Search for Signatures of Proton Medium Modifications

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Outline

- 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
- Possible new experiment in Hall C
- Summary

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

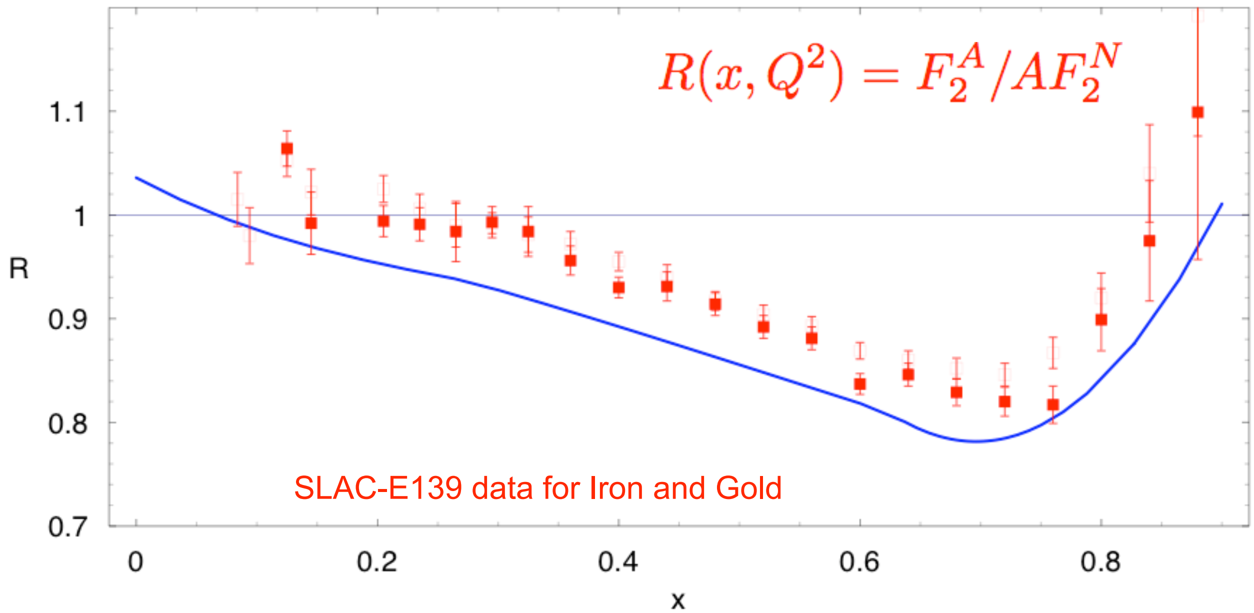
Nucleon in the Nuclear Medium

- 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

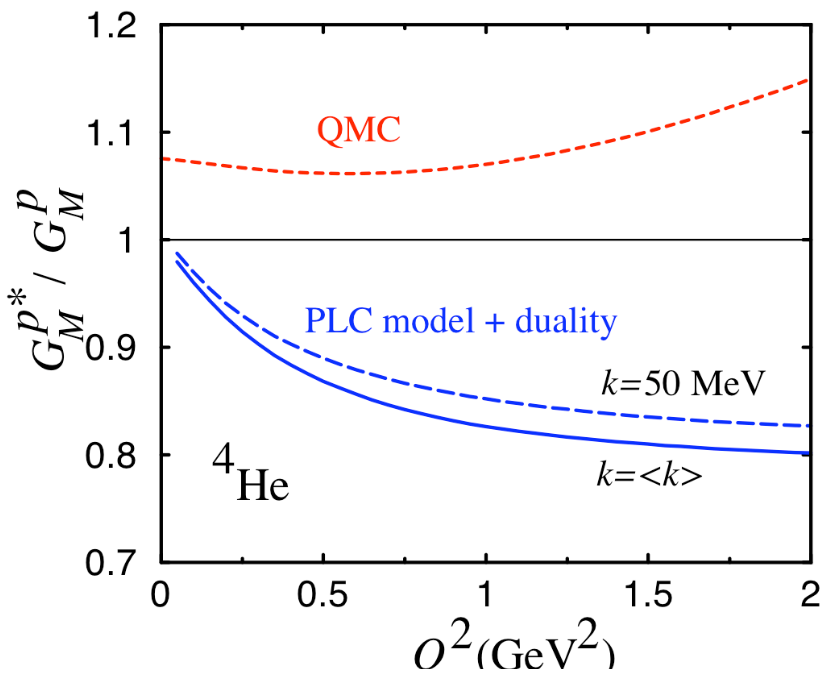


J.R. Smith and G.A. Miller, Phys. Rev. Lett. **91**, 212301 (2003)

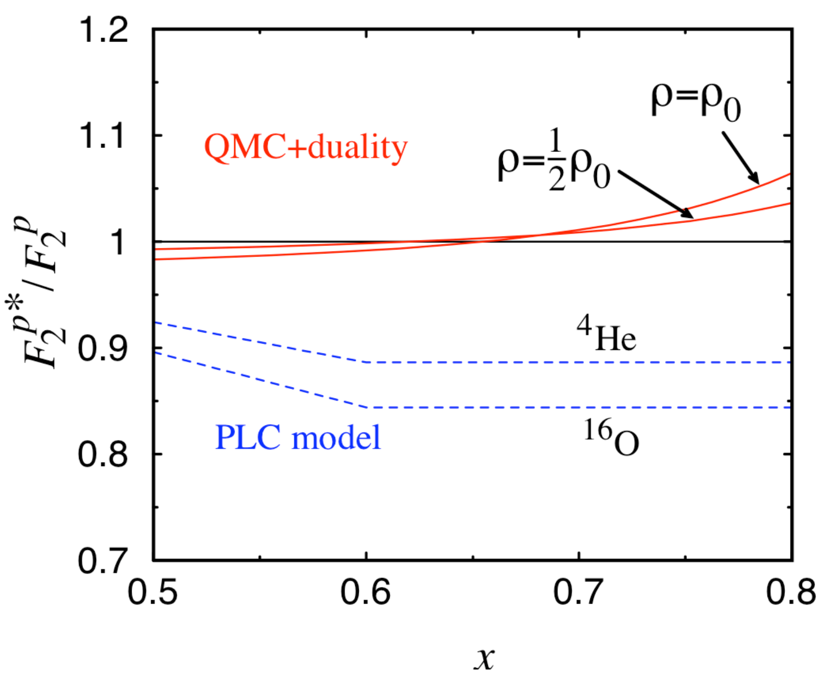
- → Nucleon structure is modified in the nuclear medium
- Note: prelim. E03-103 ^{4}He data consistent with SLAC A=12 param.

