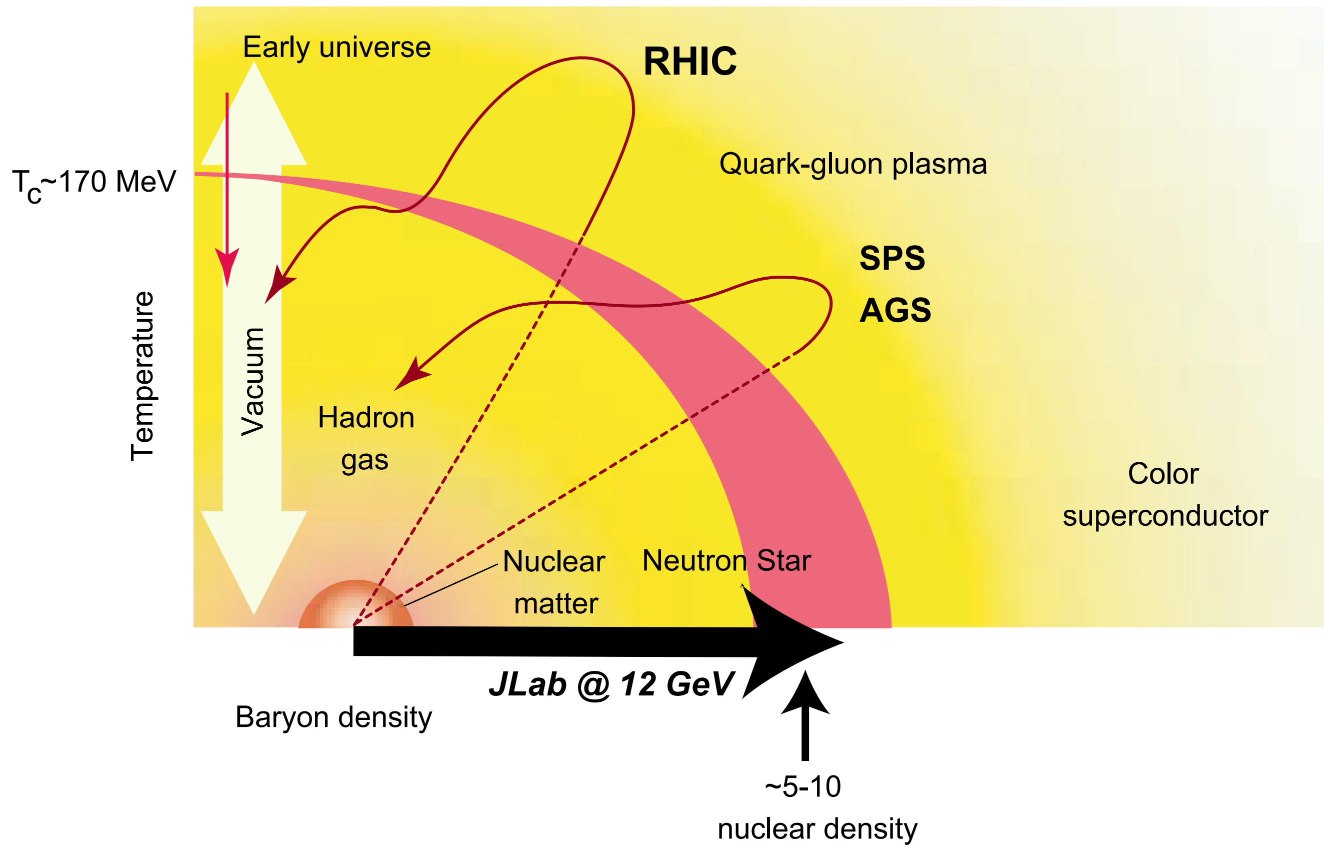
- Data effectively described by proton medium modifications
- In-medium form factors reduce double ratio by ≈ 6% at 1 GeV^2/c^2

New Experiment E03-104



New data on polarization-transfer ratio and induced polarization could put conventional model of nuclear physics to rigorous test.

