Medium Modifications from $^4He(e,e'p)^3H$

- Nucleons in the Nuclear Medium and in-medium electromagnetic form factors
- Preliminary results from JLab experiment E03-104 (Hall A Collaboration)
  - Polarization transfer
  - Induced polarization
- Momentum dependence of bound nucleon wave function

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ICTP, Trieste, Italy – May 12-16, 2008

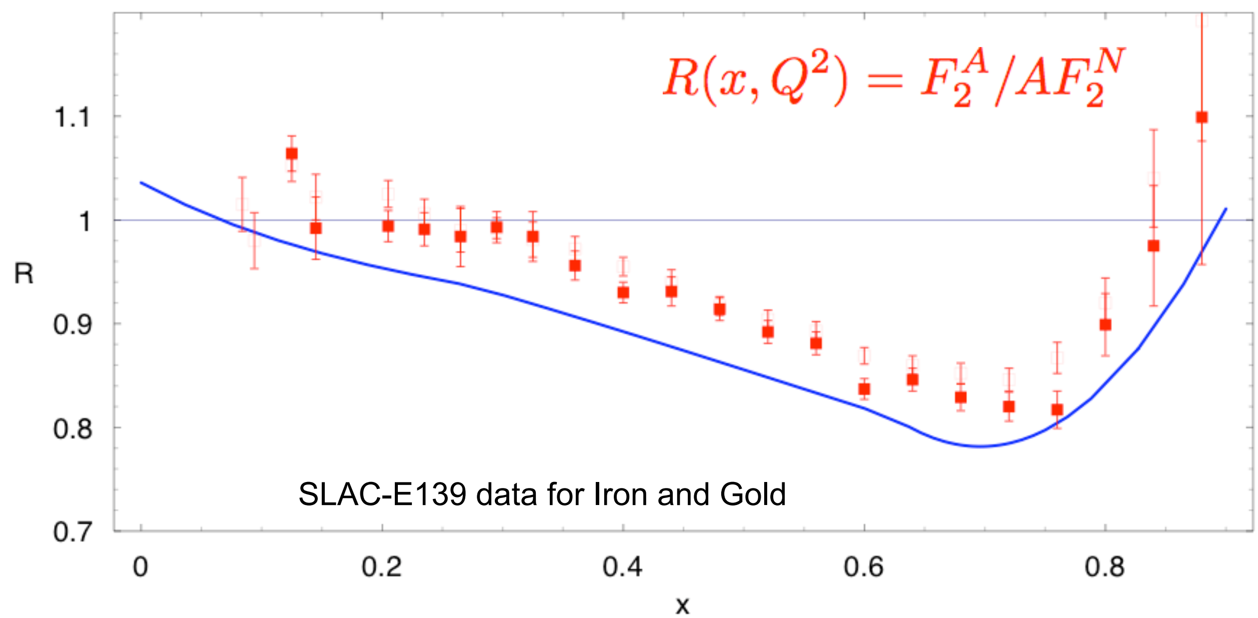
Nucleons in the Nuclear Medium

- 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 <u>non-nucleonic degrees of freedom</u>.
  - Are free nucleons and mesons, under every circumstance, the best quasi-particle to chose?

- Nucleon Medium Modifications:
  - Nucleons and mesons are not the fundamental entities in QCD.
  - Medium effects arise through <u>changes of fundamental properties of the nucleon</u>.
  - Do nucleons change their quark-gluon structure in the nuclear medium?

The EMC Effect

- The European Muon Collaboration used muon scattering to measure nuclear structure functions and observed a 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.



