Search for Proton Medium Modifications in the $^4He(e,e'p)$ Reaction

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Motivation

- Accurate description of A(e,e') data sets strong restrictions on nuclear models of neutrino reactions, A(ν_l, l^-)
- Nuclear reaction-model ingredients:
  - Relativity
  - Final-state interactions
  - Medium modifications
  - …
- Exclusive A(e,e'p) data provide for additional, sensitive tests
  - Cross sections
  - Polarization observables

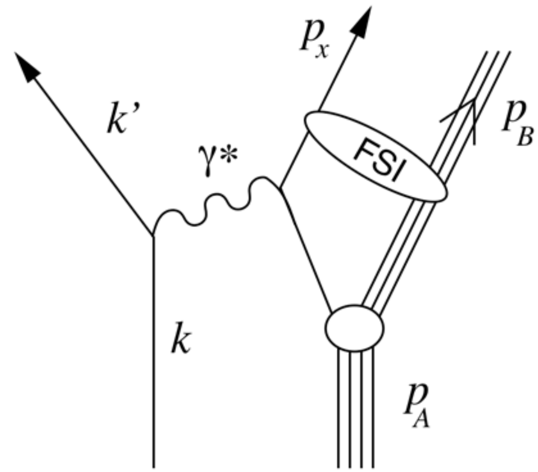
e.g., O. Benhar *et al.*, Phys. Rev. D **72**, 053005 (2005); J.E. Amaro *et al.,* Phys. Rev. C **75**, 034613 (2007); K. Tsushima, H. Kim, K. Saito, Phys. Rev. C **70**, 038501 (2004)

Outline

- Electron-nucleus scattering
  - Example model: Relativistic distorted-wave impulse approximation (RDWIA)
- Nucleons in the nuclear medium
  - Example model: Quark meson coupling model (QMC)
- Experimental results
  - Polarization-transfer technique
  - ^{1}H(e,e’p) : Free proton electromagnetic form factors
  - ^{4}He(e,e’p) : Search for proton medium modifications
- Summary

Quasielastic Scattering from Bound Nucleons

A(e,e'p): Nucleon one-body current in relativistic distorted-wave impulse approximation (RDWIA)



$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\, \bar{\psi}_F(\vec{p}+\vec{q}) \hat{J}_N^\mu(\omega,\vec{q}) \psi_B(\vec{p})$$

- Relativistic ψ_B and ψ_F wave functions for initial bound and final outgoing nucleons, respectively.
- Relativistic nucleon current operator of cc1 or cc2 forms

$$\hat{J}_N^\mu(\mathrm{cc1}) = (F_1 + \bar{\kappa}F_2)\gamma^\mu - \frac{\bar{\kappa}F_2}{2M}(P_F + \bar{P}_I)^\mu$$

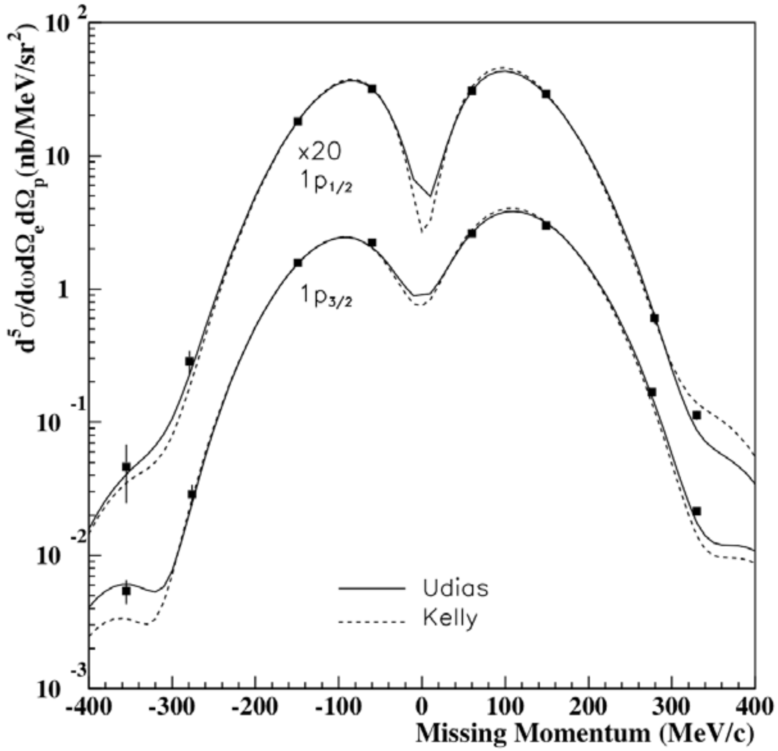
(possible medium-modified form factors enter here)

J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999)

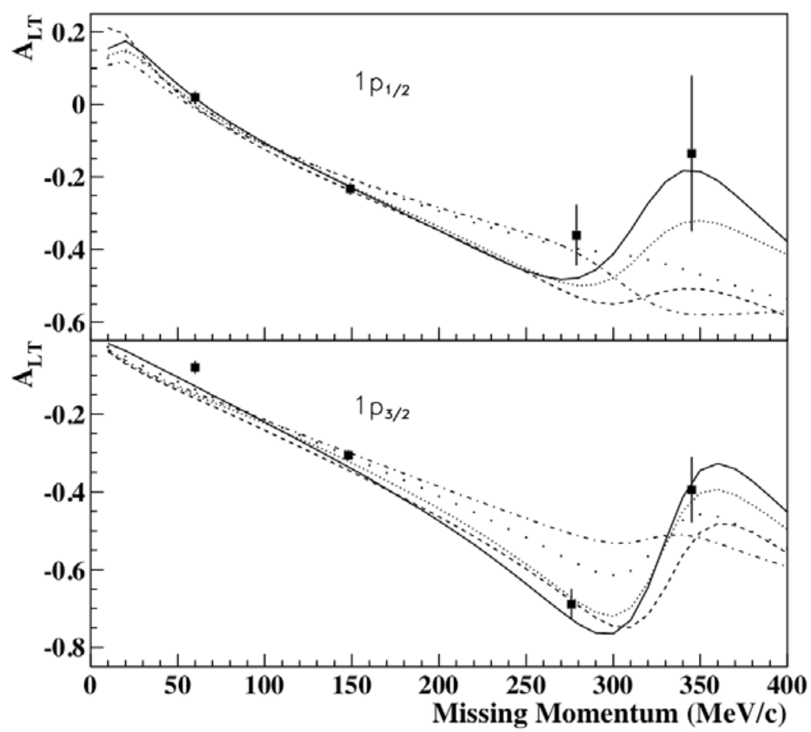
Excellent Description of Many Observables

$^{16}O(e,e'p)$ at $Q^2 = 0.8\ (GeV/c)^2$

Cross section



Left-Right Asymmetry A_{LT}



- Importance of fully relativistic calculation; here, particularly, the bound-state spinor distortion
- Also excellent description of $^{12}C(e,e'\mathbf{p})$ induced polarization.