Phase Diagram for Hadronic Matter



- At nuclear matter densities 0.17 nucleons/fm^3 nucleon wave functions nearly overlap.
- JLab energy upgrade allows to study high density configurations

Figure from: Pre-Conceptual Design Report for The Science and Experimental Equipment for The 12 GeV Upgrade of CEBAF (2004)

The EMC Effect at 12 GeV

- With the 12 GeV upgrade, Jefferson Lab can improve data at large x and in light nuclei (^{3}He, ^{4}He)
  - Determine if EMC effect depends on A or ρ

    $\rho_{^4\mathrm{He}} \approx \rho_{^{12}\mathrm{C}}$
  - Allow to evaluate models of EMC effect

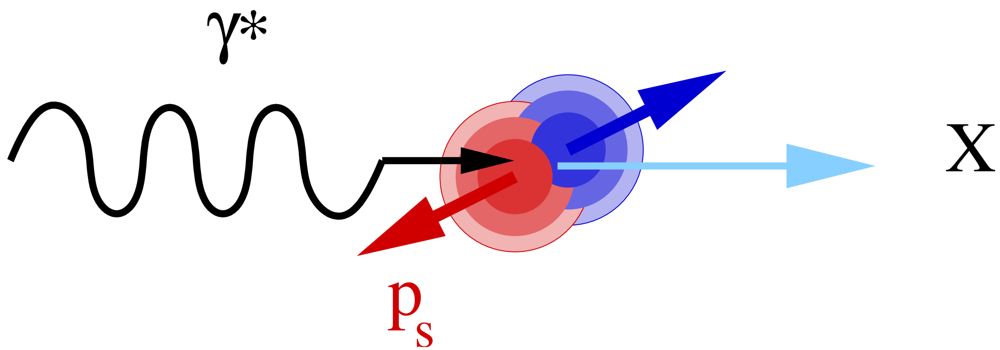
    e.g., different x-dependence in few-body nuclei and heavy nuclei
- Probing high-density configurations

  Example: Tagged EMC Effect on deuterium

Pre-Conceptual Design Report for The Science and Experimental Equipment for The 12 GeV Upgrade of CEBAF (2004); M.M. Sargsian *et al.*, J. Phys. G: Nucl. Part. Phys. **29**, 1 (2003)

Tagged EMC Effect

- Measure nuclear structure function in semi-inclusive $d(e, e'p_s)X$ reaction



- Tagged proton in backward hemisphere

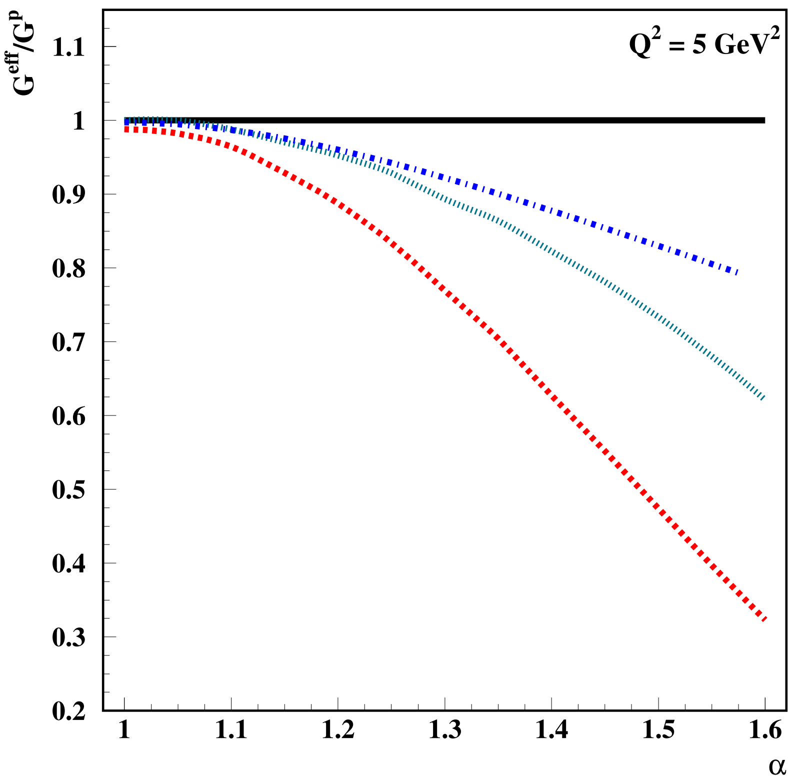
Small $|p_s|$, $\alpha \approx 1$ $\longrightarrow$ free neutron

Large $|p_s|$, $\alpha > 1$ $\longrightarrow$ high density configuration

(α: light-cone momentum fraction of spectator)