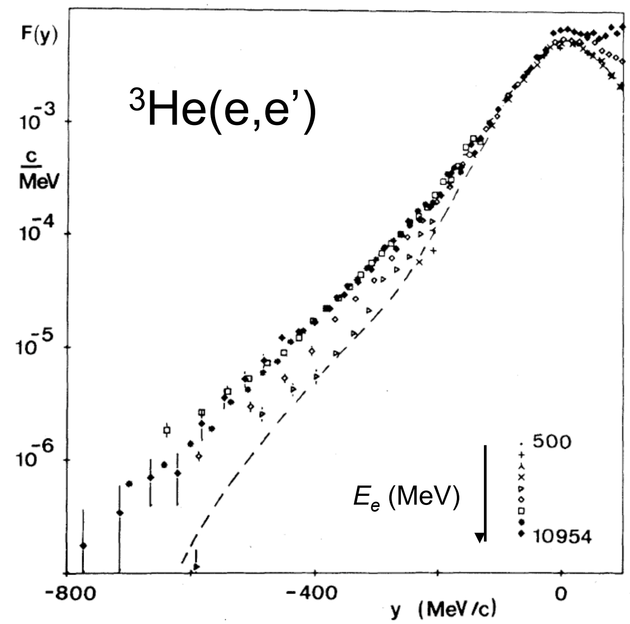
J.R. Smith and G.A. Miller, Phys. Rev. Lett. **91**, 212301 (2003)

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

y - Scaling Function

- *y* - scaling analysis of quasielastic scattering data
- 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 very sensitive to change of nucleon radius
- Limits: $Q^2 > 1\ (\text{GeV/c})^2$: $\Delta G_M < 3\%$

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



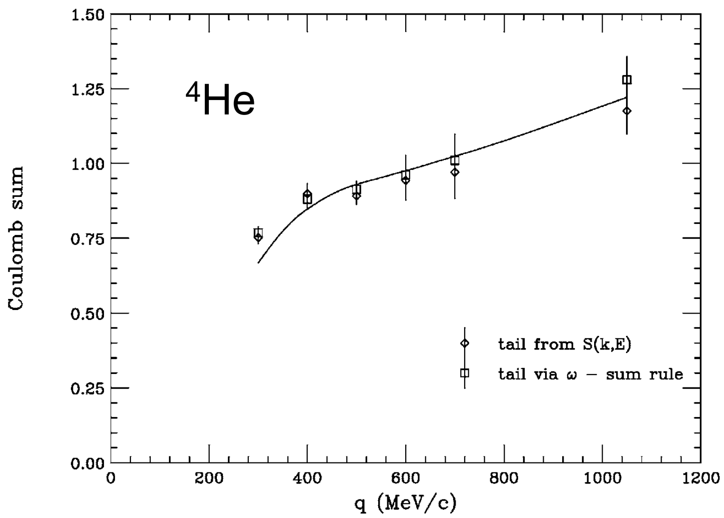
I. Sick, D. Day and J.S. McCarthy, Phys. Rev. Lett. **45**, 871 (1980);
Limit on radius from I. Sick, in: H. Klapdor (Ed.), Proc. Int. Conf. on Weak and Electromagnetic Interactions in Nuclei, Springer-Verlag, Berlin, 1986, p. 415

Coulomb Sum Rule

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

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

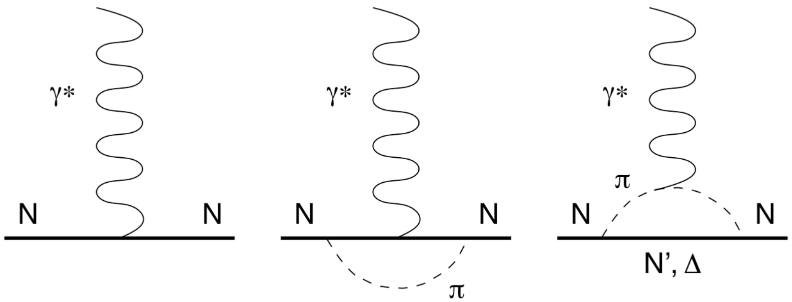
- Experimental findings controversial:
  - No quenching in the data observed [2]
  - Quenching of S_L is experimentally established [3]
  - Good agreement between theory and experiment for ^{4}He when using free-nucleon form factors [4]
- Limits: $Q^2 \leq 0.5$ (GeV/c)^2: $\Delta G_E < 15\%$ or even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



[1] I. Sick, Phys. Lett. B **157**, 13 (1985)
[2] J. Jourdan, Nucl. Phys. A **603**, 117 (1996)
[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)

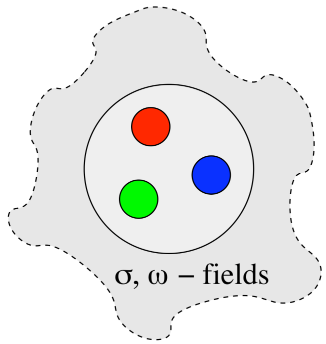
Quark Meson Coupling Model (QMC)

- 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.

