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

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2007 JLab Users Group Meeting, June 18-20, 2007
Jefferson Lab, Newport News, VA

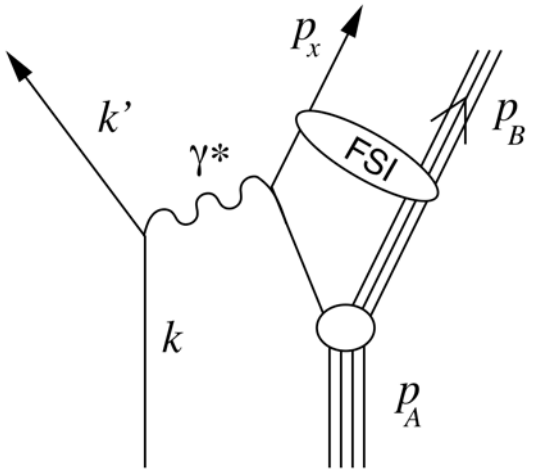
Outline

- Relativistic distorted-wave impulse approximation (RDWIA)
- Nucleon medium modifications
  - Signatures and experimental limits
  - Models for in-medium form factors
- Results from JLab ^{4}He(**e**,e'**p**) experiments
  - Polarization-transfer technique
  - Competing interpretations of previous data from E93-049
  - New constraints from preliminary data* from E03-104
- Summary

*Simona Malace (USC postdoc) and Michael Paolone (USC grad. student)

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

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

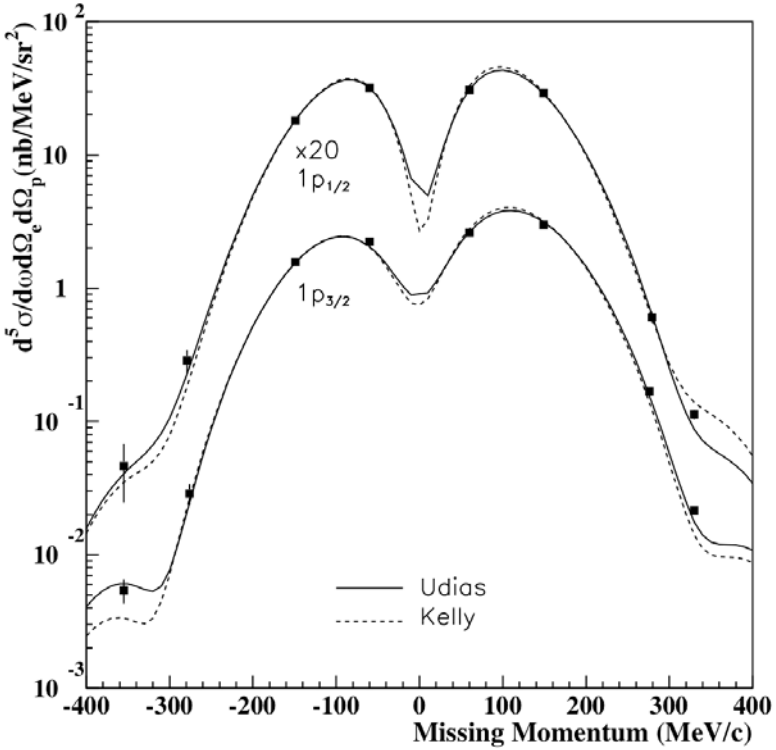
(possible medium-modified form factors enter here)

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

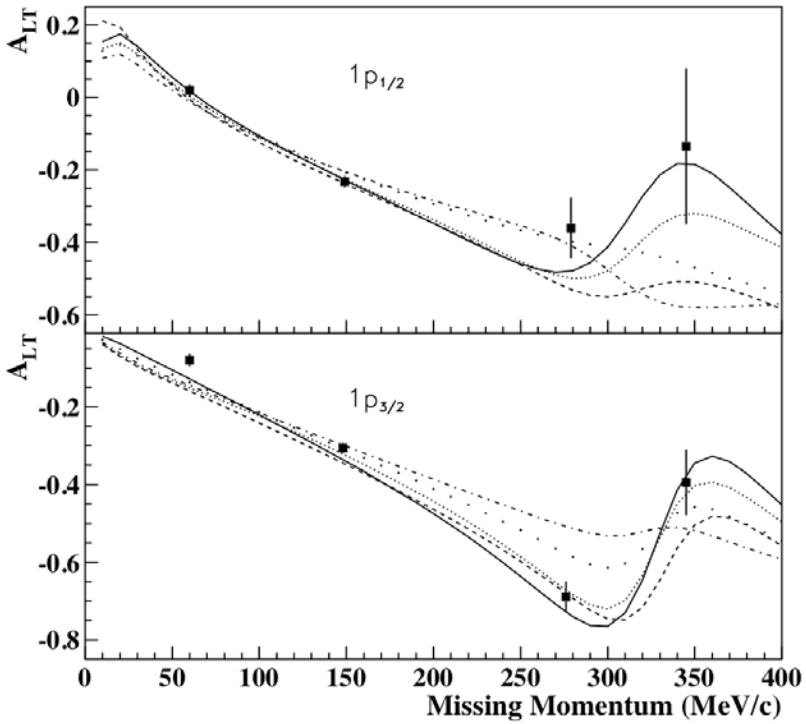
Excellent Description of Many Observables

$^{16}O(e,e'p)$ 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)

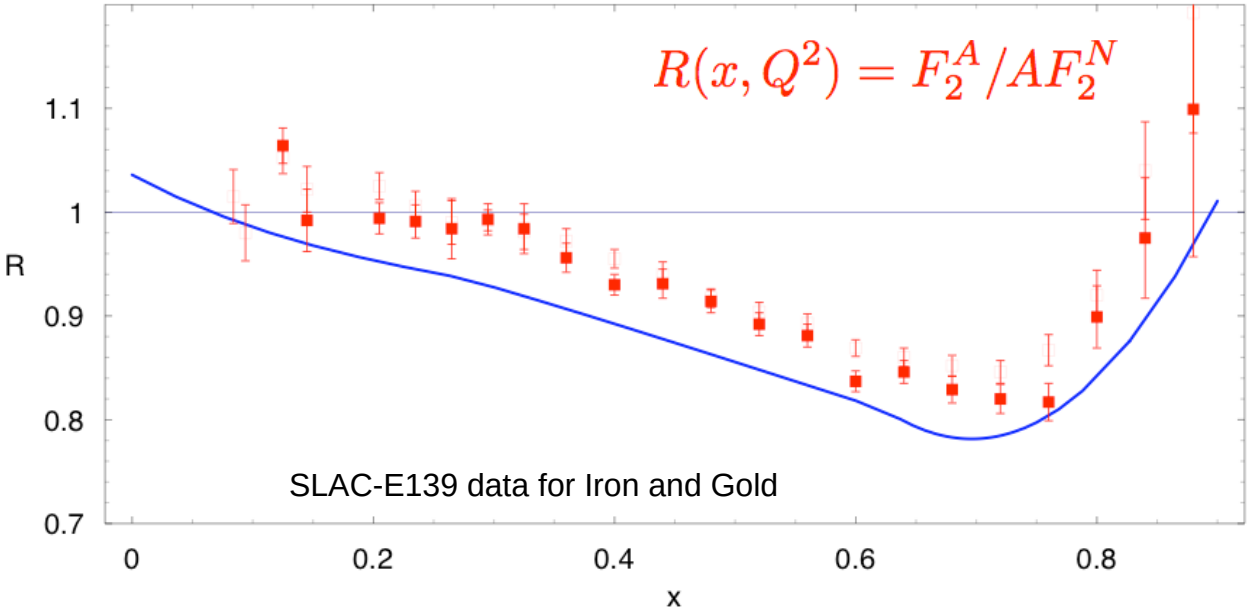
Nucleon in the Nuclear Medium

- Conventional Nuclear Physics:
  - Nuclei are effectively and well described as point-like protons and neutrons (+ form factor) and interaction through effective forces (meson exchange)
  - Medium effects arise through non-nucleonic degrees of freedom

- Nucleon Medium Modifications:
  - Nucleons and mesons are not the fundamental entities in QCD
  - In the chiral limit, phase transition to quark-gluon plasma
  - Medium effects arise through changes of fundamental properties of the nucleon

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



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

- → Nucleon structure is modified in the nuclear medium
- Note: prelim. E03-103 ^{4}He data consistent with SLAC A=12 param.