Constraints on Models of EMC Effect

Bound nucleon form factors ← quark-hadron duality → EMC Effect



Magnetic Form Factor G_M



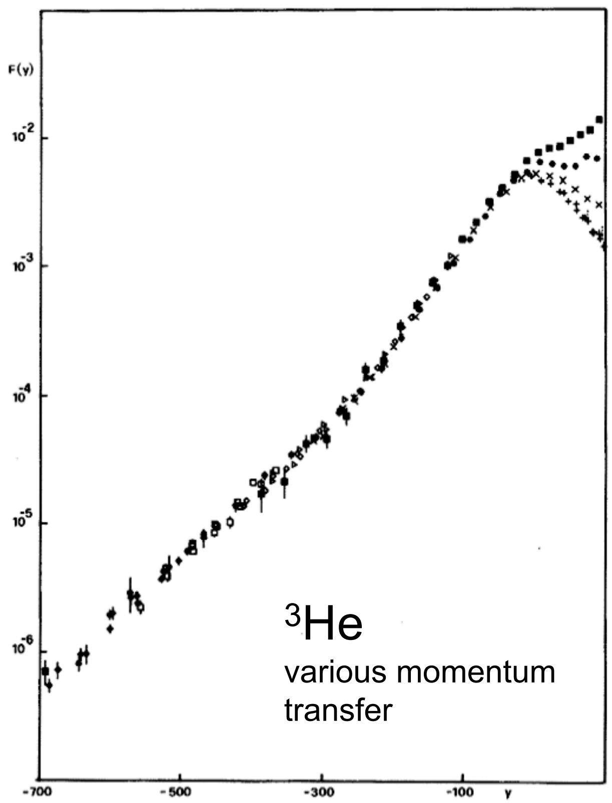
Structure Functions F_2

W. Melnitchouk, K. Tsushima, and A.W. Thomas, Eur. Phys. J. A**14**, 105 (2002)

Y - Scaling

$$F(y)dy = \frac{d\sigma(q,\omega)/d\Omega d\omega}{\left[Z d\sigma(q)/d\Omega_p + N d\sigma(q)/d\Omega_n\right] d\omega}$$

F(y)



y

- Inclusive (e,e') data in the quasielastic region
- Limits for medium modifications; best constraints from y-scaling
  - $Q^2 > 1$ (GeV/c)^2, $\Delta G_M < 3\%$ [1]
- y-scaling studied for A=12, 40, 56, 197, and 208 nuclei; $Q^2 = 0.2 - 0.8$ GeV^2; no limits given [2].

[1] I. Sick, Phys. Lett. B **157**, 13 (1985) , I. Sick, in: H. Klapdor Ed., Proc. Int. Conf. on Weak and Electromagnetic Interactions in Nuclei, Springer-Verlag, Berlin, 1986, p.415.
[2] K.S. Kim and L.E. Wright, arXiv:0705.0049 [nucl-th]

Coulomb Sum Rule

- CSR: Integral of the quasi-elastic electric response $R_L(q,\omega)$

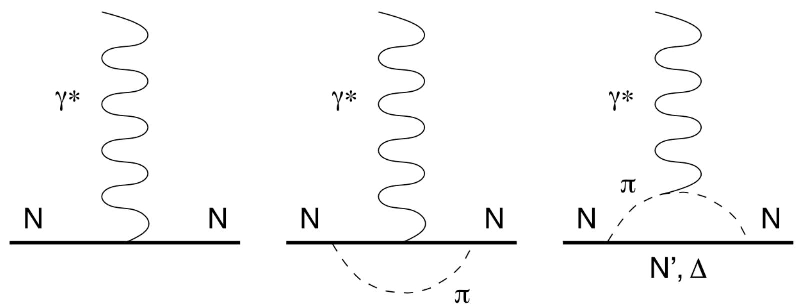
$$S_L(q) = \frac{1}{Z}\int_{0+}^{\infty} \frac{R_L(q,\omega)}{\tilde{G}_E^2} d\omega \quad \to 1$$

- Experimental findings controversial
  - No quenching in the data is observed [1,2]
  - Quenching of S_L is experimentally established [3]
  - Good agreement between theory and experiment for ^{4}He when using free-nucleon form factors [4]
- Limits
  $Q^2 \leq 0.5$ (GeV/c)^2: $\Delta G_E \leq 5\%$ [4]
- New data, especially at higher values of q, expected from JLab E05-110 on ^{4}He, ^{12}C, ^{56}Fe, ^{208}Pb [Choi, Chen, and Meziani]

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

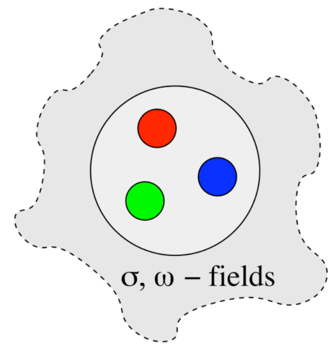
Quark Meson Coupling Model (QMC)

- 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.

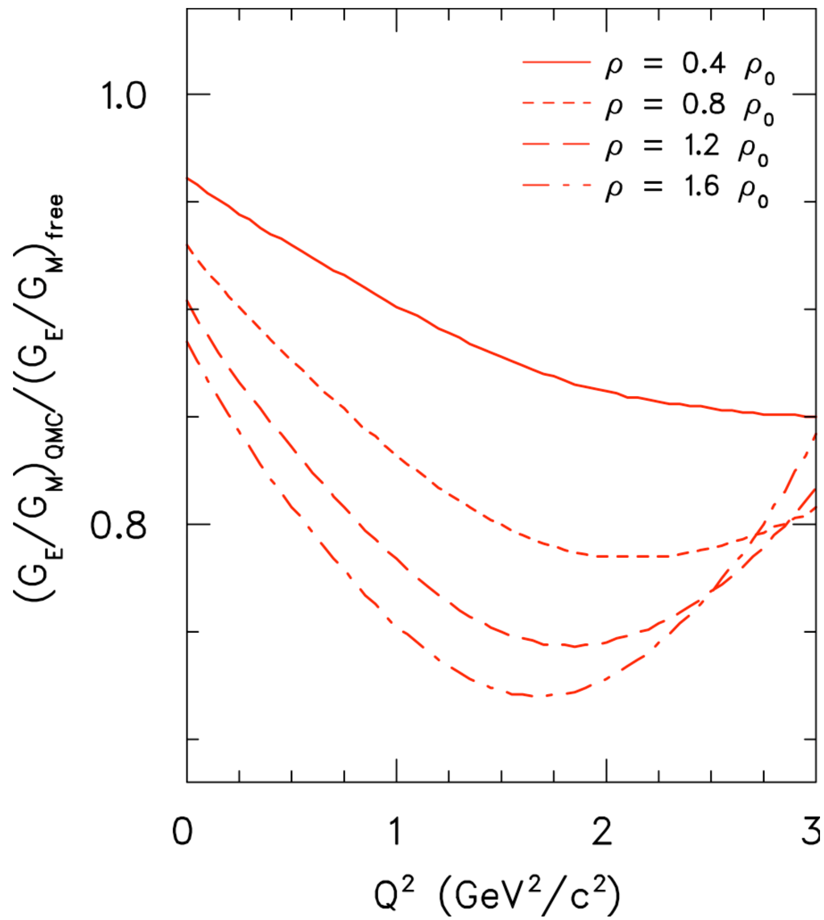


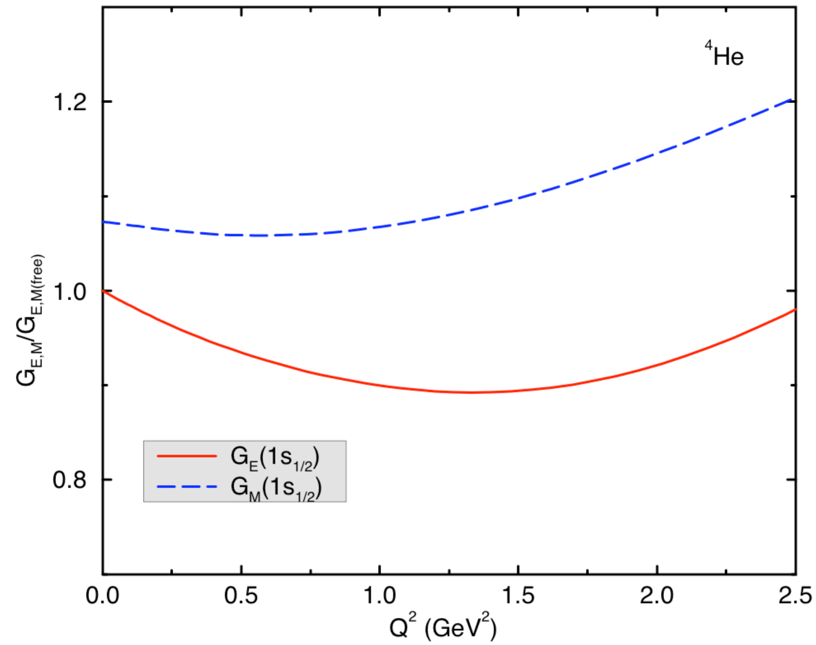
- Scalar and vector fields of nuclear matter couple directly to confined quarks.