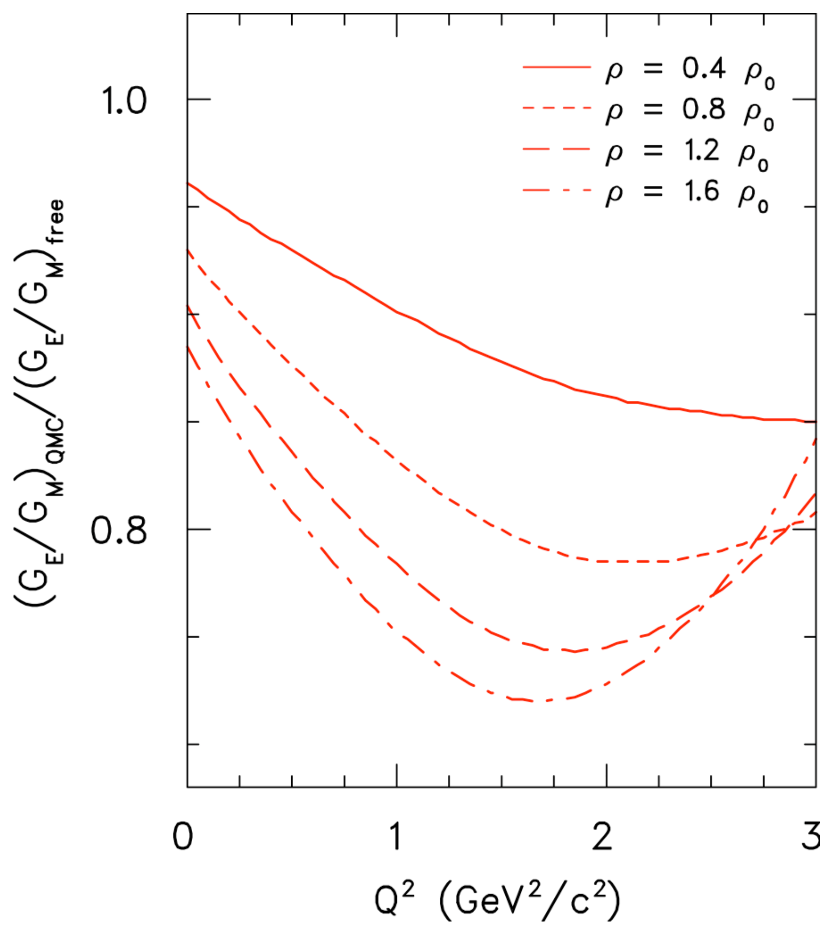


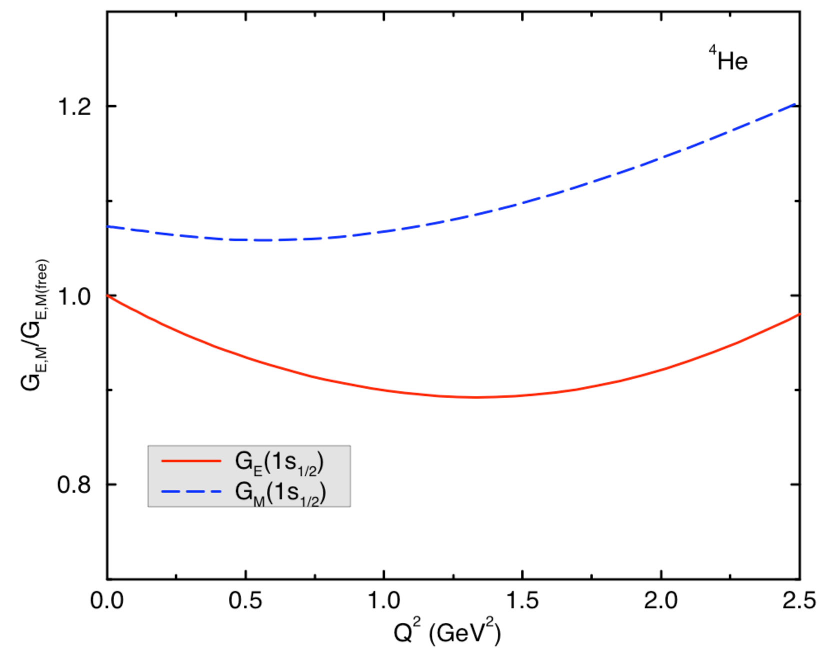
- Scalar and vector fields of nuclear matter couple directly to confined quarks.