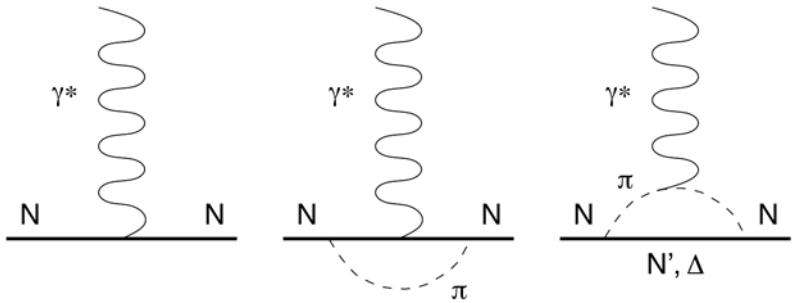
Limits for Medium Modifications

- Best constraints from y-scaling
  - $Q^2 > 1$ (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]
  - $Q^2 \leq 0.5$ (GeV/c)^2: $\Delta G_E < 15\%$ or even $< 5\%$
- Exclusive A(e,e'p) processes
  - LT Separation

[1] I. Sick, Phys. Lett. B **157**, 13 (1985)
[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)

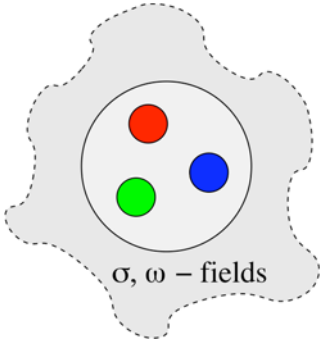
Quark Meson Coupling Model (QMC)

- 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.

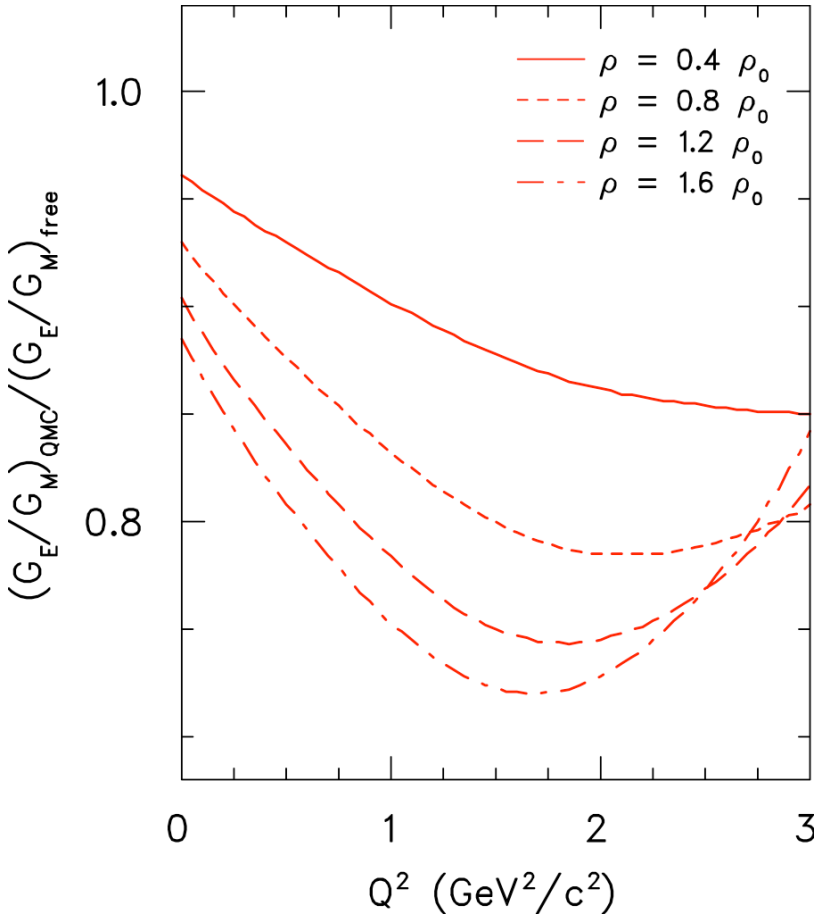


- Scalar and vector fields of nuclear matter couple directly to confined quarks.

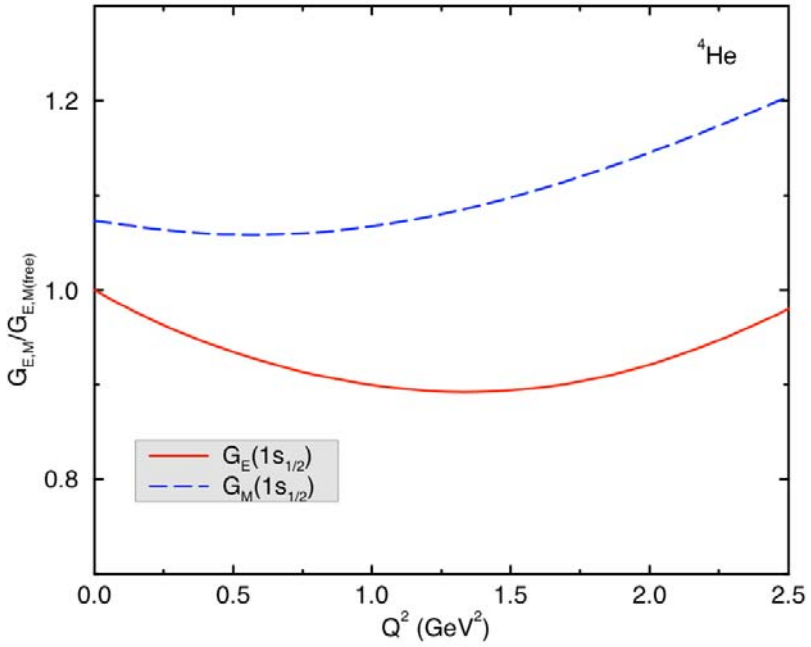
→ Modification of internal structure of bound nucleon

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)

Bound Proton EM Form Factors

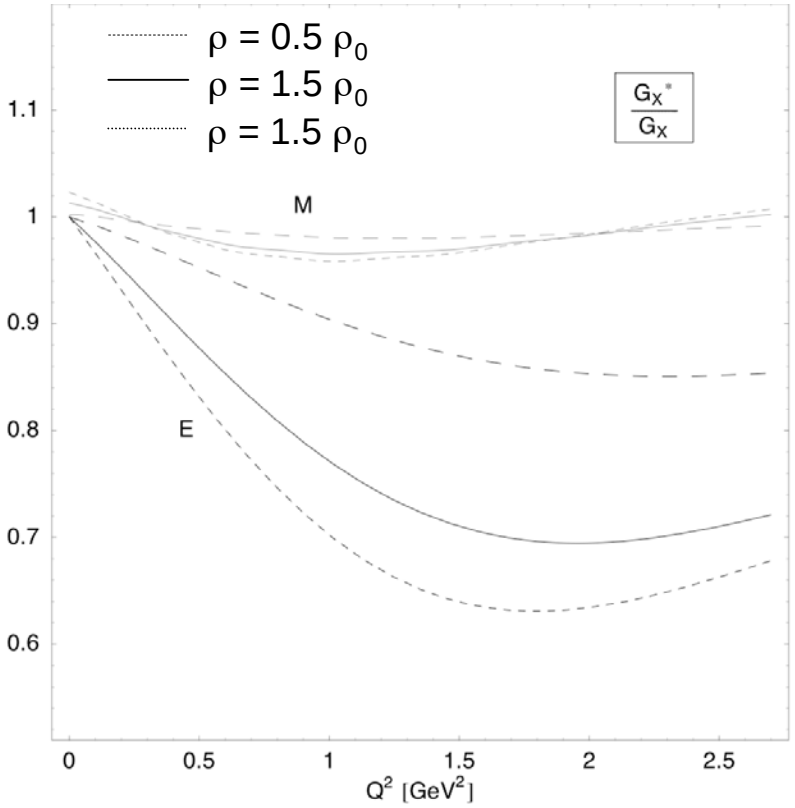


D.H. Lu *et al.*, Phys. Rev. C **60**, 068201 (1999)



- 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.