→ 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

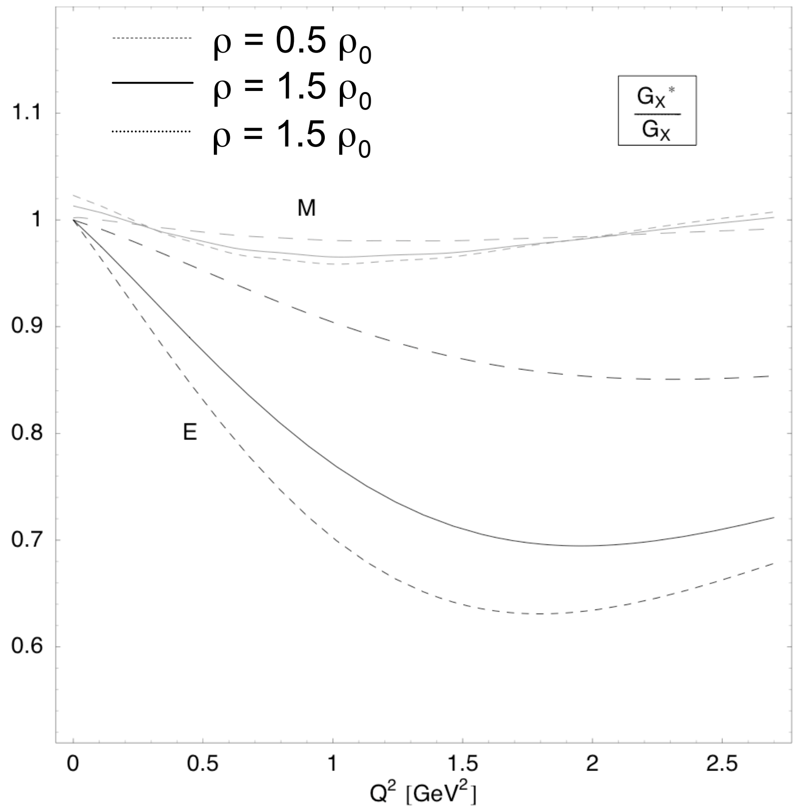




D.H. Lu *et al.*, Phys. Rev. C **60**, 068201 (1999)

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

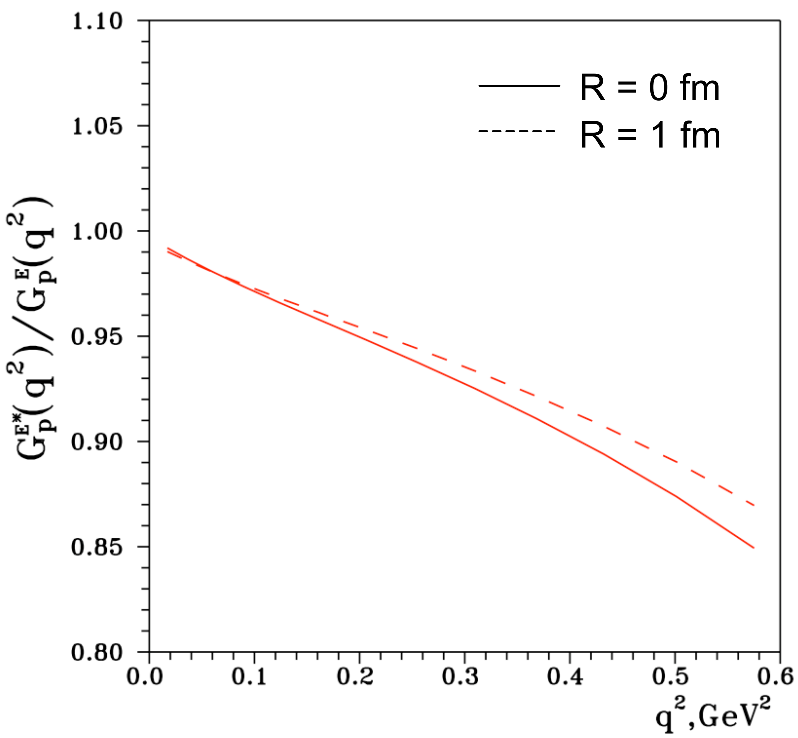
Chiral Quark Soliton Model (CQSM)

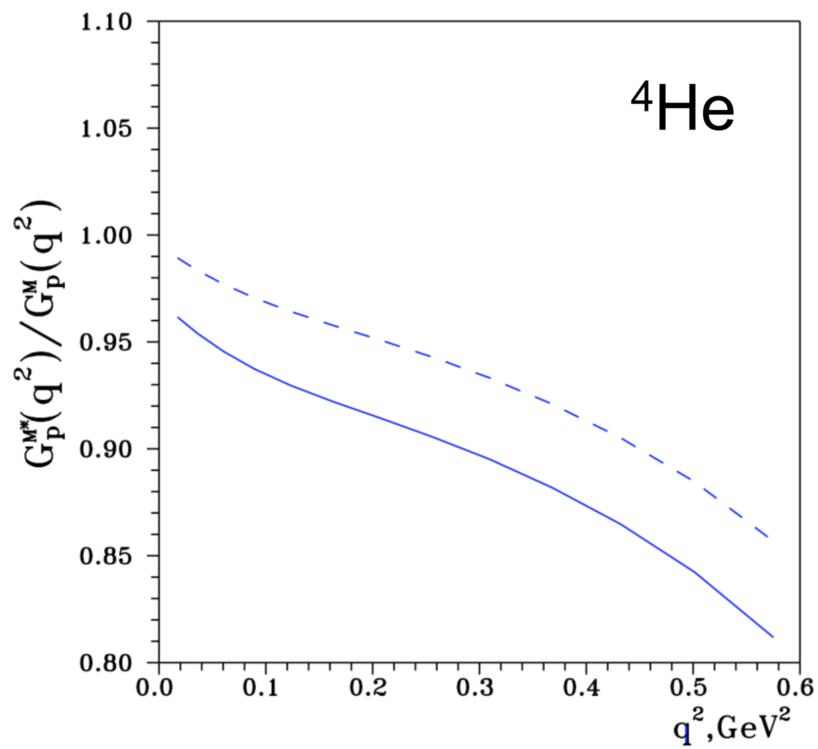


- Chiral-soliton model provides the quark and antiquark substructure of the proton, embedded in nuclear matter.
- Medium modifications:
  - significant for the ratio G_E/G_M
  - no strong enhancement of the magnetic moment

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.