→ 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)

QMC: Bound Proton EM Form Factors

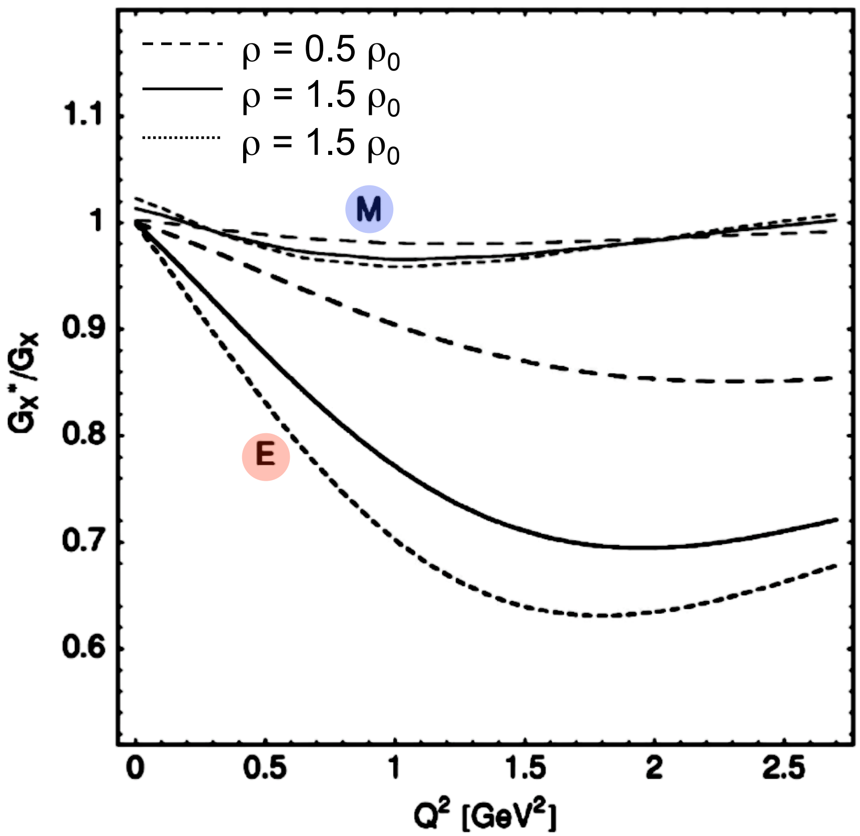




D.H. Lu *et al.*, Phys. Rev. C **60**, 068201 (1999)

- Electromagnetic rms radii and magnetic moments of the bound proton are increased.
- At low Q^2: 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 G_E, only moderate for G_M
  - no strong enhancement of the magnetic moment

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

Other Models

- **Extended Skyrme Model**

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

  - Model of the nucleon based on Skyrme Lagrangian
  - Results for ^{4}He comparable to QMC, but differ in detail
  - $(G_E/G_M)_{medium}/(G_E/G_M)_{free} \approx 1$ for R = 1 fm

- **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.

- **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.

Medium-modified form factors are not an experimental observable. How can we test these predictions?