J. Gao *et al.*, Phys. Rev. Lett. **84**, 3265 (2000); J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999)

Nucleon in the Nuclear Medium

QCD *vs.* conventional Nuclear Physics

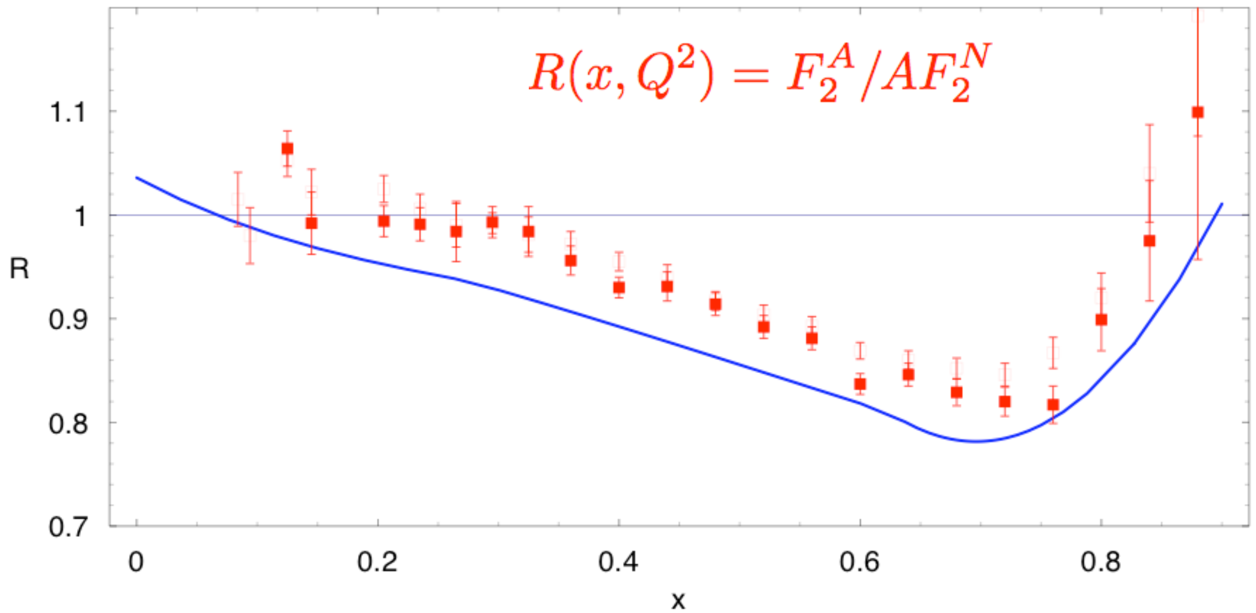
- Conventional Nuclear Physics:
  Nucleons are effectively and well described as
  - point-like protons and neutrons (+ form factor)
  - interaction through effective forces (meson exchange)

- Underlying theory: QCD
  - Nucleons and mesons are not the fundamental entities
  - In the chiral limit, phase transition to quark-gluon plasma

P.A.M. Guichon and A.W. Thomas, Phys. Rev. Lett. **93**, 132502 (2004)

The EMC Effect

- 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



- → Nucleon structure is modified in the nuclear medium

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

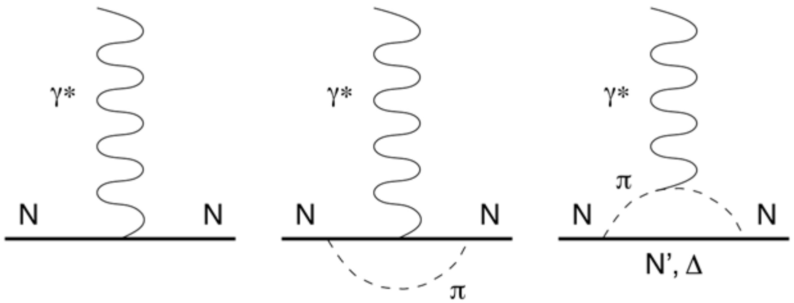
Limits for Medium Modifications

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

[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)

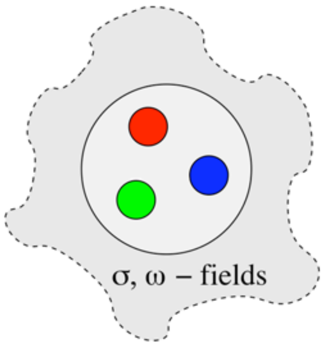
Quark Meson Coupling Model (QMC)

- Structure of the nucleon described by valence quarks in a bag (Cloudy-bag model).



intermediate baryon restricted to N or Δ

- Nuclear system described using effective scalar (σ) and vector (ω) meson fields.

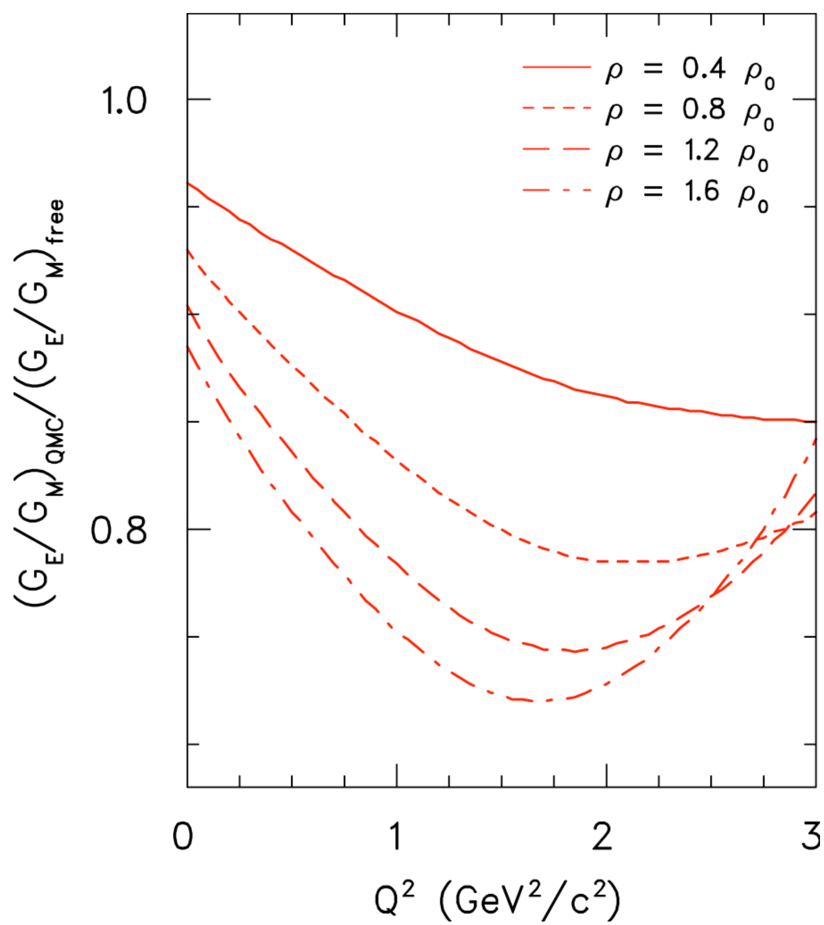


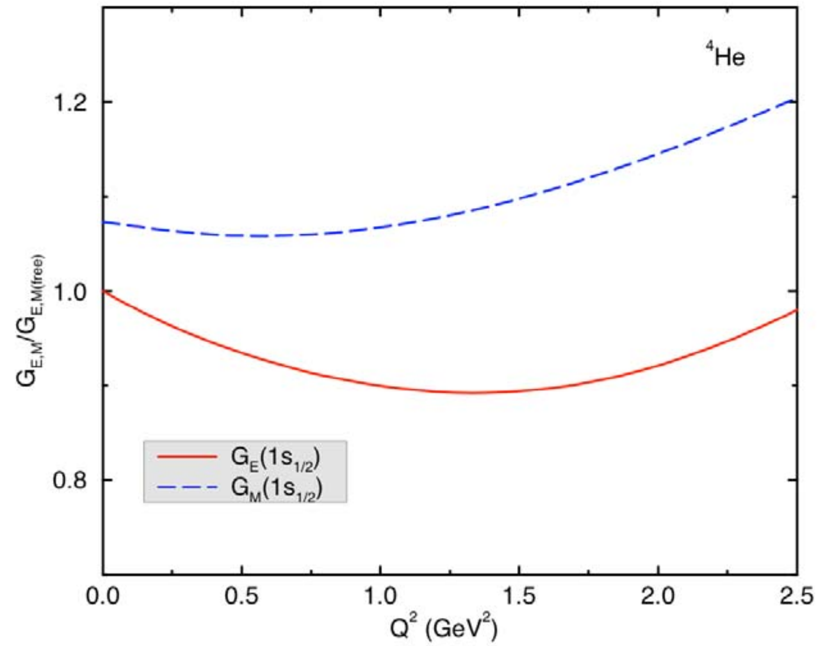
- Scalar and vector fields of nuclear matter couple directly to confined quarks.