- **In-medium Generalized Parton Distributions**
  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

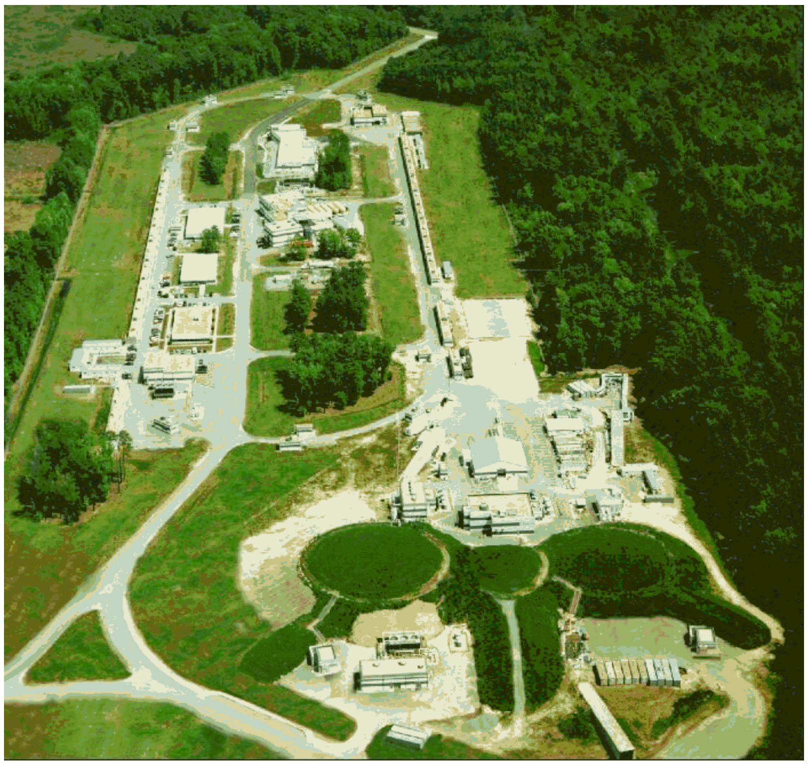
- Free electron-nucleon scattering

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

- 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).

Thomas Jefferson National Accelerator Facility



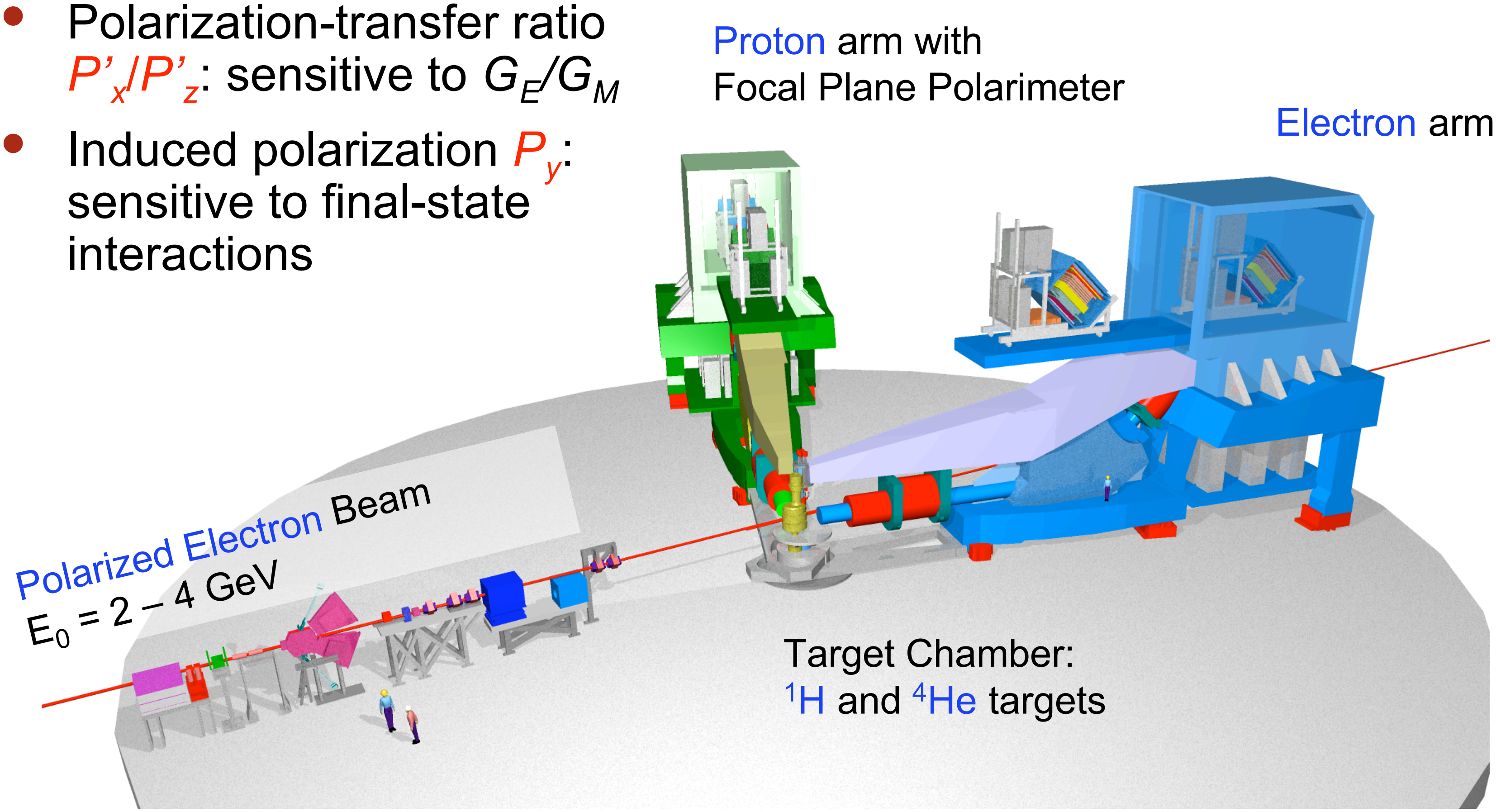
JLab in Newport News, VA

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

Hall A Experiments E93-049 and E03-104

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

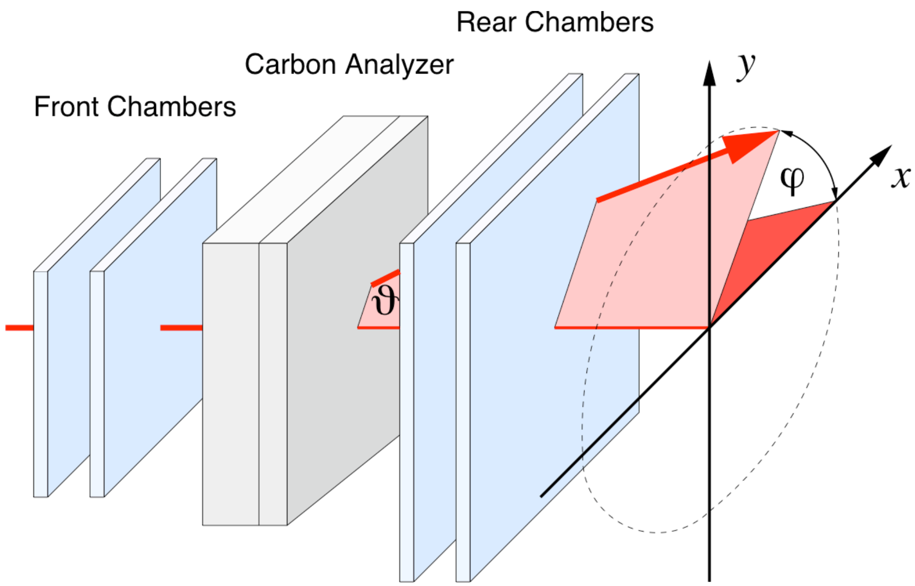
- Polarization-transfer ratio P'_x/P'_z: sensitive to G_E/G_M
- Induced polarization P_y: sensitive to final-state interactions