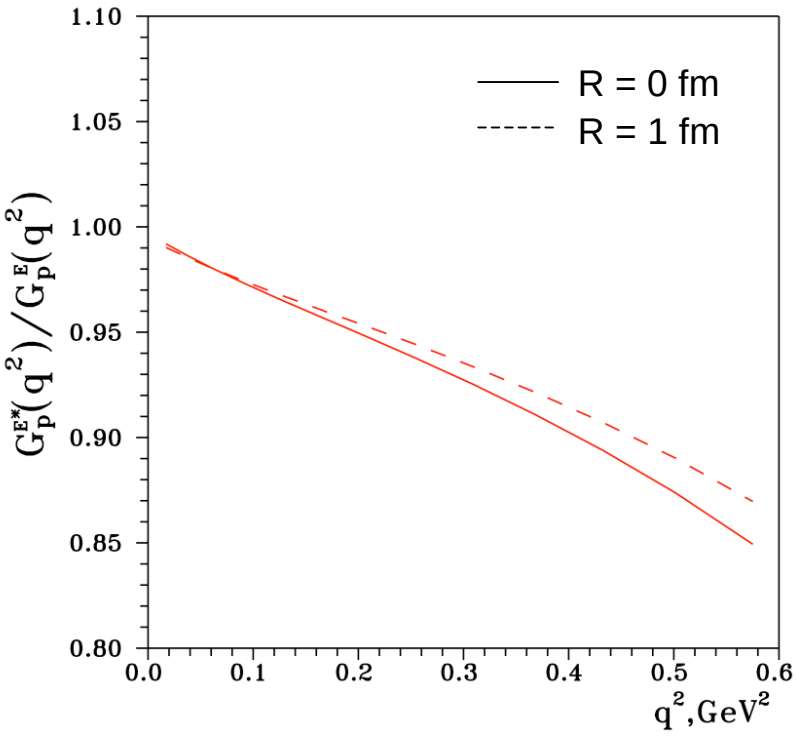
Chiral Quark Soliton Model (CQSM)

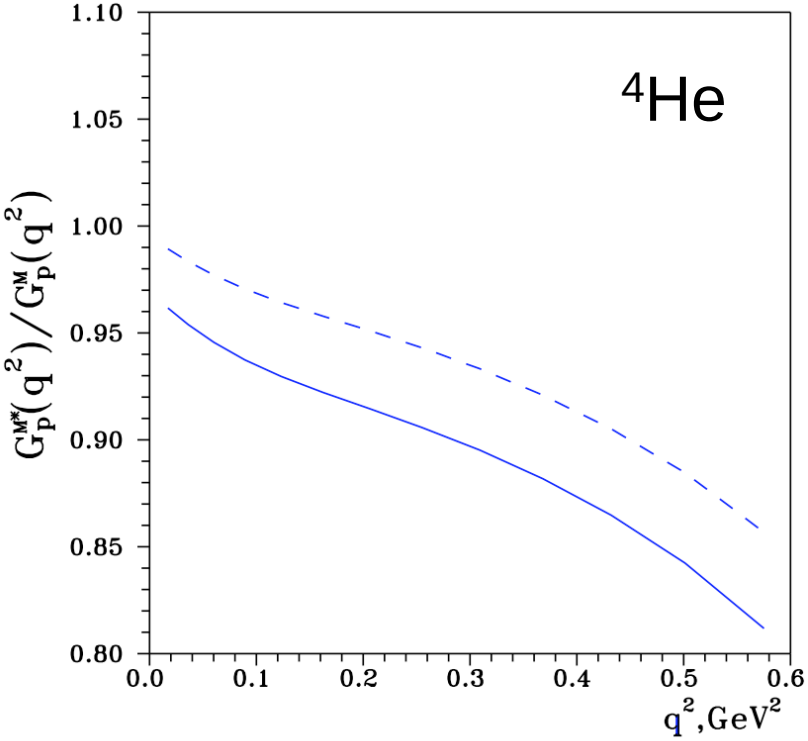


- Chiral-soliton model provides the quark and antiquark substructure of the proton, embedded in nuclear matter.
- Medium modifications:
  - significant for the ratio G_E/G_M
  - no strong enhancement of the magnetic moment

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

Extended Skyrme Model





- Model of the nucleon based on Skyrme Lagrangian
- Results comparable to QMC, but differ in details
- $(G_E/G_M)_{medium}/(G_E/G_M)_{free} \approx 1$ for R = 1 fm

U. Yakhshiev, U. Meißner, A. Wirzba, Eur. Phys. J. A **16**, 569 (2003)

Other Models

- **Nambu–Jona-Lasinio model**

  T. Horikawa, W. Bentz, Nucl. Phys. A **762**, 102 (2005)

  - Nucleon as quark-diquark bound state + nuclear matter in the mean field approximation.
  - Medium modifications: increase of the electric size in the medium
  - Medium modifications decrease with increasing Q^2 for both, spin and orbital form factors.

- **S. Liuti**

  S. Liuti, hep-ph/0608251, hep-ph/0601125

  - Connection between the modifications induced by the nuclear medium of the nucleon form factors and of the deep inelastic structure functions, obtained using the concept of generalized parton distributions.