→ Modification of internal structure of bound nucleon

QMC: 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); **Other models**: e.g.: J.R. Smith and G.A. Miller, Phys. Rev. C **70**, 065205 (2004); T. Horikawa, W. Bentz, Nucl. Phys. A **762**, 102 (2005)

Bound Proton EM Form Factors



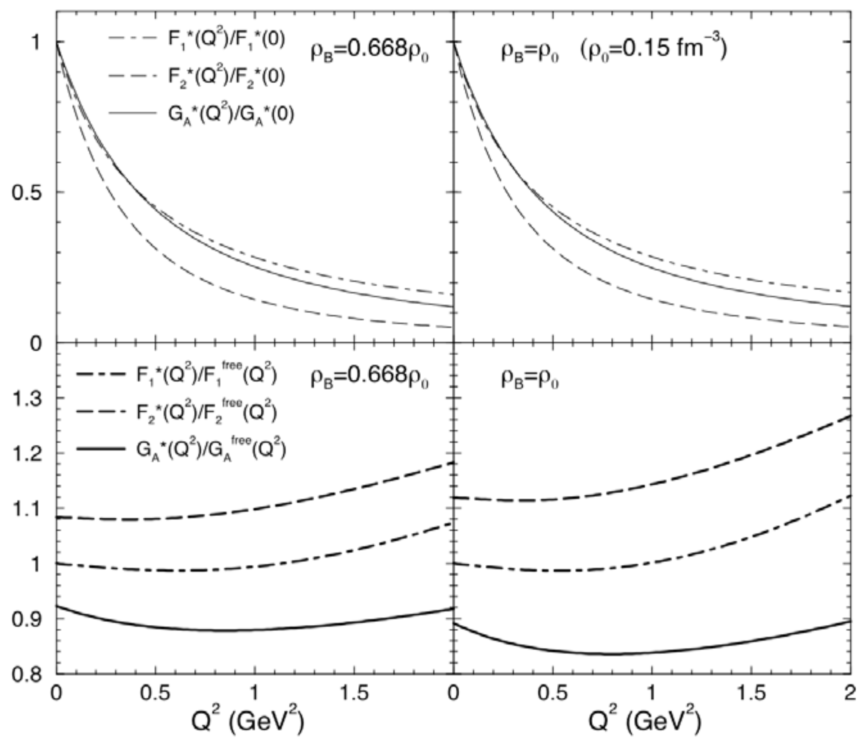


D.H. Lu *et al.*, Phys. Rev. C **60**, 068201 (1999)

- Electromagnetic rms radii and magnetic moments of the bound proton are increased
- Charge form factor much more sensitive to the nuclear medium than the magnetic ones.

Effect on charged-current ν-A scattering

QMC bound nucleon form factors of vector and axial-vector currents



- Tsushima *et al*. compute the inclusive $^{12}C(\nu_\mu, \mu^-)X$ cross sections using a relativistic Fermi gas model with the calculated bound nucleon form factors.
- The effect of the bound nucleon form factors for this reaction is a reduction of 8% for the total cross section, relative to that calculated with the free nucleon form factors.

K. Tsushima, Hungchong Kim, and K. Saito, Phys. Rev. C **70**, 038501 (2004)

Polarization-Transfer Technique

- Free electron-nucleon scattering

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

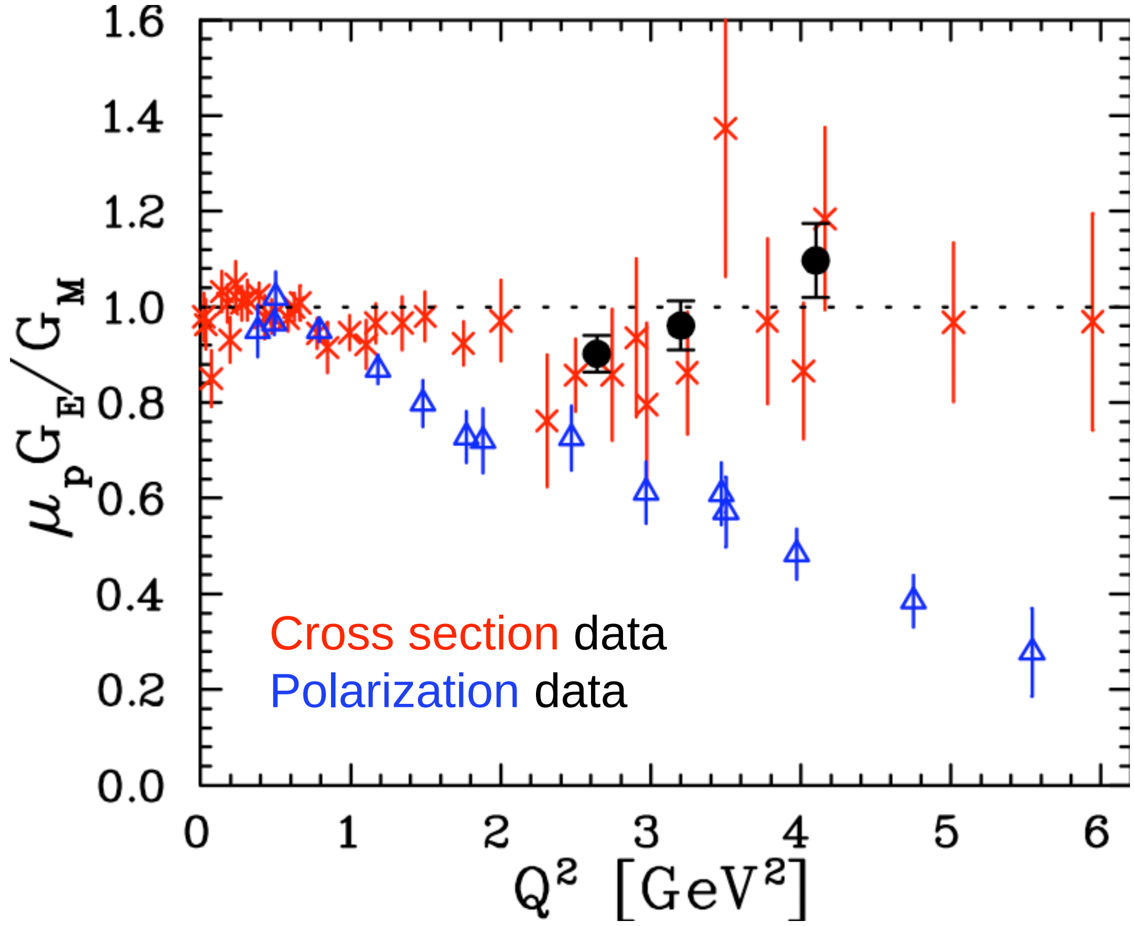
- Bound nucleons → evaluation within model

Reaction-mechanism effects in $A(\vec{e}, e'\vec{p})B$ predicted to be small and minimal for

  - Quasielastic scattering
  - Low missing momentum
  - Symmetry about $\boldsymbol{p}_m = 0$

R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981); for reaction-mechanism effects, *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).