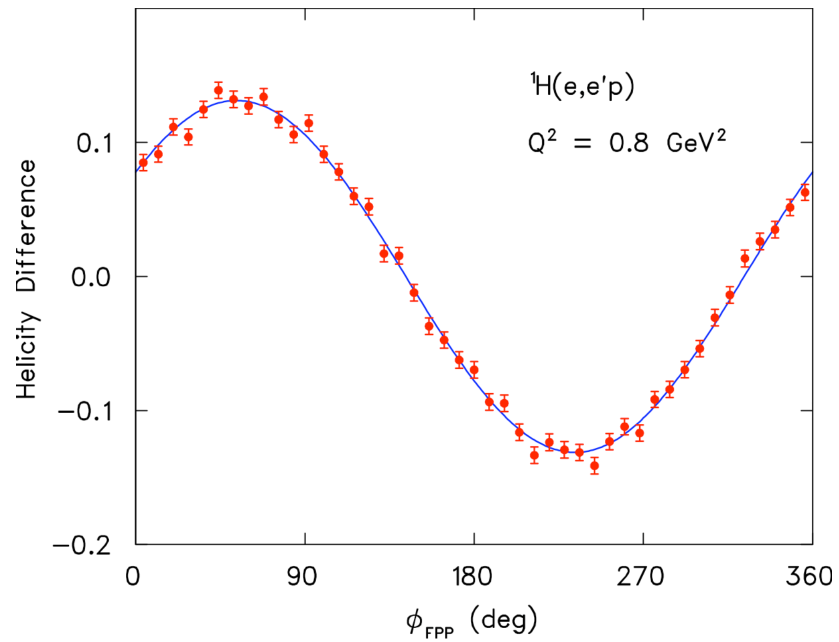


S. Dieterich, *et al.*, Phys. Lett. **B500**,47(2001); S. Strauch, *et al.*, Phys. Rev. Lett. **91**, 052301(2003); JLab E03-104, R.Ent, R. Ransome, S. Strauch, P. Ulmer (spokespersons)

Polarization Measurement

Focal-Plane Polarimeter



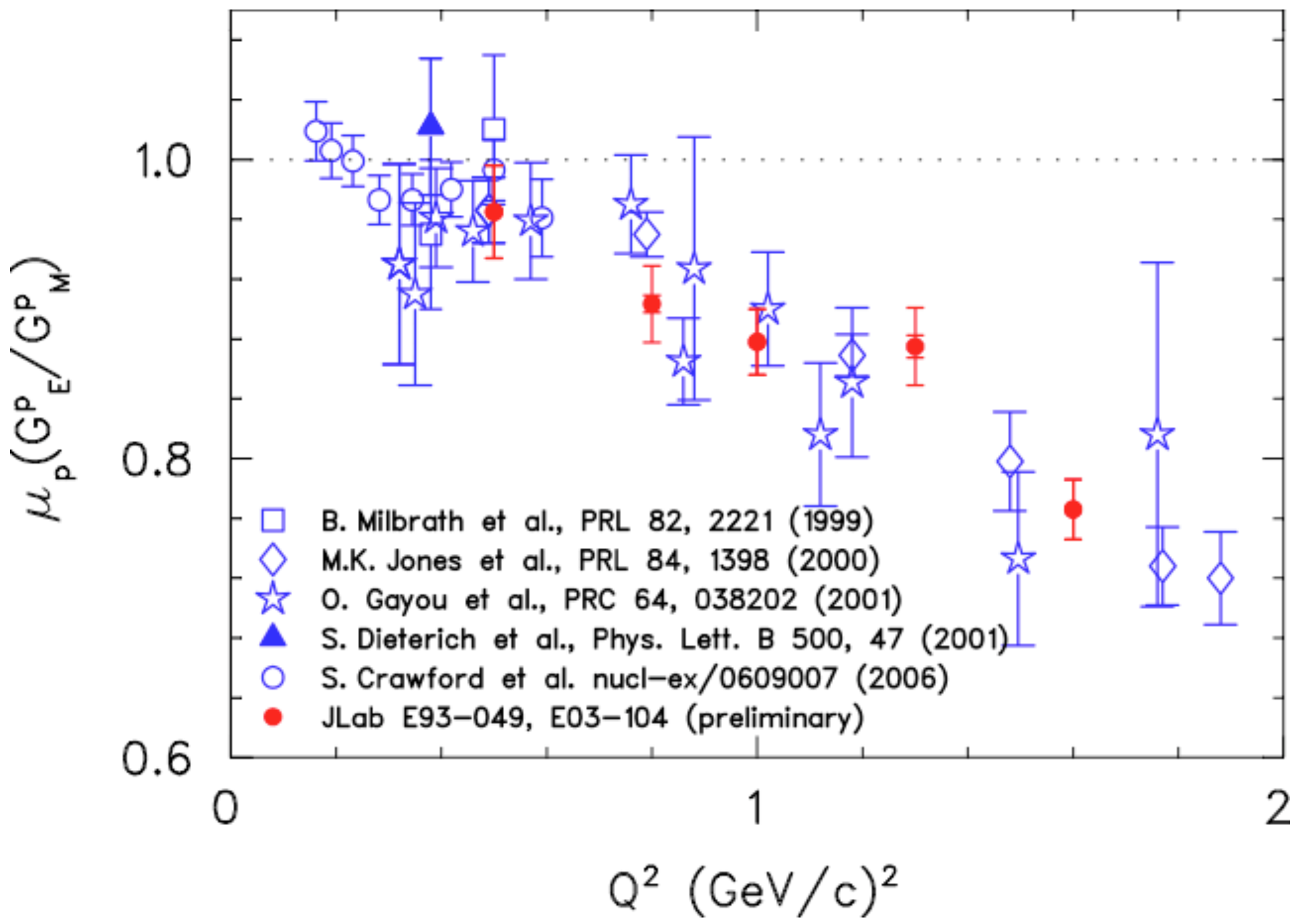


Observed angular distribution

$$I(\vartheta,\varphi) = I_0(\vartheta)\,(1+\epsilon_y\cos\varphi+\epsilon_x\sin\varphi)$$
$$= I_0(\vartheta)\,[1+A_C(P_y\cos\varphi-P_x\sin\varphi)]$$