Polarization-Transfer Technique

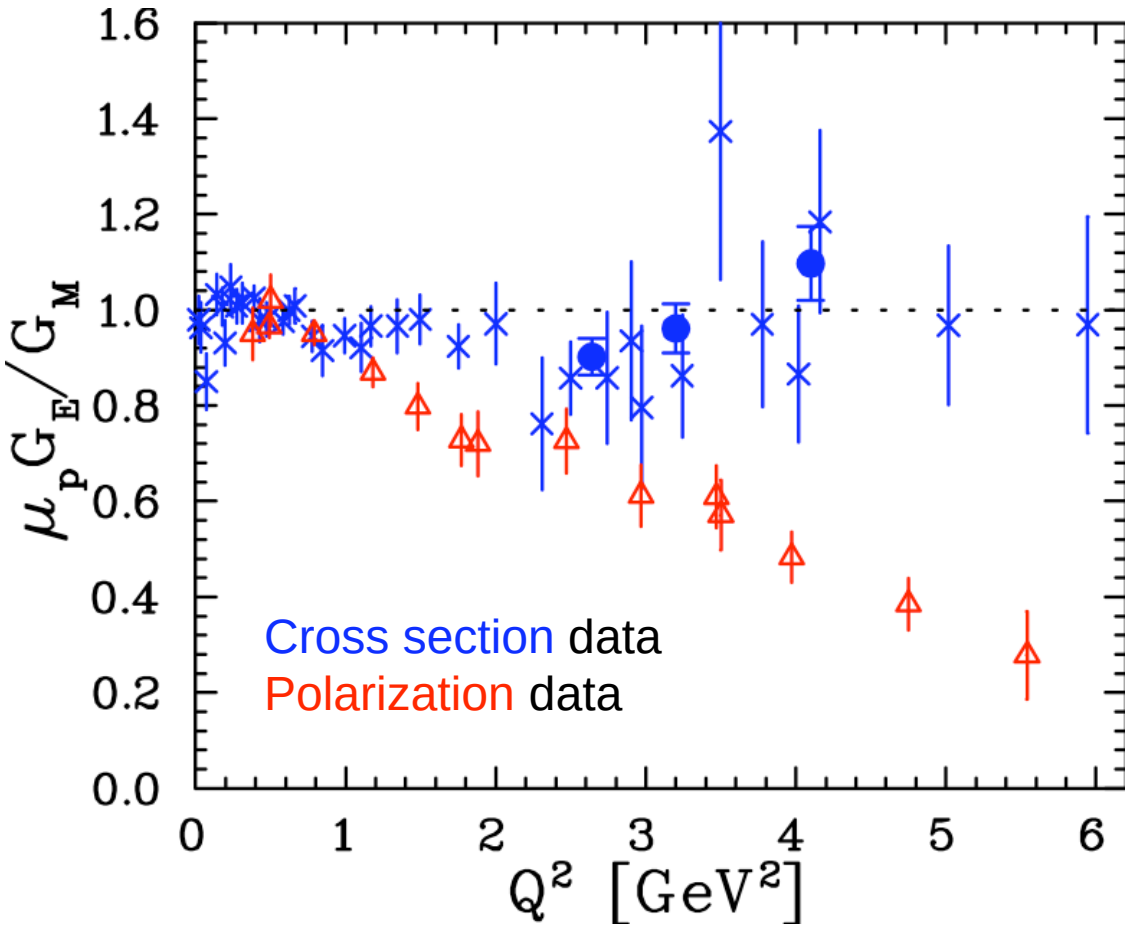
- Free electron-nucleon scattering

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

- 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

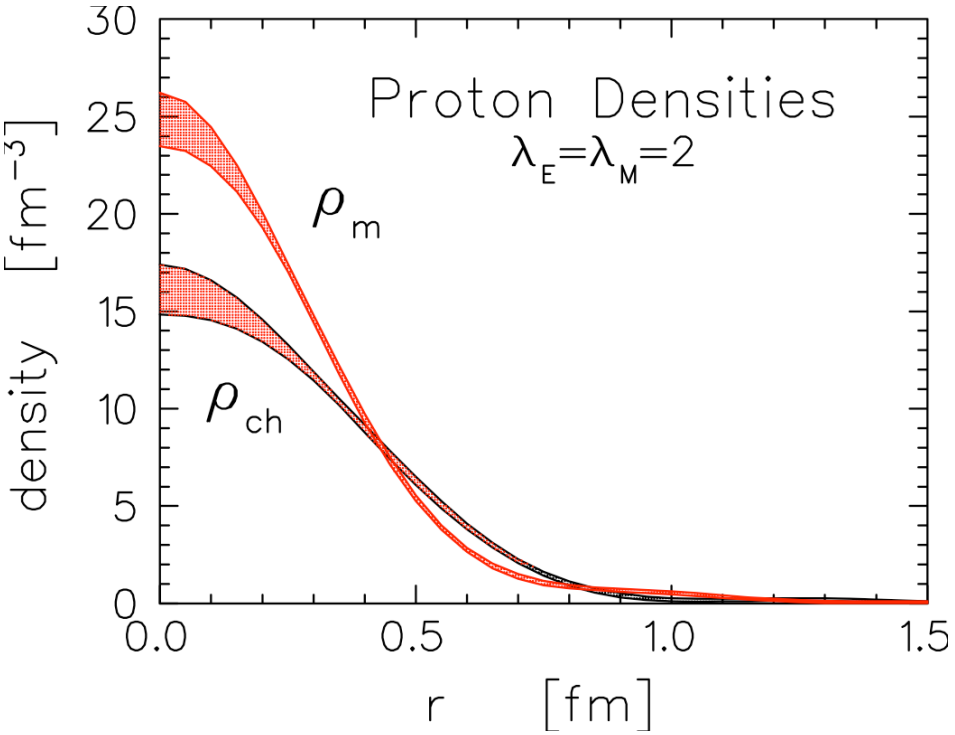


- Systematic decrease of G_E / G_M indicating difference in spatial distribution of charge and magnetization currents in the proton.
- Discrepancy can possibly be resolved by the inclusion of two photon effects in Rosenbluth analysis.

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

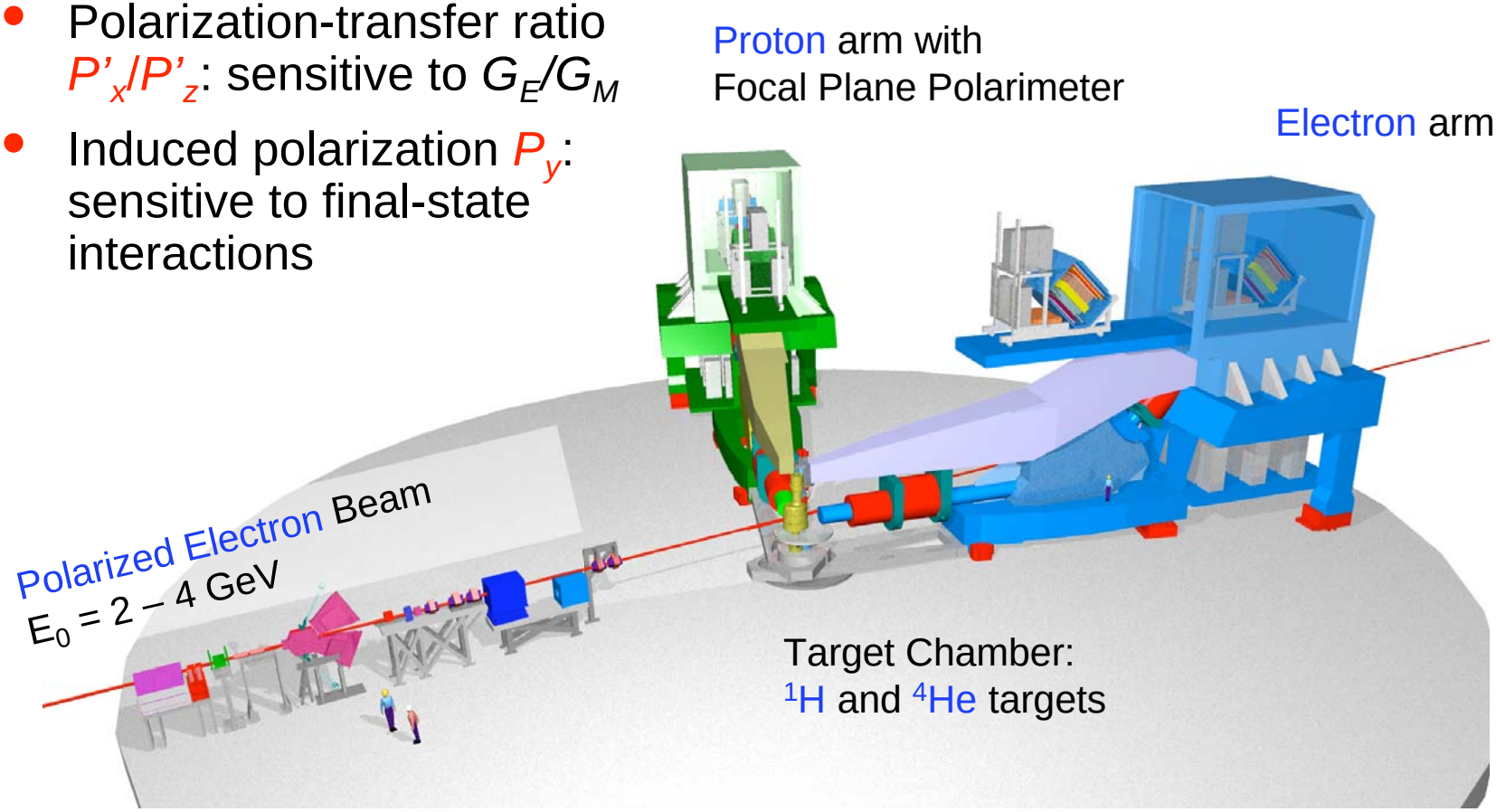
$$\alpha_E > \beta_M$$

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

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

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

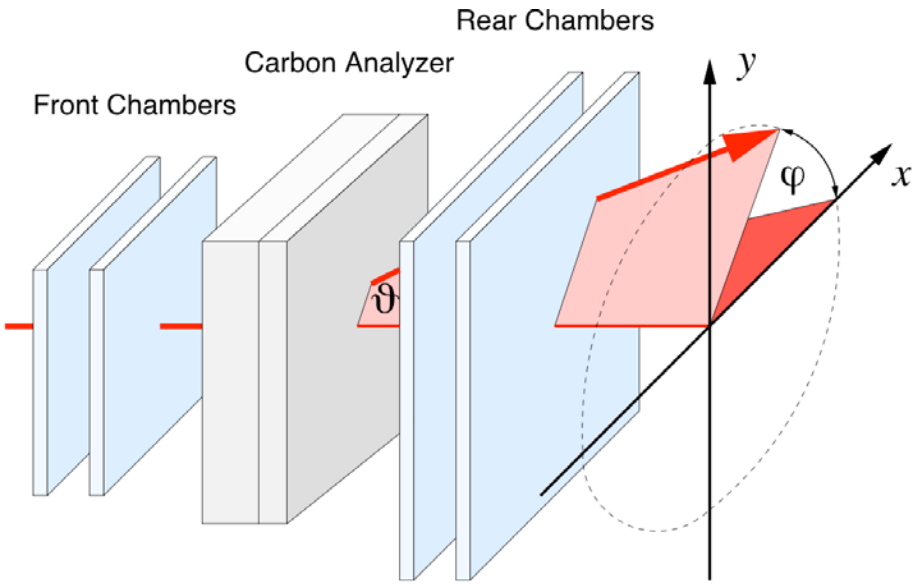
- Polarization-transfer ratio P'_x/P'_z: sensitive to G_E/G_M
- Induced polarization P_y: sensitive to final-state interactions