Proton Elastic Form-Factor Ratio

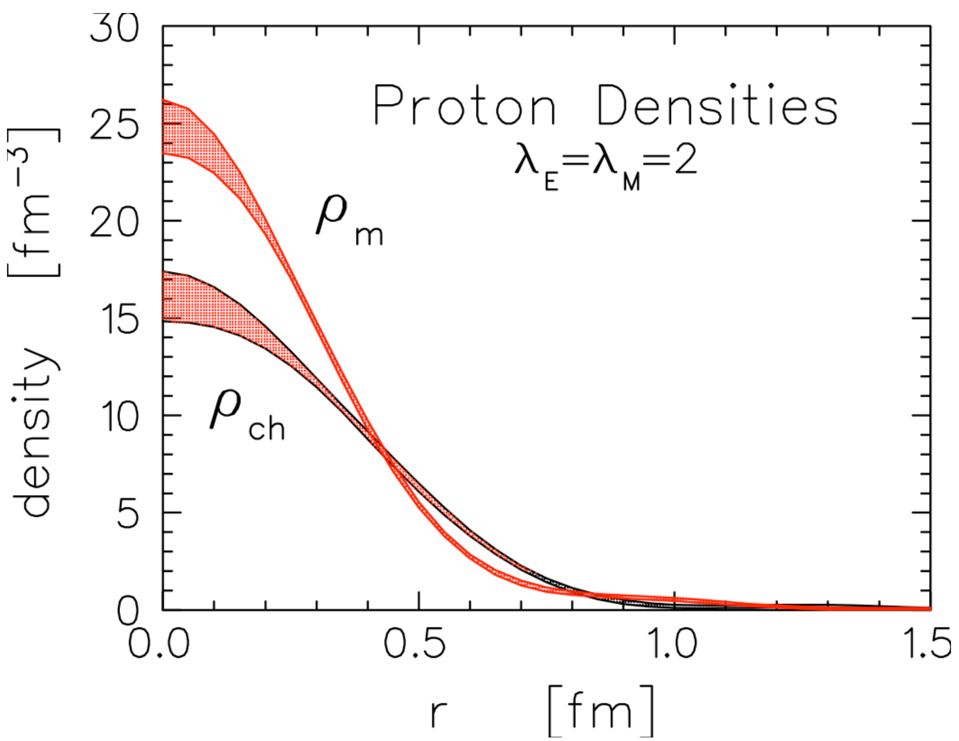


- Systematic decrease of G_E / G_M indicating difference in spatial distribution of charge and magnetization currents in the proton.

Figure from: I.A. Qattan, Phys. Rev. Lett. **94**, 142301 (2005)

Proton Charge and Magnetization Densities

Parameterization of nucleon e.m. form factors based upon radial densities



- Proton charge density is broader than magnetization density

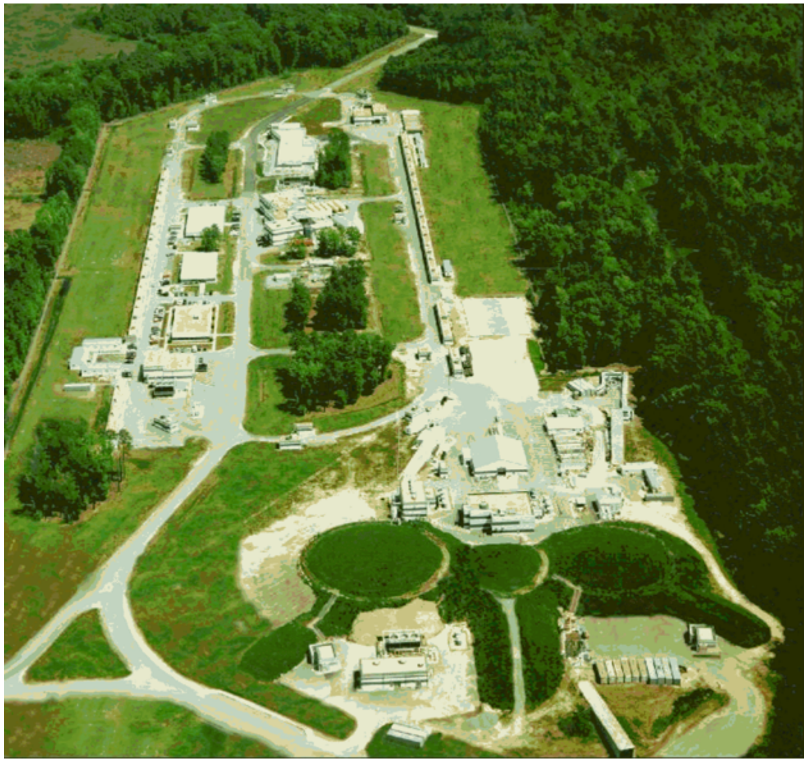
$$\langle r_E^2 \rangle > \frac{1}{\mu_p} \langle r_M^2 \rangle$$

- Consistent with polarizabilities

$$\alpha_E > \beta_M$$

J.J. Kelly, Phys. Rev. C **66**, 065203 (2002)
S. Kondratyuk, K. Kubodera, and F. Myhrer, Phys. Rev. C **71** , 028201 (2005)

Thomas Jefferson National Accelerator Facility



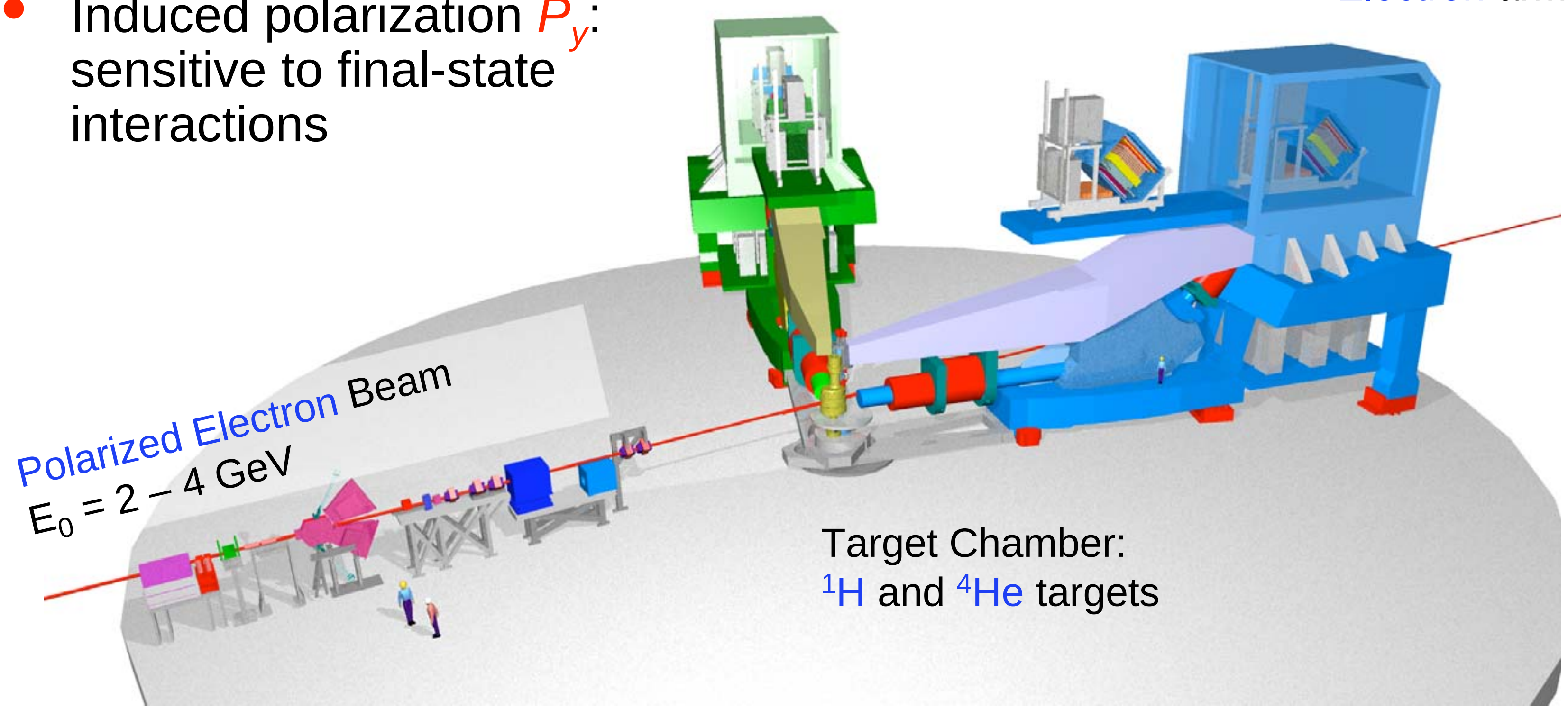
JLab in Newport News, VA

- Electron-beam accelerator
- Polarized electron beam
- Beam energies up to $E_0 = 6$ GeV
- Three experimental Halls A, B, and C

E93-049 and E03-104 at Jefferson Lab Hall A

$^4\mathrm{He}(\boldsymbol{e},\boldsymbol{e}'\vec{\boldsymbol{p}})^3\mathrm{H}$ in quasielastic kinematics Q^2 = 0.5 – 2.6 (GeV/c)^2