Free Proton Form-Factor Ratio G_E/G_M

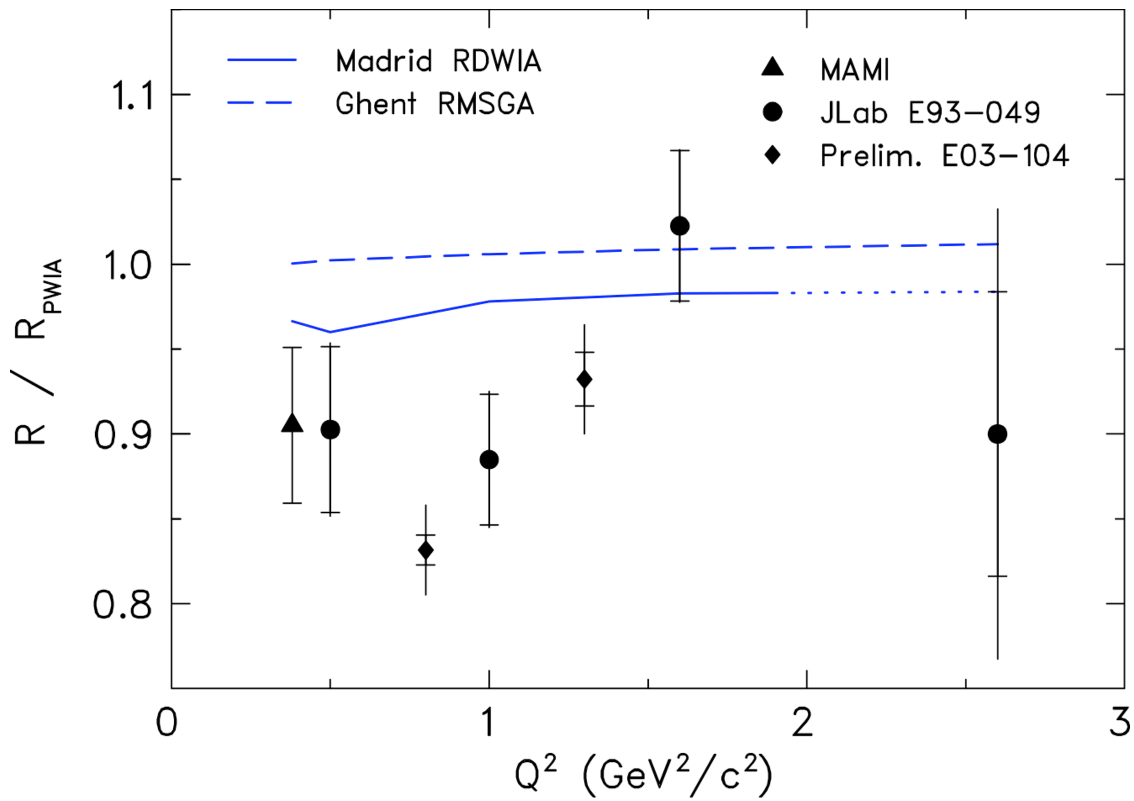
Polarization-transfer data



- Preliminary results from E03-104 with small statistical uncertainties $\delta(P'x/P'z) \approx 0.7\%$
- Full analysis of E03-104 will have reduced systematic uncertainties

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

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

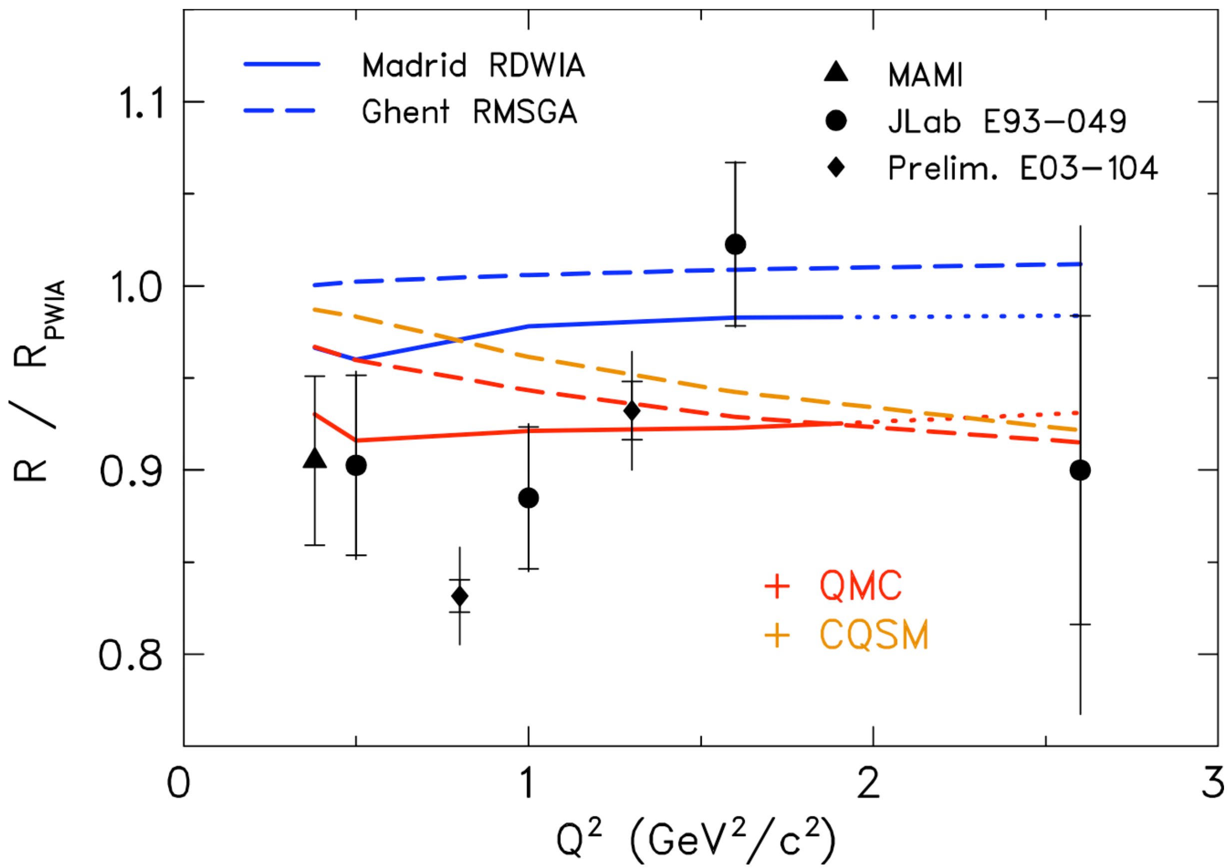


- Enhancement of lower components (spinor distortions) in RDWIA
- RDWIA and RMSGA models can not describe the data.
- Small sensitivity to
  - bound-state wave function
  - current operator
  - optical potential