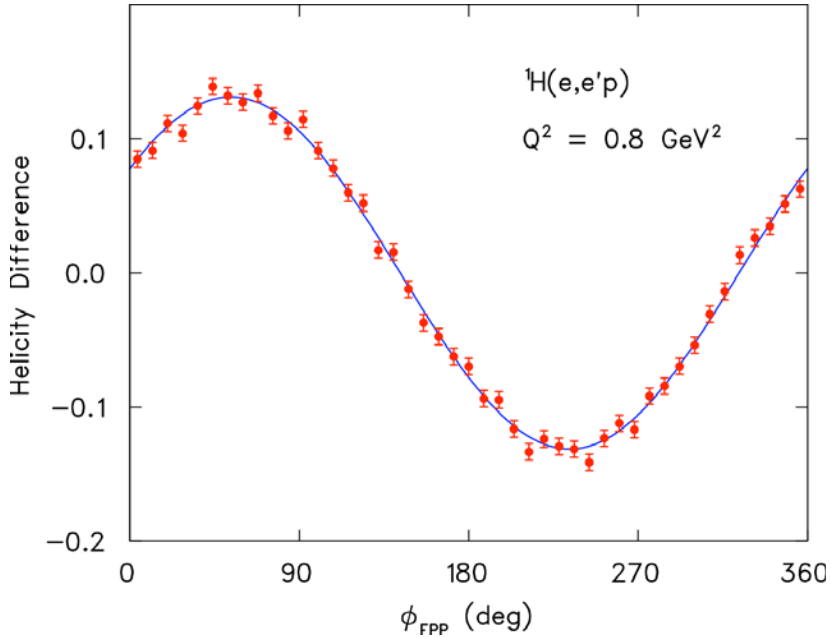


S. Dieterich, *et al.*, Phys. Lett. **B500**,47(2001); S. Strauch, *et al.*, Phys. Rev. Lett. **91**, 052301(2003); JLab E03-104, R.Ent, R. Ransome, S. Strauch, P. Ulmer (spokespersons)