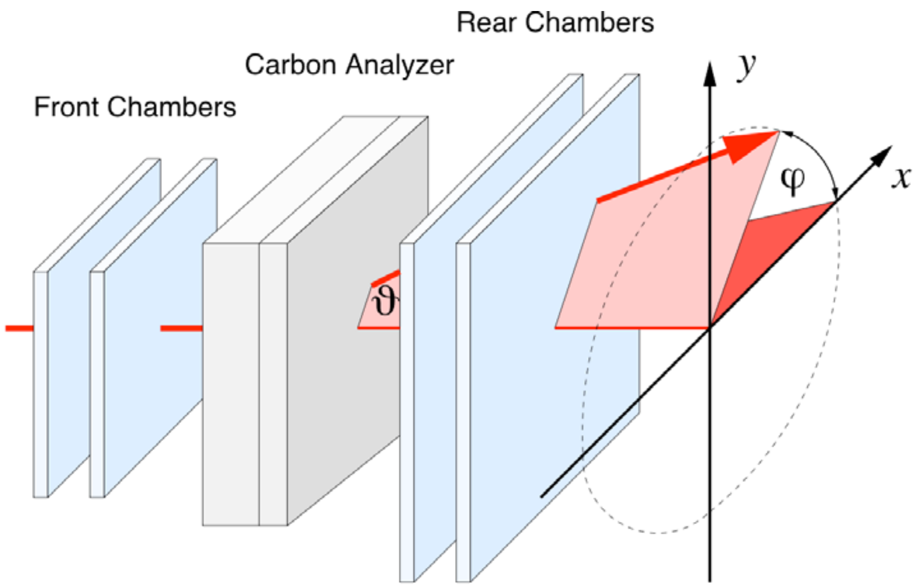
- Polarization-transfer ratio P'_x/P'_z: sensitive to G_E/G_M
- Induced polarization P_y: sensitive to final-state interactions

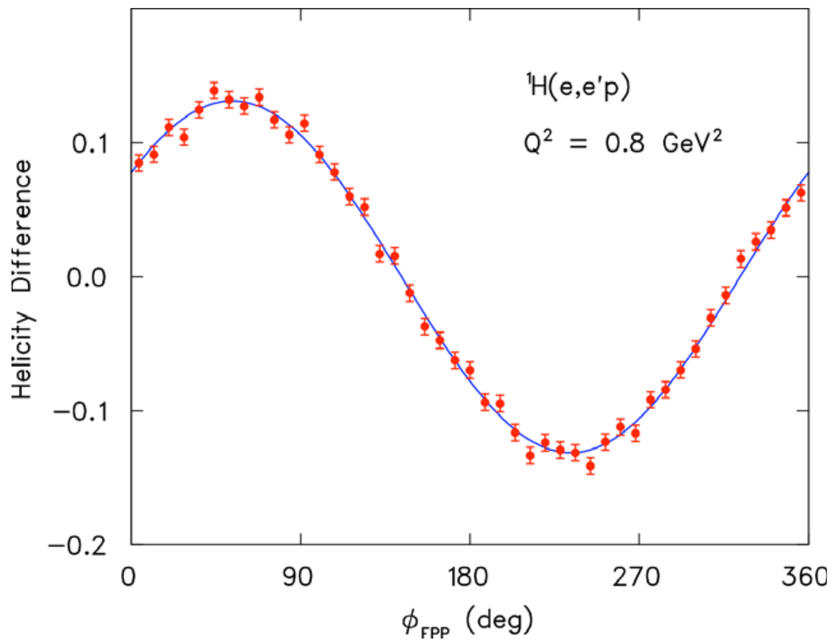


S. Dieterich, *et al.*, Phys. Lett. **B500**,47(2001); S. Strauch, *et al.*, Phys. Rev. Lett. **91**, 052301(2003); JLab E03-104, R.Ent, R. Ransome, S. Strauch, P. Ulmer (spokespersons)

Polarization Measurement

Focal-Plane Polarimeter

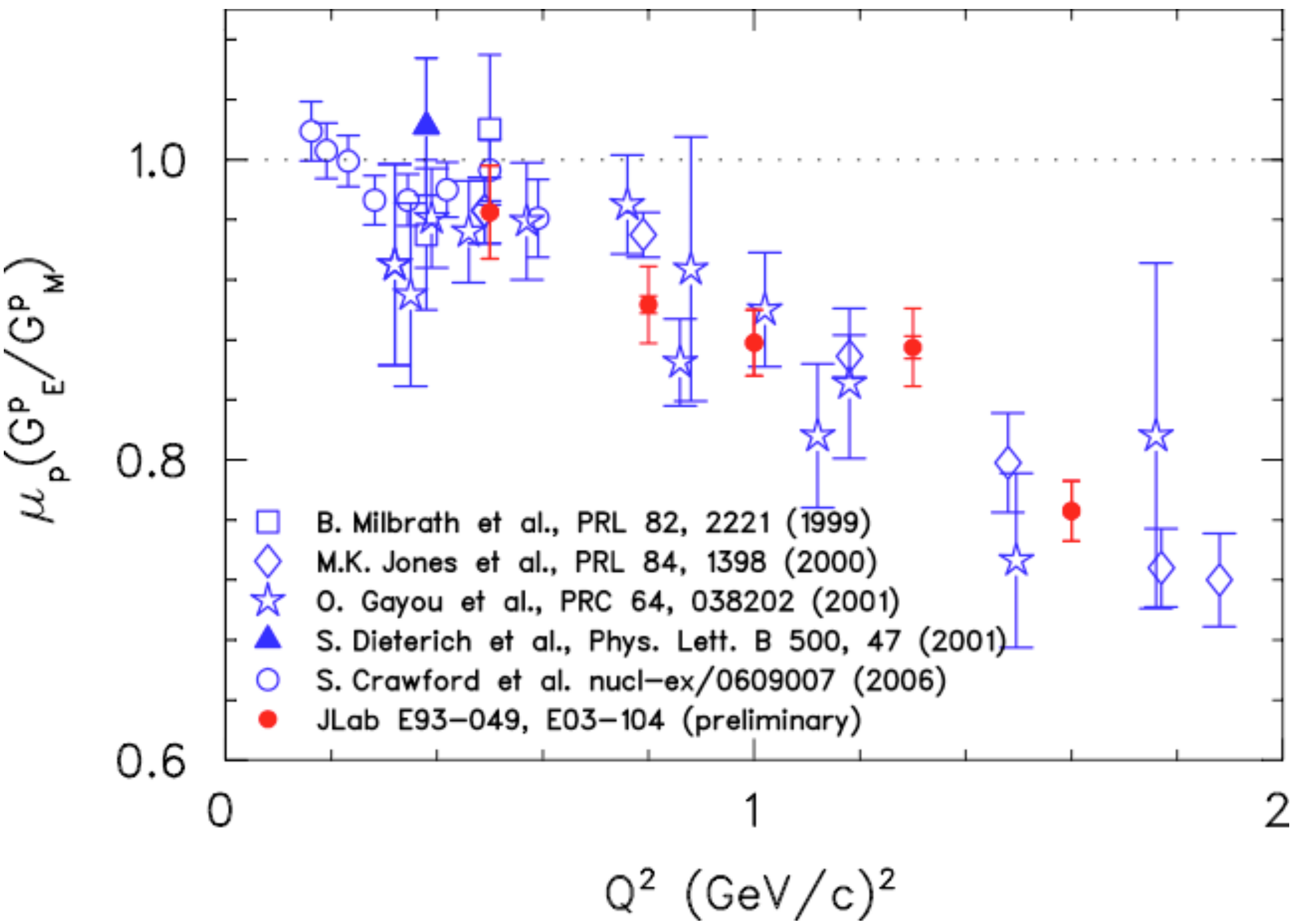




Observed angular distribution

$$
\begin{aligned}
I(\vartheta, \varphi) &= I_0(\vartheta)\left(1 + \epsilon_y \cos\varphi + \epsilon_x \sin\varphi\right) \\
&= I_0(\vartheta)\left[1 + A_C\left(P_y \cos\varphi - P_x \sin\varphi\right)\right]
\end{aligned}
$$