α-Dependence Cross-Section Ratio G

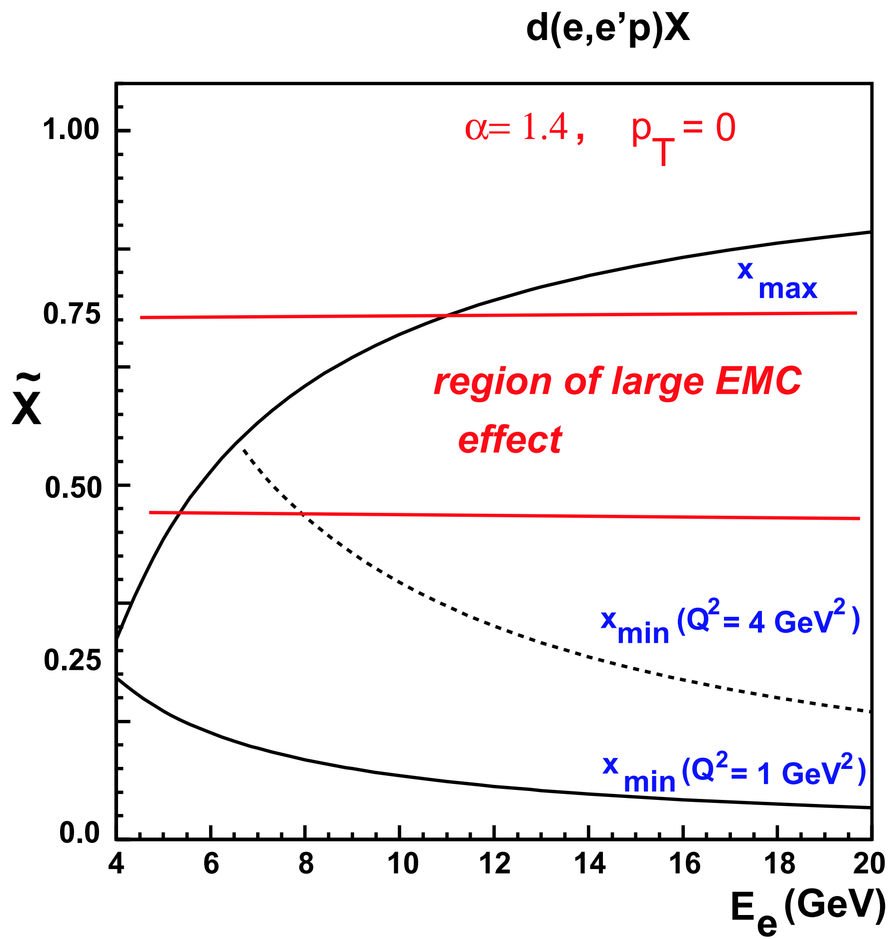
$$G(\alpha) = \frac{\sigma(x_1, \text{large EMC effect})}{\sigma(x_2, \text{no EMC effect})}$$



- off-shell model (dot-dashed) Melnitchouk, Schreiber, Thomas (1994)
- color-delocalization model (dotted) Close, Roberts, Ross (1983)
- color-screening model (dashed) Frankfurt, Strikman (1985)

Figure from M.M. Sargsian *et al.*, J. Phys. G: Nucl. Part. Phys. **29**, 1 (2003)

CLAS Experiment with 11 GeV Beam



- Region of large EMC effect and α = 1.4 accessible with 11 GeV electron beam

$\tilde{x}$: momentum fraction carried by the struck quark in the moving nucleon

Figure from M.M. Sargsian *et al.*, J. Phys. G: Nucl. Part. Phys. **29**, 1 (2003)

Summary

- **Vector Mesons** in the nuclear medium
  - Heavy-ion experiments: dropping of ρ mass in medium
  - New photoproduction experiments (CBTAPS, CLAS)
- **Nucleons** in the nuclear medium
  - EMC effect: conventional theory unable to provide explanation
  - Present $^{4}\mathrm{He}(\vec{e}, e'\vec{p})^{3}\mathrm{H}$ recoil polarization data
    - Significant deviation from RDWIA and microscopic results, effectively described by proton medium modifications
    - Possibly larger contribution from spin-dependent charge-exchange reaction
    - Induced polarization crucial
- JLab upgrade makes possible probing of high nuclear densities
  - Extend measurements to high x, low A
  - Tagged EMC effect in deuterium