Polarization Measurement

Focal-Plane Polarimeter

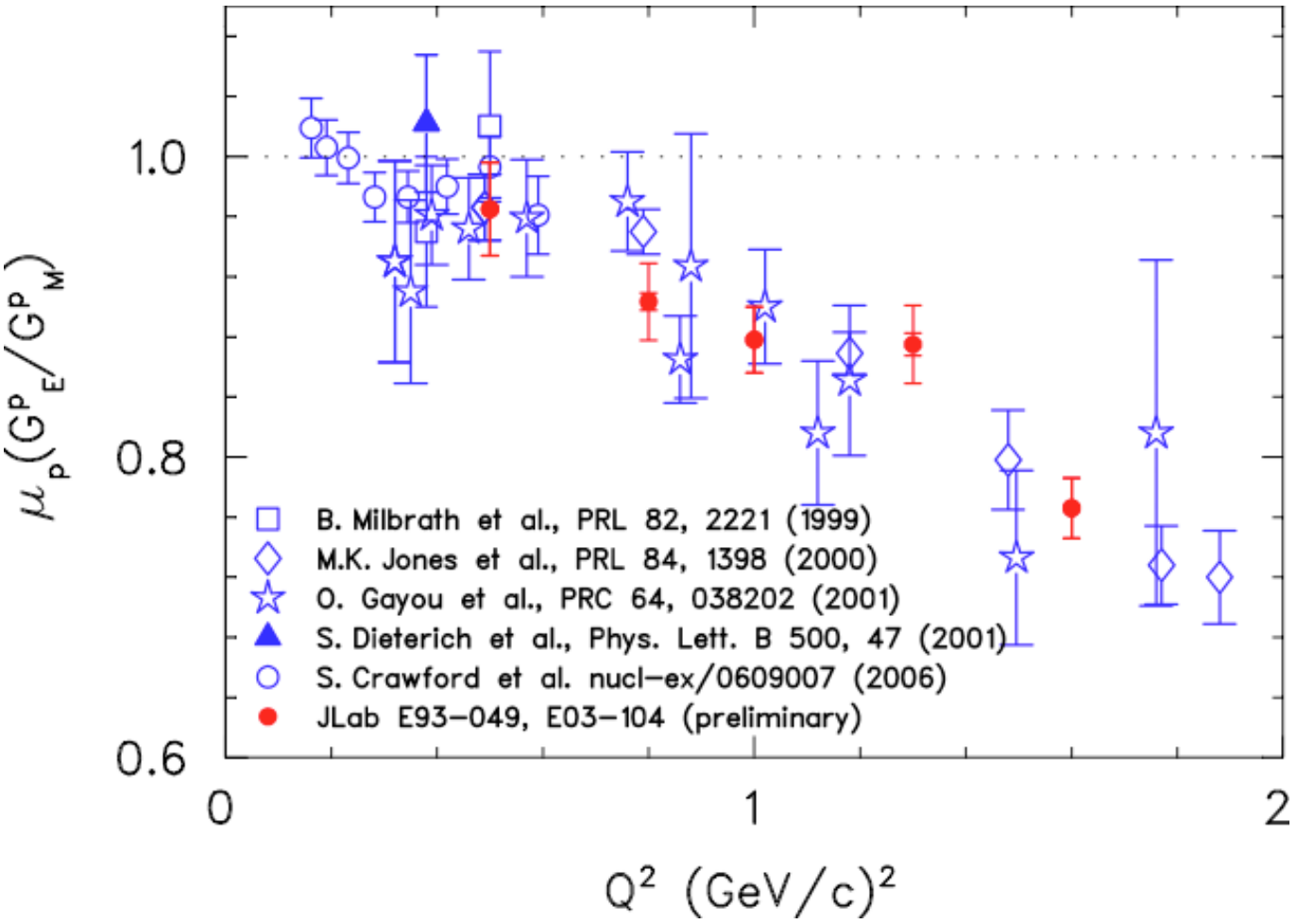




Observed angular distribution

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

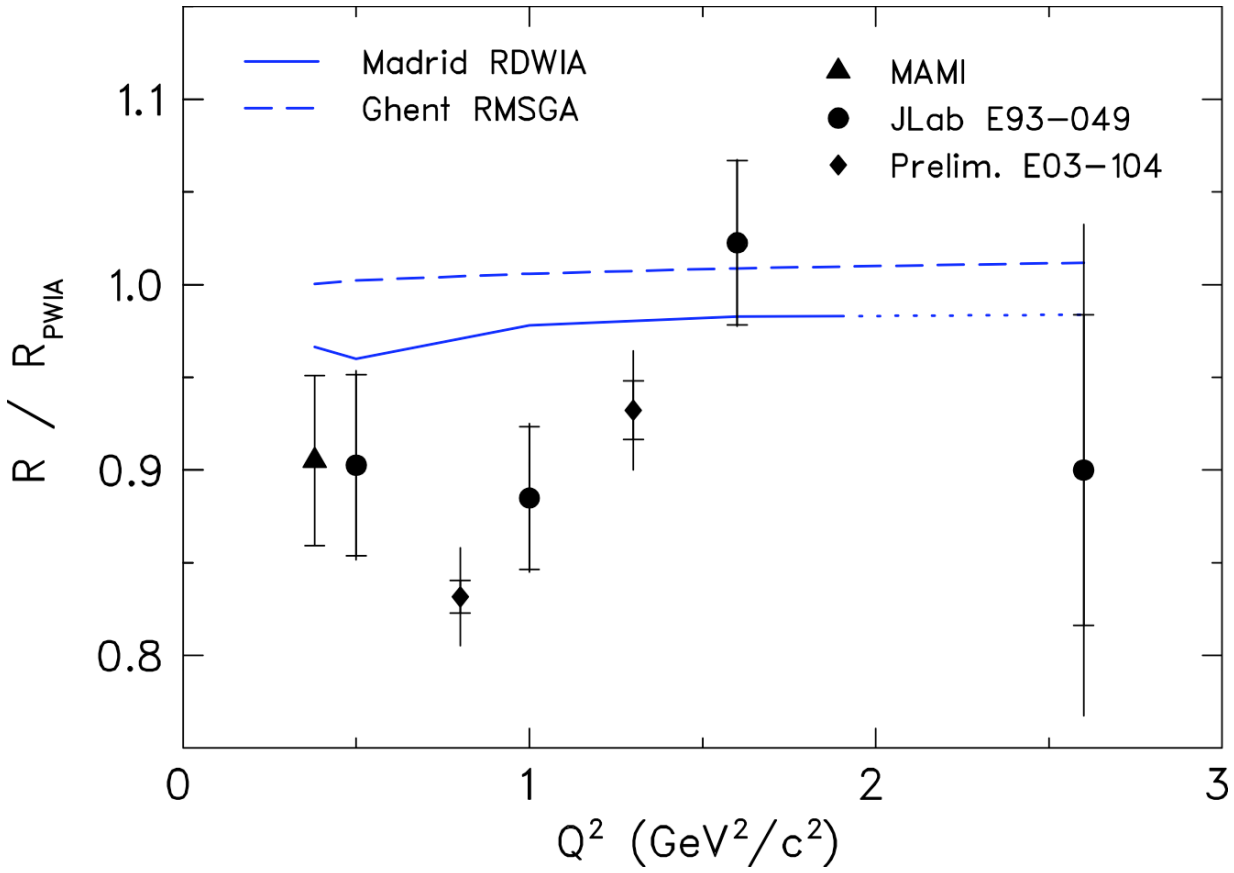
Free Proton Form-Factor Ratio G_E/G_M



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

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

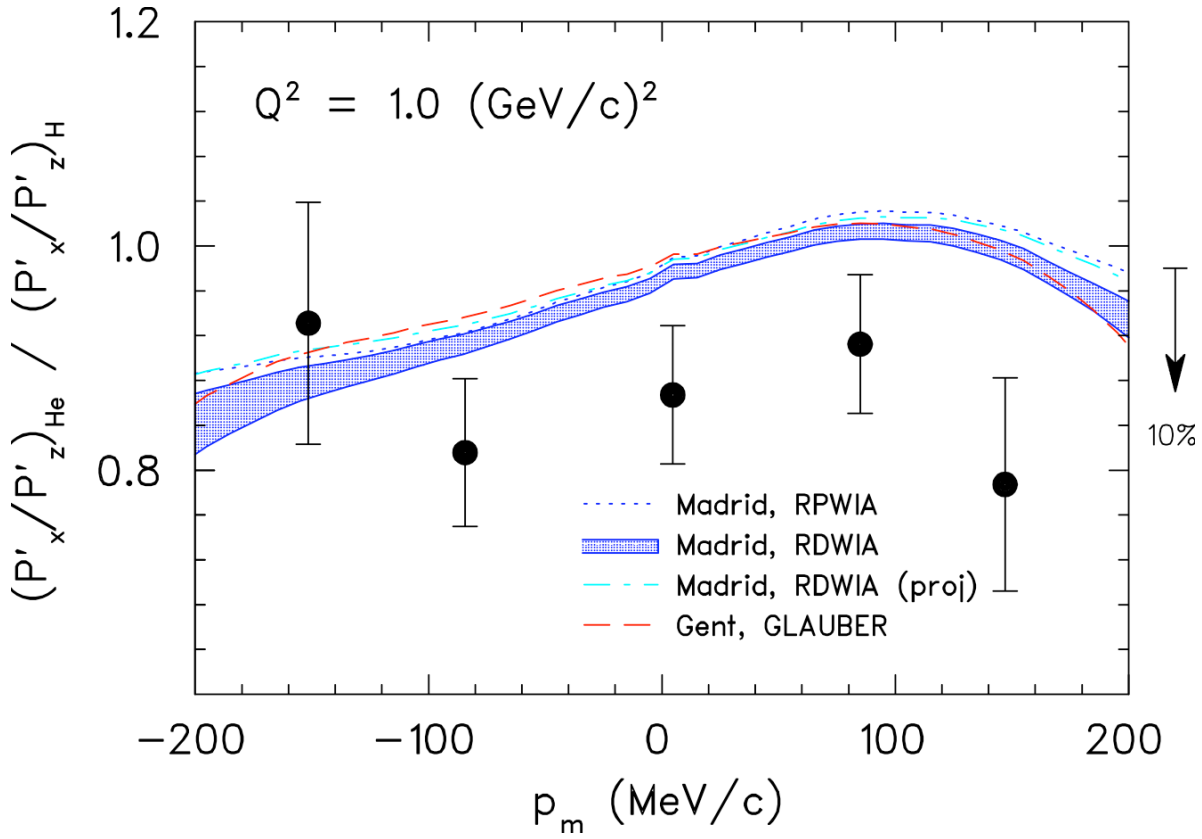
$$R = P'_x/P'_z(^4\mathrm{He})\,/P'_x/P'_z(^1\mathrm{H})$$



- RDWIA and RMSGA models can not describe the data.
- New data will set tight constraints, and possibly hint at an unexpected trend in Q^2

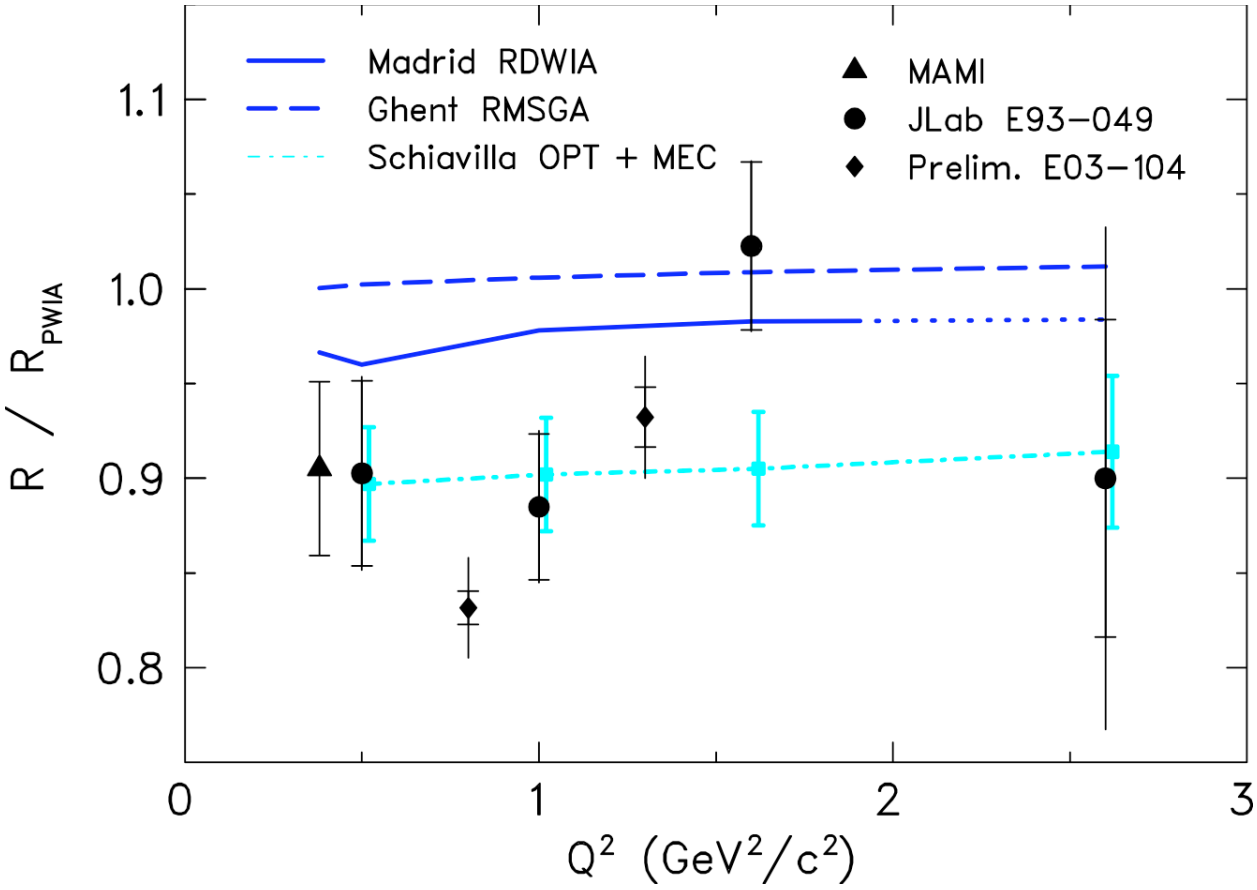
RDWIA: J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999);
RMSGA: P. Lava *et al.*, Phys. Rev. C **71**, 014605 (2005), D. Debruyne *et al.*, Phys. Rev. C **62**, 024611 (2000)