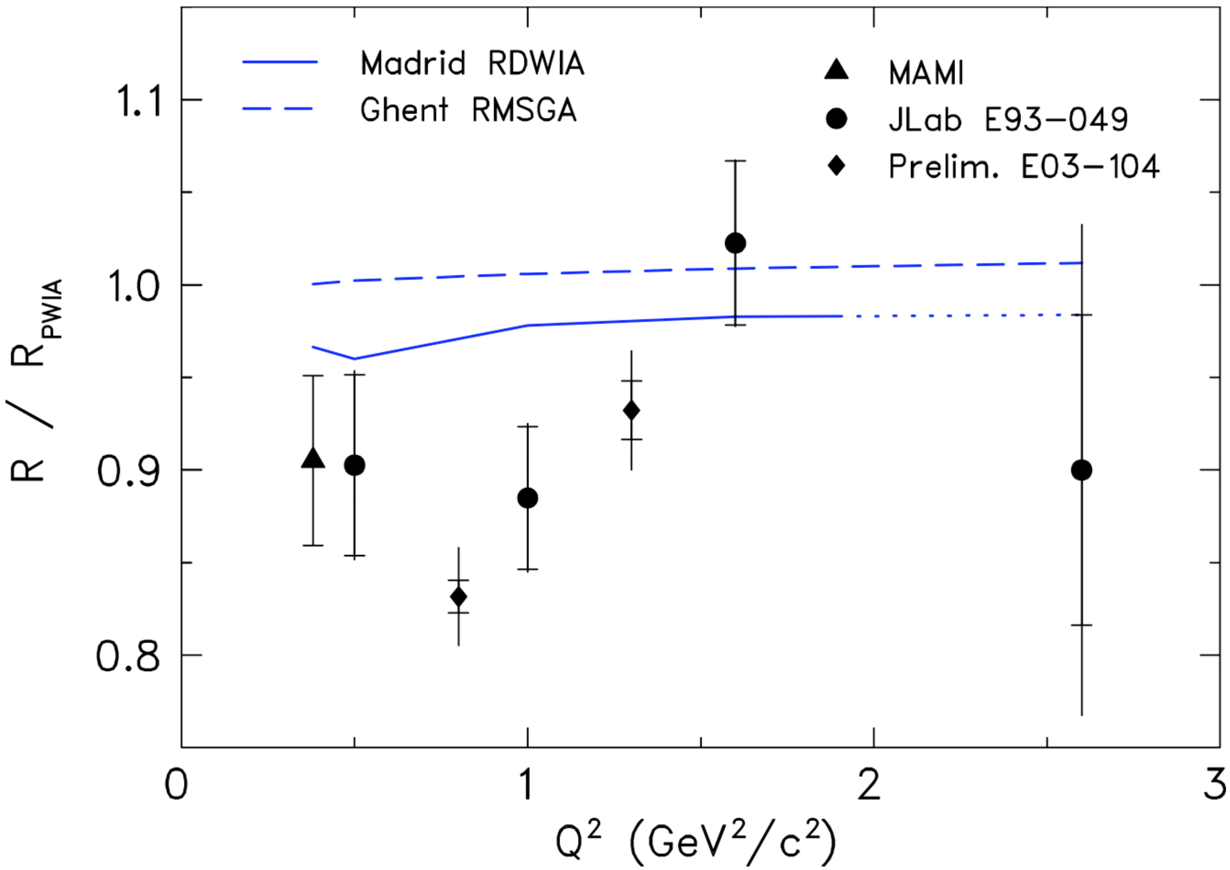
Free Proton Form-Factor Ratio G_E/G_M



- Preliminary results from E03-104 with small statistical uncertainties $\delta(P'x/P'z) \approx 0.7$ %

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

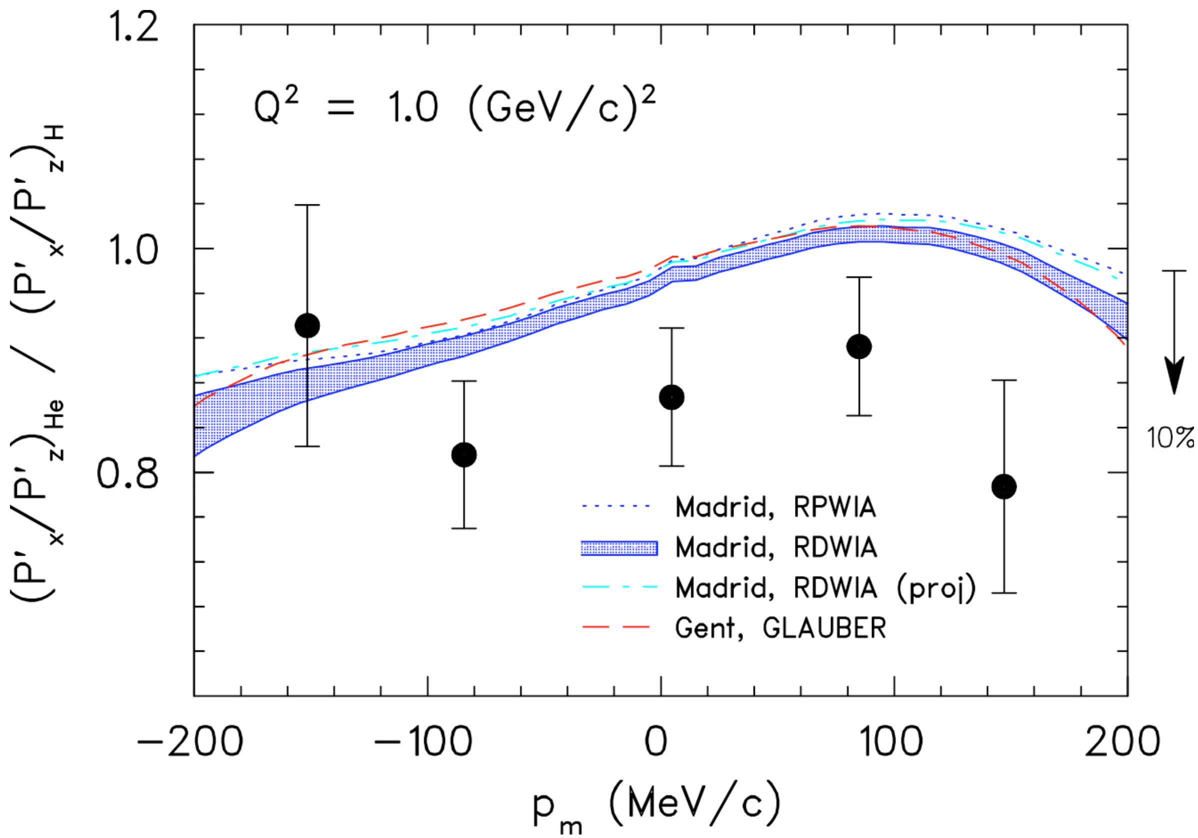
$$R = P'_x/P'_z(^4\mathrm{He})\,/P'_x/P'_z(^1\mathrm{H})$$



- RDWIA and RMSGA models can not describe the data.