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

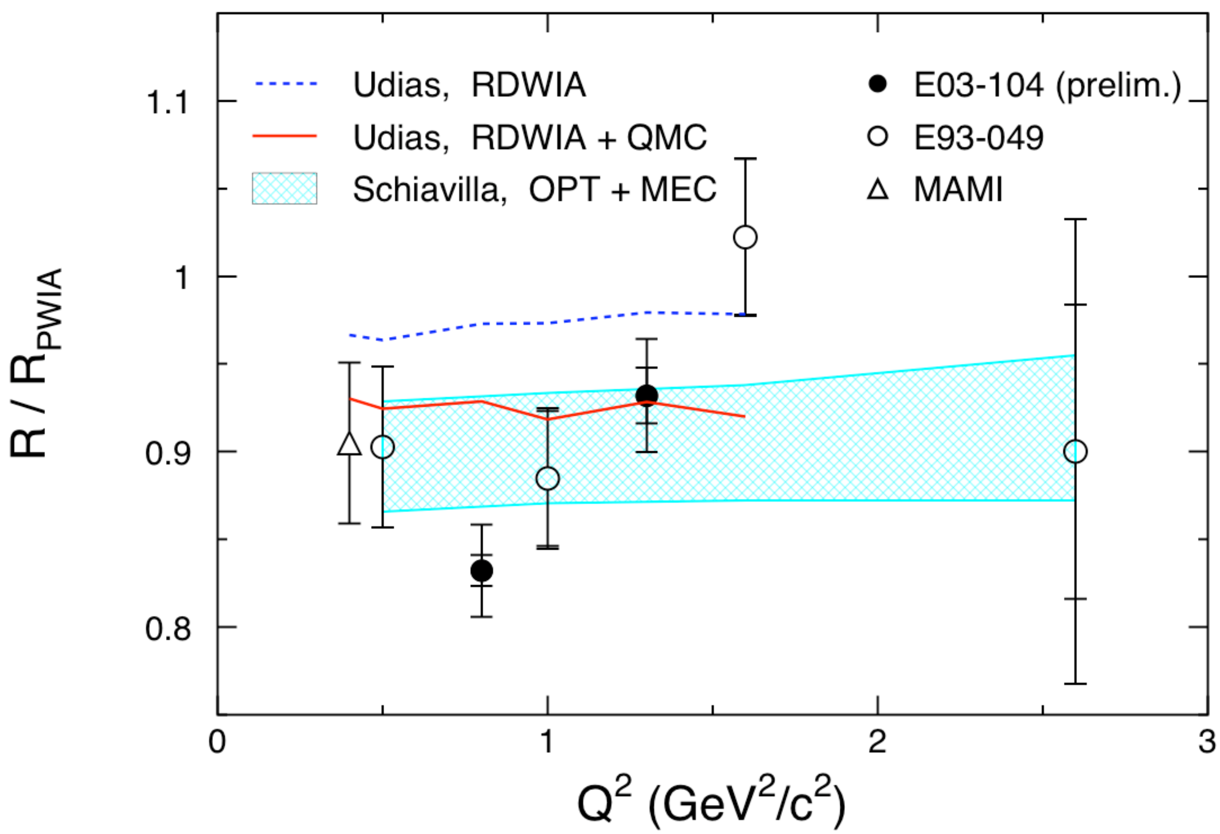
RDWIA: J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999);
RMSGA: P. Lava *et al.*, Phys. Rev. C **71**, 014605 (2005), D. Debruyne *et al.*, Phys. Rev. C **62**, 024611 (2000)

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



- Previous data effectively described by proton medium modified form factors are considered in the current operator.
- Preliminary data from E03-104 possibly hint at an unexpected trend in Q^2