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

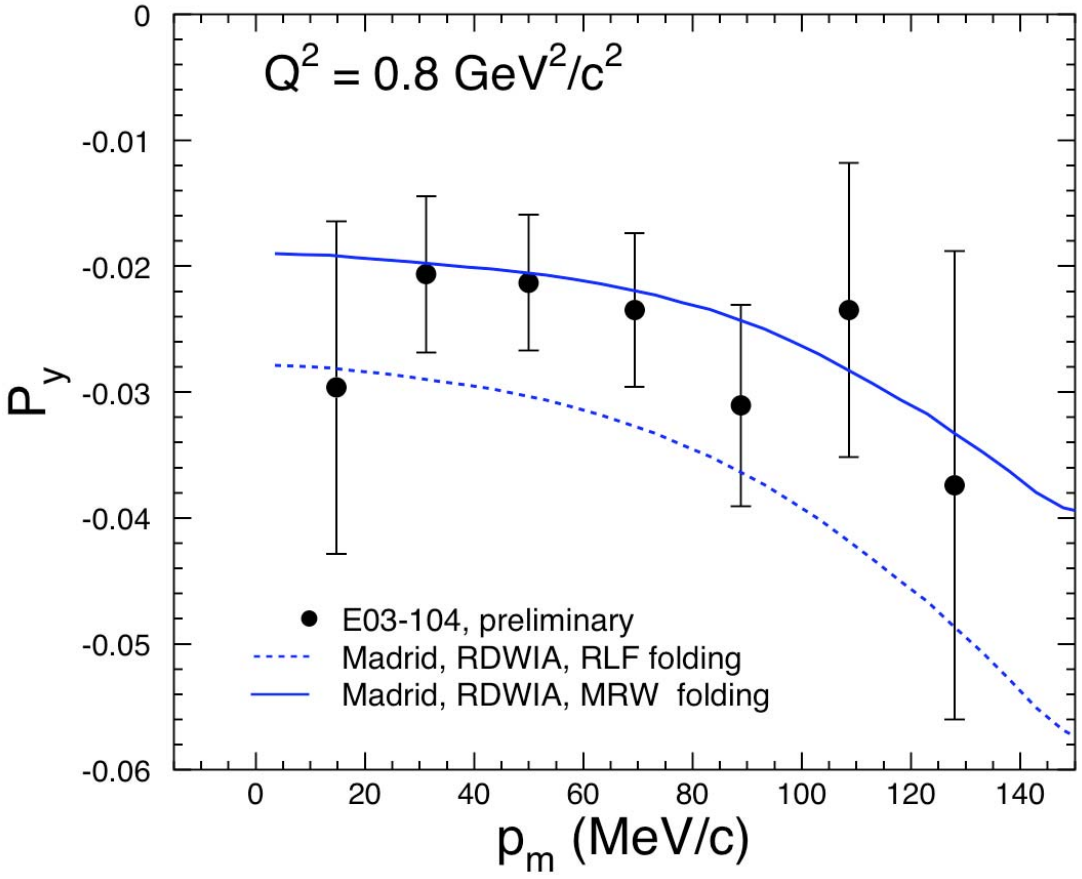
Spin-Dependent Charge-Exchange FSI



- 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

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

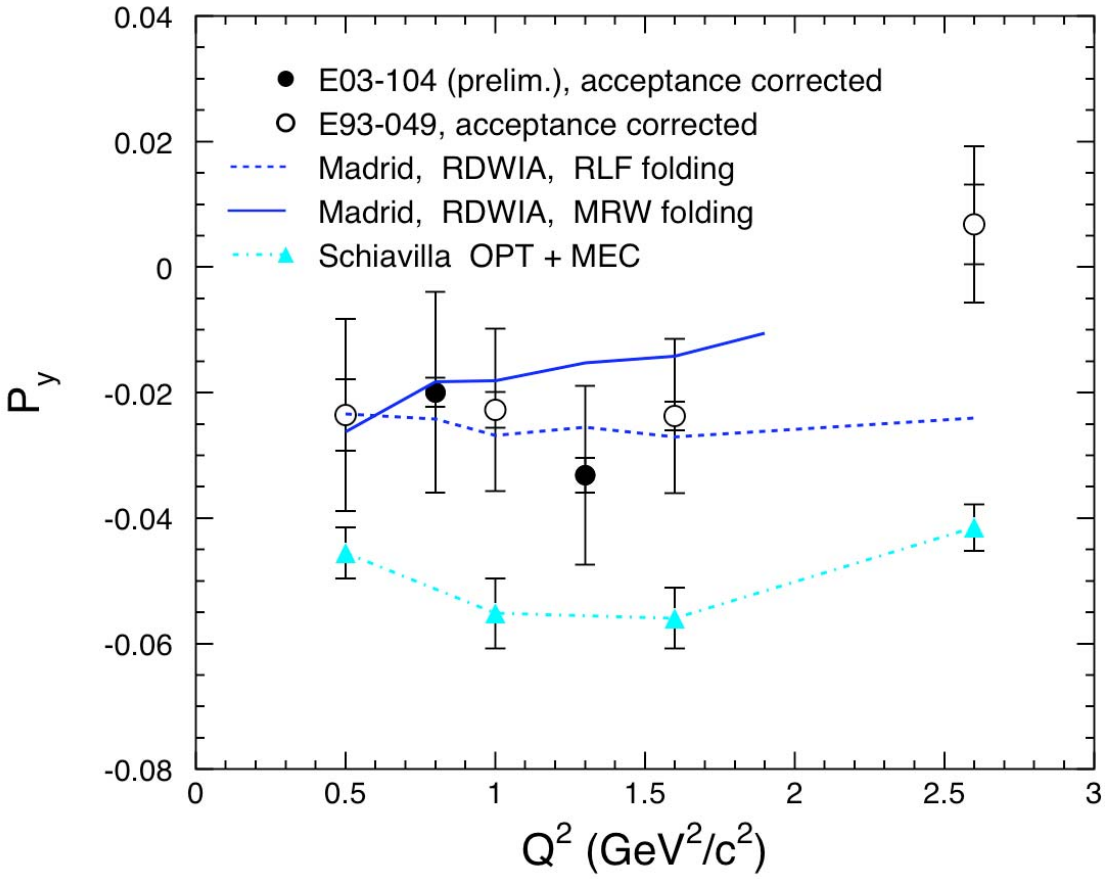
Induced Polarization in ^{4}He$(e,e'\vec{p})$



- P_y is a measure of final-state interactions
- Observed final-state interactions small and increase with missing momentum
- RDWIA results consistent with data
- RDWIA can be used to correct data for HRS acceptance (30% - 40% effect)

E03-104 induced polarization still very preliminary.
Uncertainties are statistical only; systematic uncertainties < 0.02