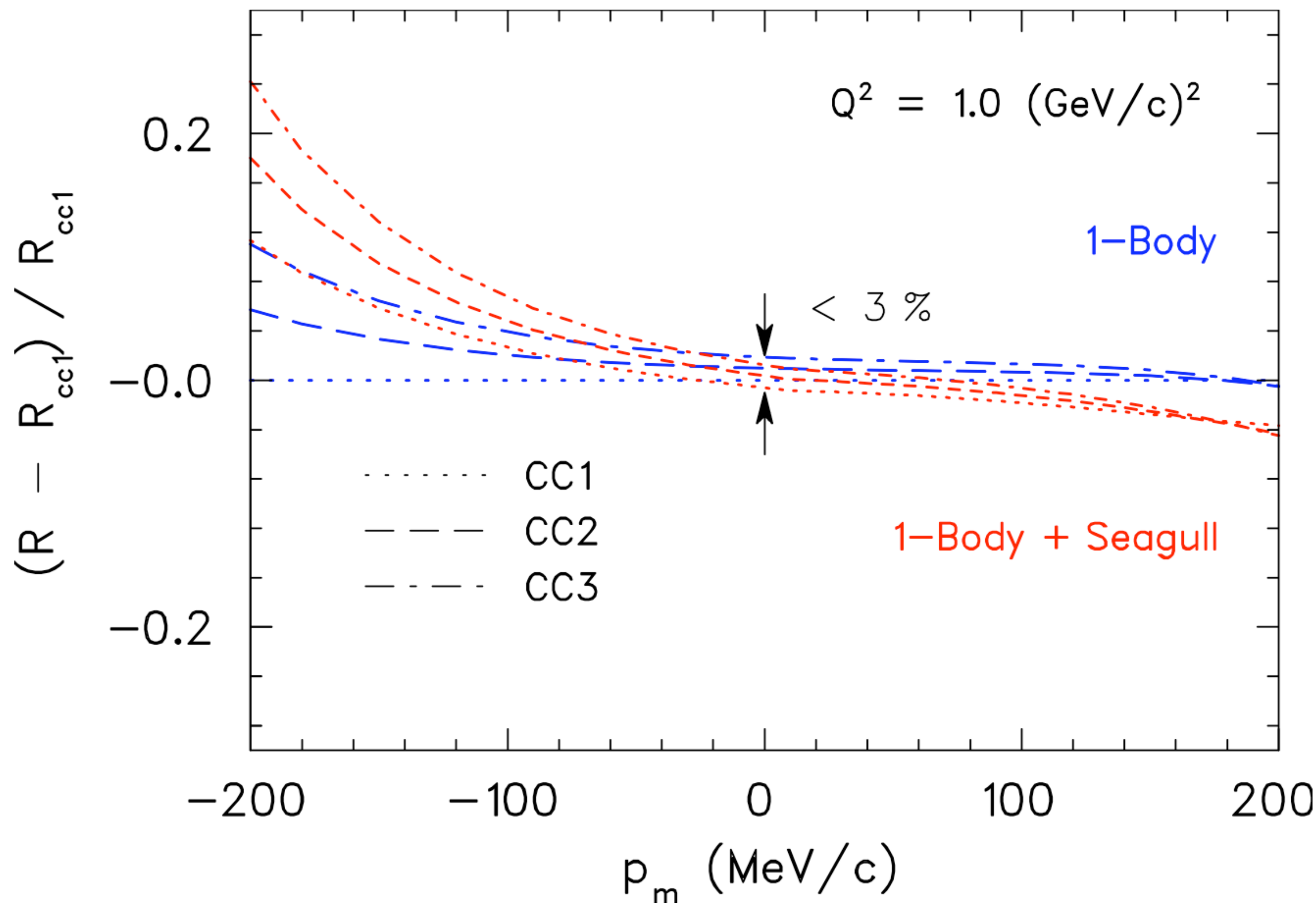
RDWIA: J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999);
RMSGA: P. Lava *et al.*, Phys. Rev. C **71**, 014605 (2005), D. Debruyne *et al.*, Phys. Rev. C **62**, 024611 (2000)

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



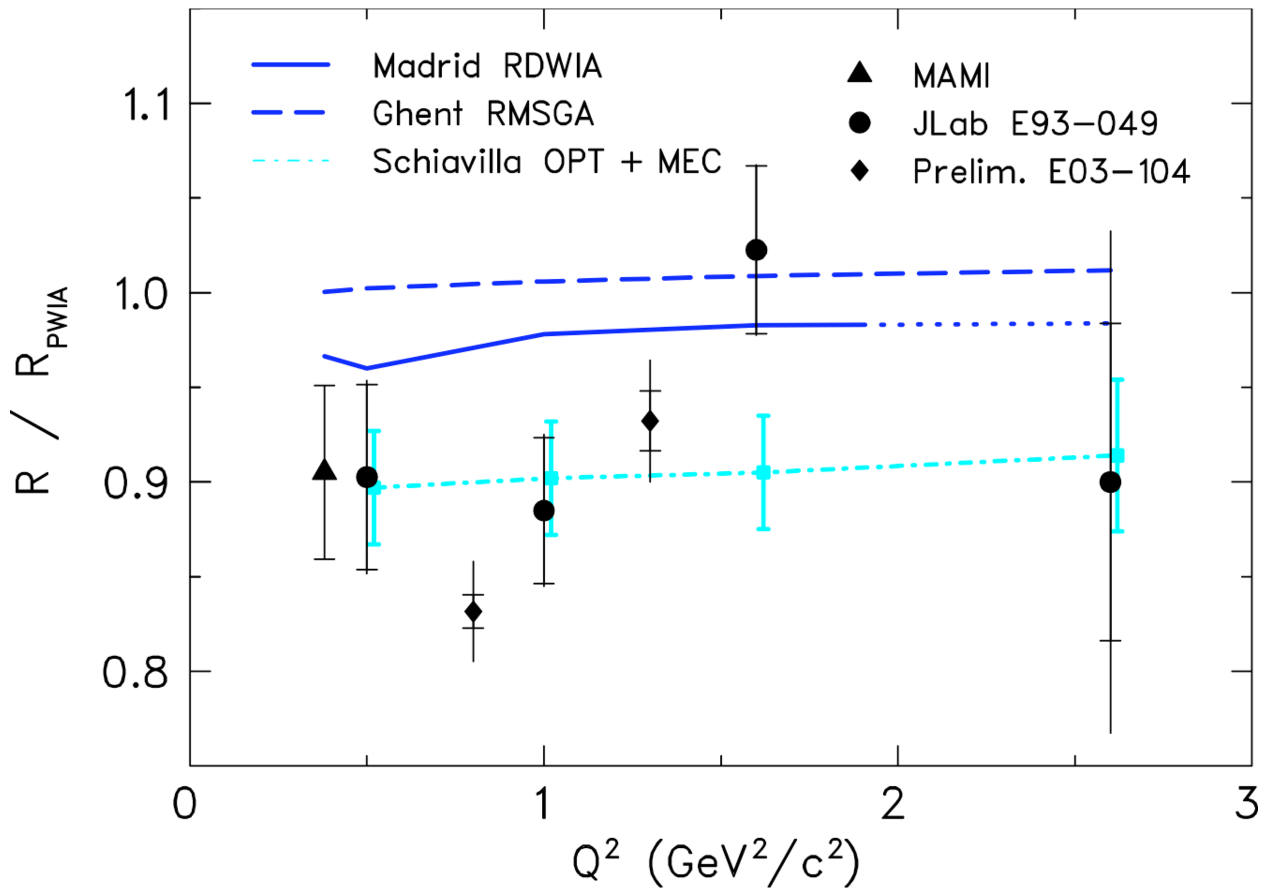
- $R^{RDWIA} \approx 0.97 \times R^{RPWIA}$
- Small sensitivity to
  - bound-state wave function
  - current operator
  - optical potential
- Enhancement of lower components (spinor distortions) in RDWIA

Limited Role of MEC in $^4He(e,e'p)^3H$



Relativistic mean-field calculation: A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C **66**, 034610 (2002)