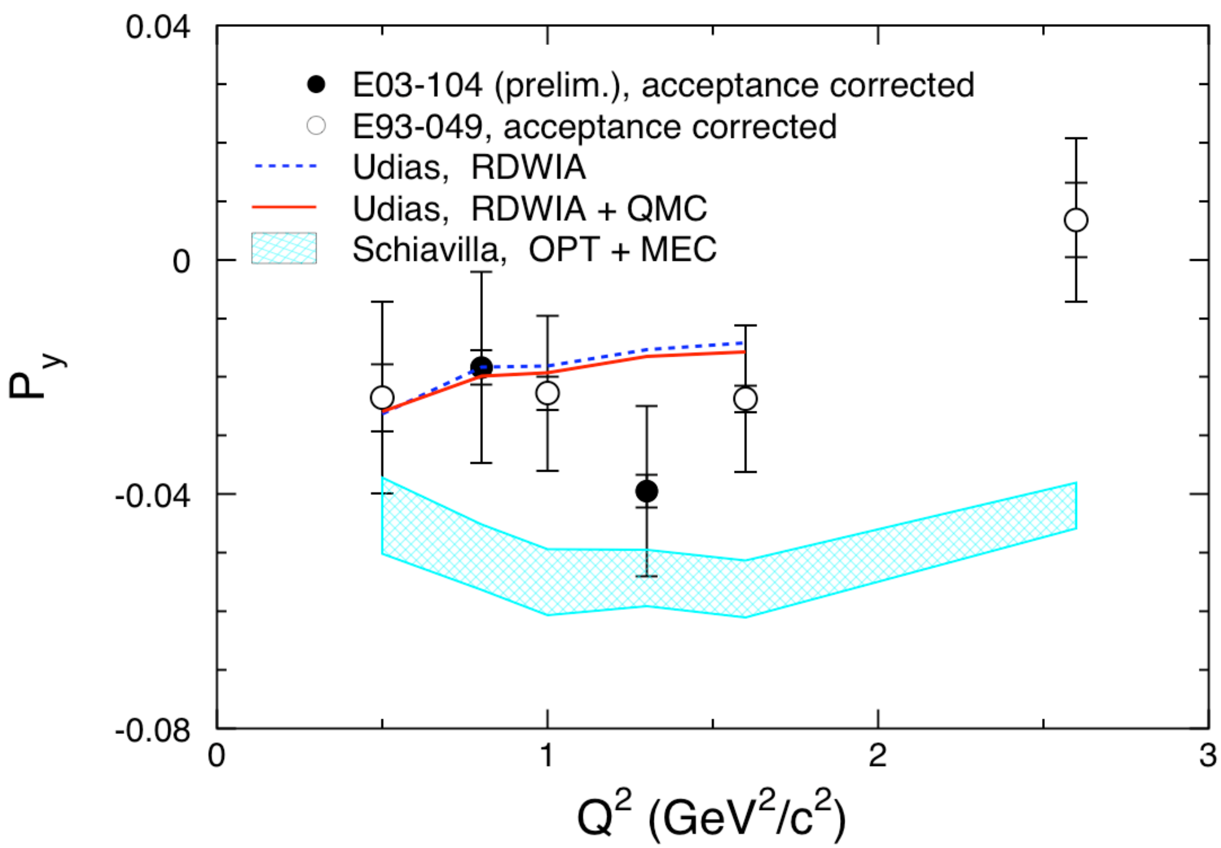
Charge-Exchange FSI



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

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

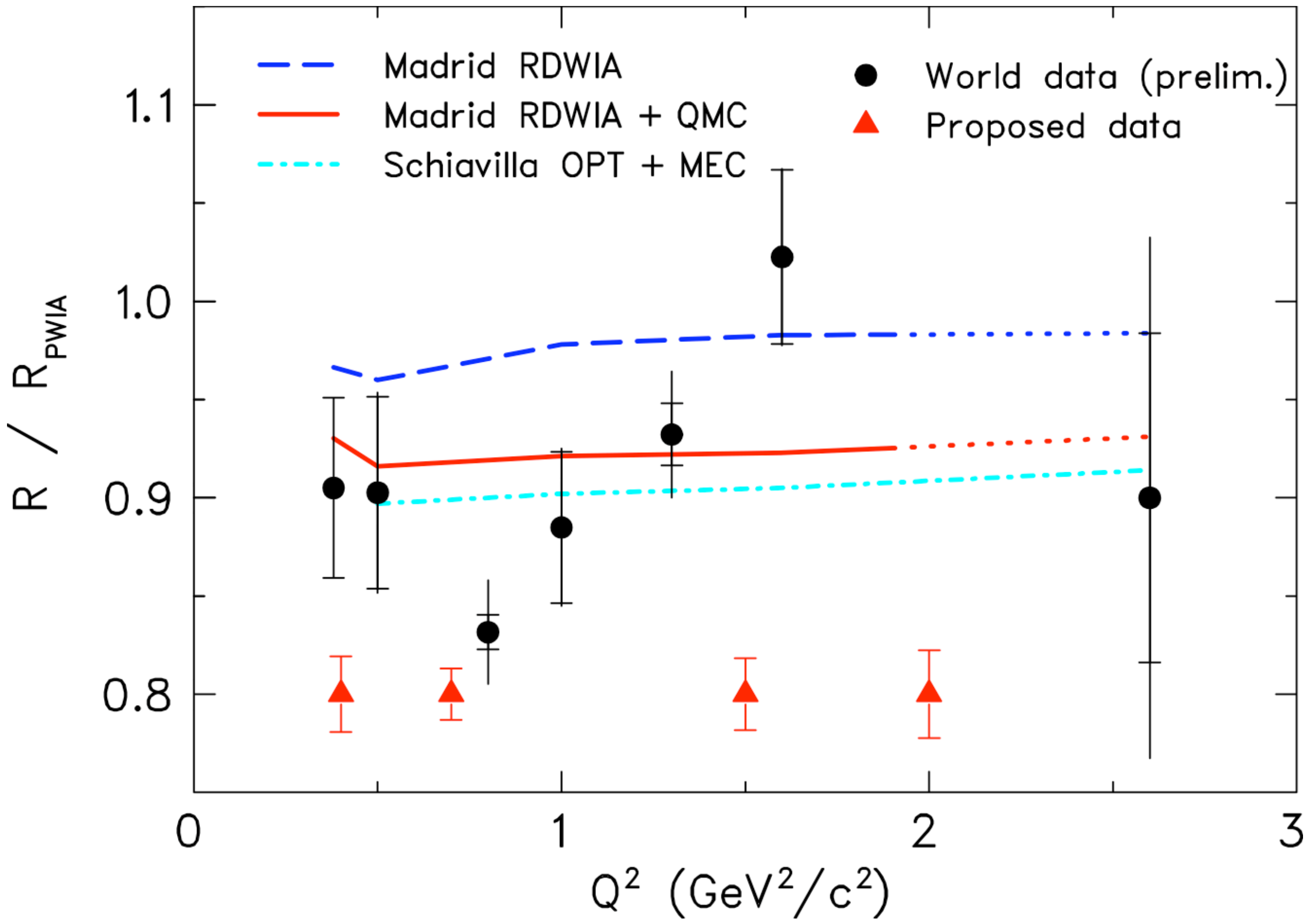
Induced Polarization in $^4He(e,e'\vec{p})$



- P_y is a measure of final-state interactions
- Observed final-state interaction small and with 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

More Detailed Study of Q^2 Distribution



- Anticipated data in 27 days of beam time on ^{4}He

E. Brash, G. Huber, S.Strauch

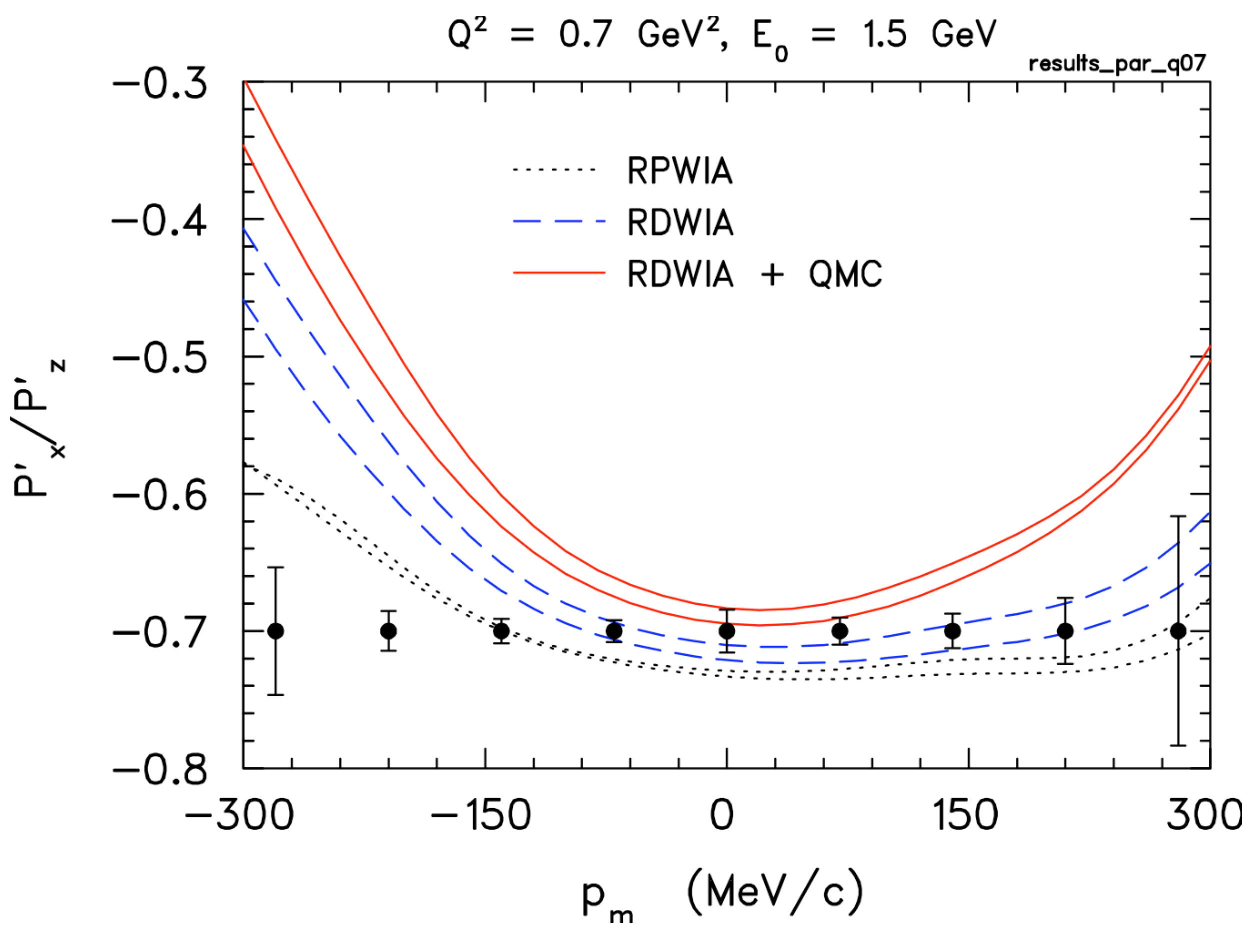
Color Screening Model of the EMC Effect

- Dynamical model: combination of two ideas
  - Point-like quark configurations (PLC) interact weakly with other nucleons.
  - Quarks in nucleon with $x > 0.5$ belong to these small-size configurations (no pion field)

- Ciofi *et al.* argue that medium modifications should strongly depend on the nucleon momentum (nucleon virtuality)
  - At p_m = 0 MeV/c, modification should vanish.
  - "Would be nice to study modification of the nucleon form factors as a function of the nucleon momentum." [Mark Strikman]

C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, and M.I. Strikman, ncul-th/0706.2937;
M. Strikman, JLab User's Group Meeting (2007)

Missing-Momentum Distribution



- Hall C proposed data
- Improved constraints on models through missing-momentum distribution

Summary

- **Proton in the nuclear medium**
  - Models predict change of the internal structure of a bound nucleon
  - Corrections due to in-medium form factors 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
  - Experiment in Hall C could measure missing-momentum distributions and extend the data set to larger Q^2