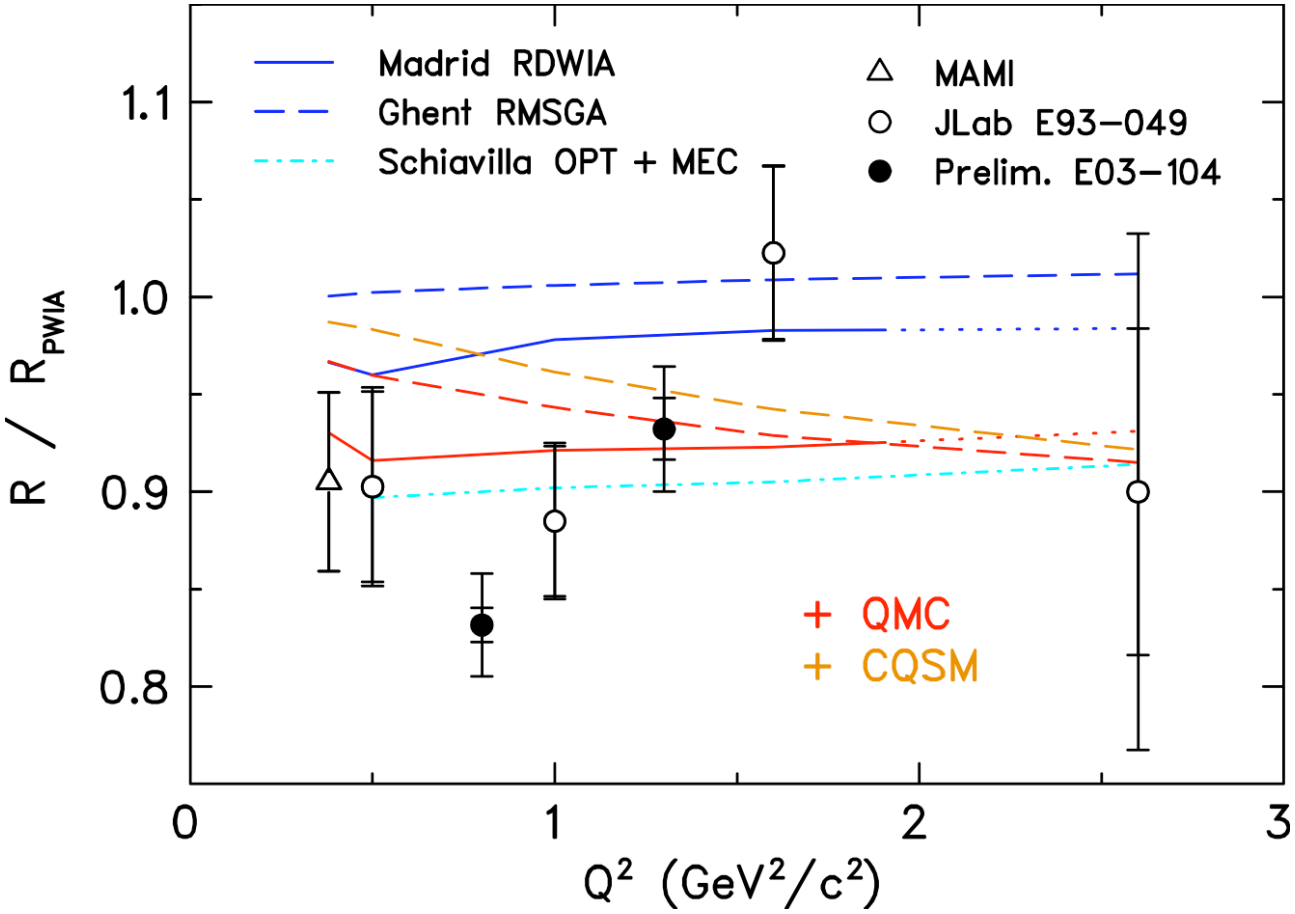
Induced Polarization in ^{4}He$(\vec{e},e'\vec{p})$



- Observed final-state interaction small and with only very weak Q^2 dependence
- RDWIA results consistent with data
- Spin-dependent charge exchange terms not constrained by N-N scattering and possibly overestimated
- E03-104 took specific data that will set tight constraints on FSI

Inner uncertainties are statistical only;
full analysis of E03-104 will have reduced systematic uncertainties

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



Inner uncertainties are statistical only; full analysis of E03-104 will have reduced systematic uncertainties

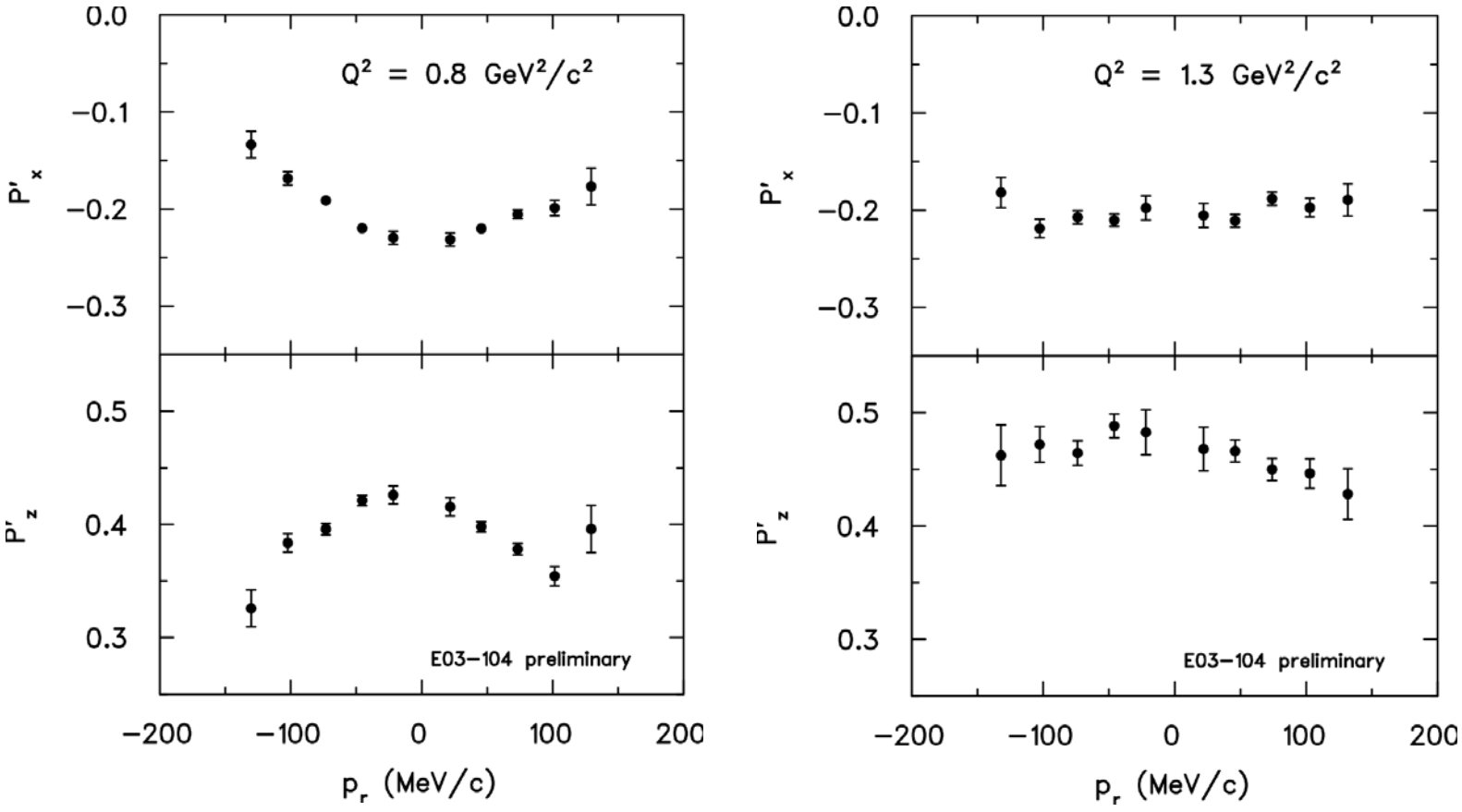
- Previous data effectively described by proton medium modified form factors
- Alternative explanation given by spin-dependent charge exchange FSI
- Neither accounts for preliminary Q^2 = 0.8 GeV^2 data

Summary

- **Proton in the nuclear medium**
  - Models 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

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



- Considerable missing momentum dependence of P'_x and P'_z for $Q^2 = 0.8$ GeV^2 and $Q^2 = 1.3$ GeV^2
- E03-104 will allow for more detailed study of polarization transfer