Spin-Dependent Charge-Exchange FSI

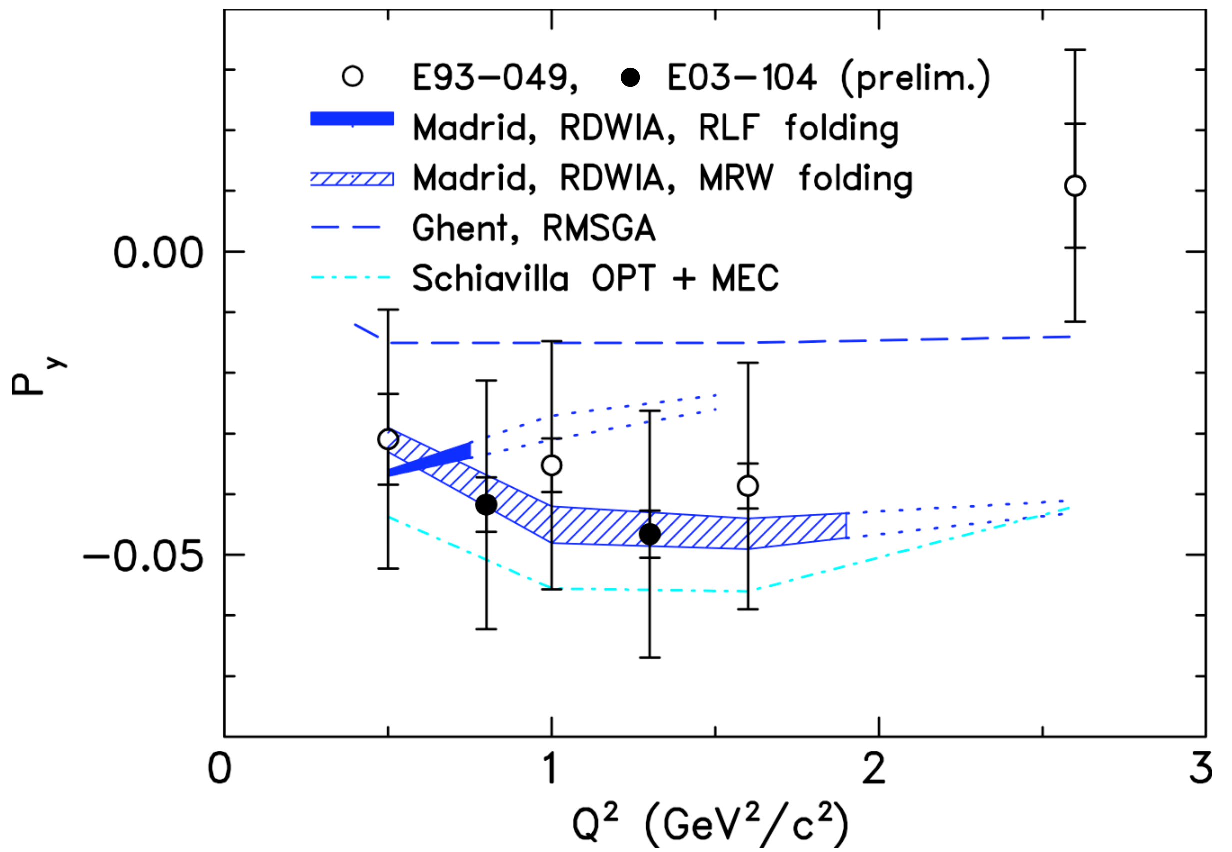


- R suppressed by about 4% from MEC
- Spin-dependent charge exchange FSI suppresses R by about 6%
- CH-EX term not well constrained ⇒ need P_y from E03-104

RDWIA: J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999)
RMSGA: P. Lava *et al.*, Phys. Rev. C **71**, 014605 (2005), D. Debruyne *et al.*, Phys. Rev. C **62**, 024611 (2000)
R. Schiavilla *et al.*, Phys. Rev. Lett. **94**, 072303 (2005)

Induced Polarization in $^4\text{He}(e,e'\vec{p})$

- P_y is a measure of final-state interactions



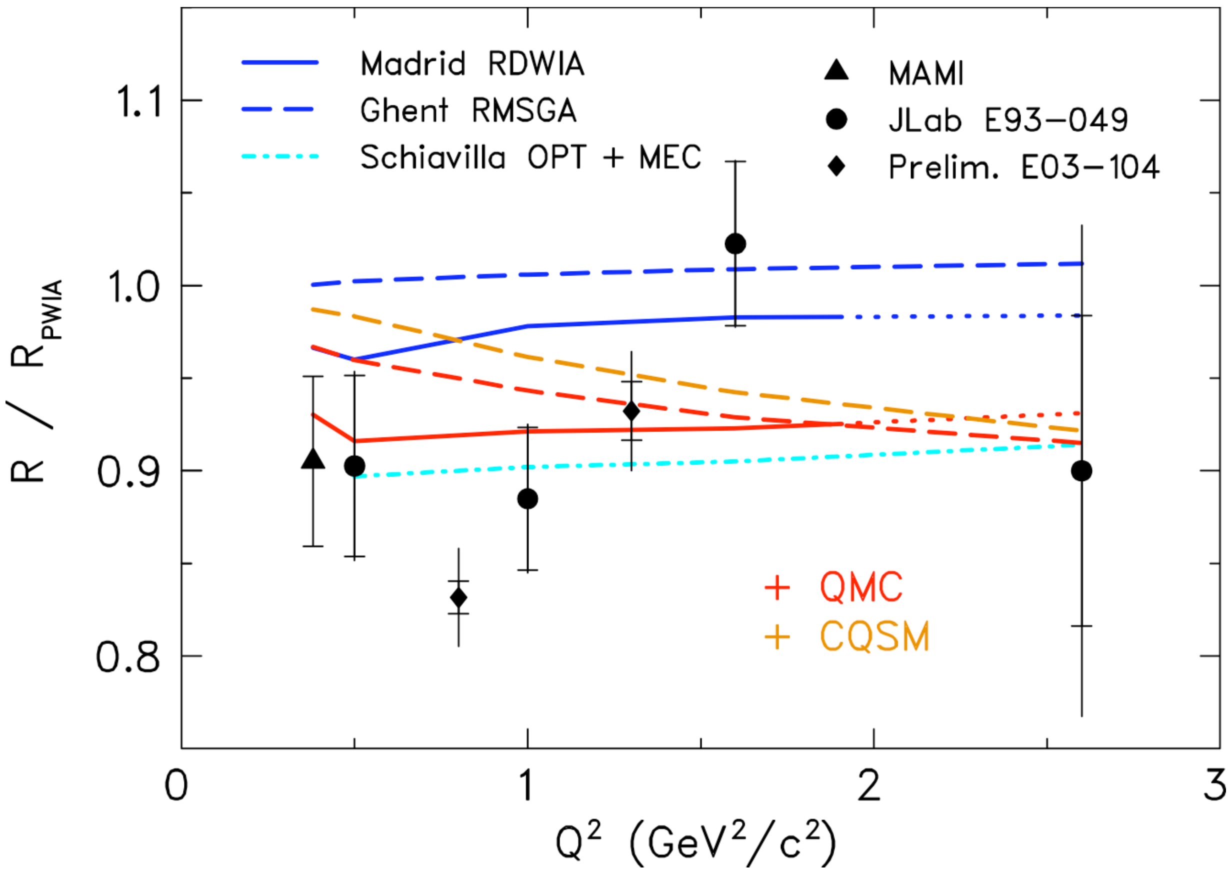
R. Schiavilla *et al.* (results **not** acceptance averaged; acceptance averaged RDWIA results are typically 40% larger than point values)

- Final-state interactions small, RDWIA results consistent with data
- Need smaller systematic uncertainties from **E03-104** to constrain models

R. Schiavilla *et al.*, Phys. Rev. Lett. **94**, 072303 (2005)

In-Medium Form Factors

$$G_{E,M}(Q^2,\rho) = \frac{G_{E,M}^{\mathrm{QMC}}(Q^2,\rho)}{G_{E,M}^{\mathrm{QMC}}(Q^2,0)} G_{E,M}^{\mathrm{free}}(Q^2)$$



- Data effectively described by proton medium modified form factors
- New data set additional tight constraints

Summary

- **Proton in the nuclear medium**
  - Models (like Quark Meson Coupling) predict change of the internal structure of a bound nucleon
  - Corrections due to in-medium form factors (electromagnetic, axial) could be significant

- **Polarization transfer in $^{4}He(e,e'p)$**
  - Significant deviation from RDWIA results; data effectively described by proton medium modifications
  - Alternative interpretation in terms of strong charge-exchange FSI
  - Induced polarization crucial to clarify role of FSI
  - New results from E03-104 will provide needed constraints