Strategy:

- Choose an observable with high sensitivity to nucleon structure while being at the same time least sensitive to conventional medium effects.
- Chose a dense yet simple nuclear target, which allows for microscopic calculations.
- Provide high-precision data to put Nuclear Physics models to rigorous test.

Polarization-Transfer Technique

- Free electron-nucleon scattering

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

$$^1\mathrm{H}(\vec{e}, e'\vec{p})$$

- Bound nucleons → evaluation within model

  Reaction-mechanism effects predicted to be small and minimal for

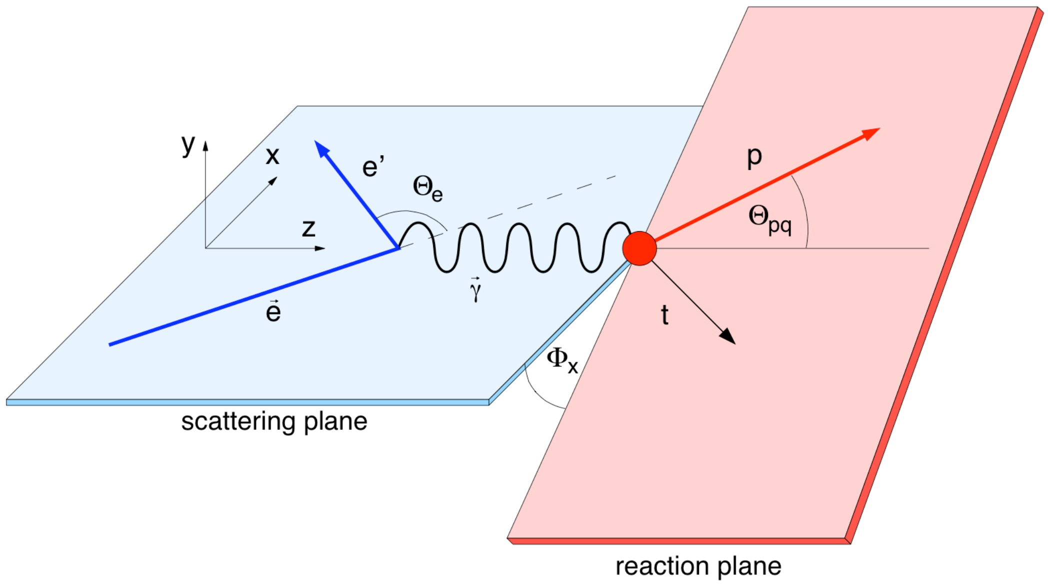
  - Quasielastic scattering
  - Small missing momenta
  - Symmetry about $\boldsymbol{p}_m = 0$

$$A(\vec{e}, e'\vec{p})B$$

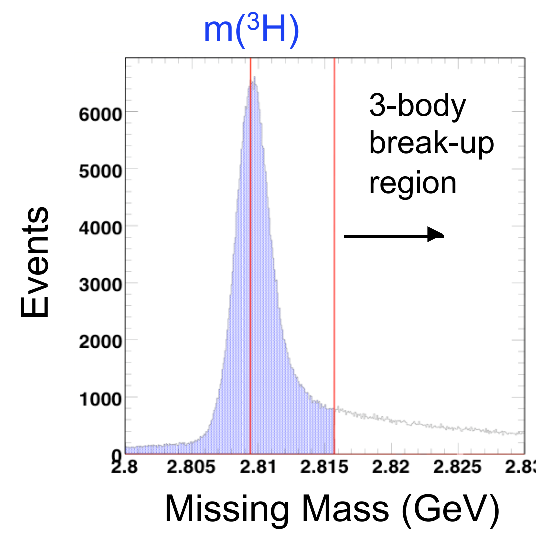
R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981); for reaction-mechanism effects, *e.g.*, J.M. Laget, Nucl. Phys. A **579**, 333 (1994), J.J. Kelly, Phys. Rev. C **59**, 3256 (1999), A. Meucci, C. Guisti, and F.D. Pacati, Phys. Rev. C **66**, 034610 (2002).

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

- Kinematics: low missing momentum, quasielastic scattering



- Channel identification by missing mass (Mike Paolone)

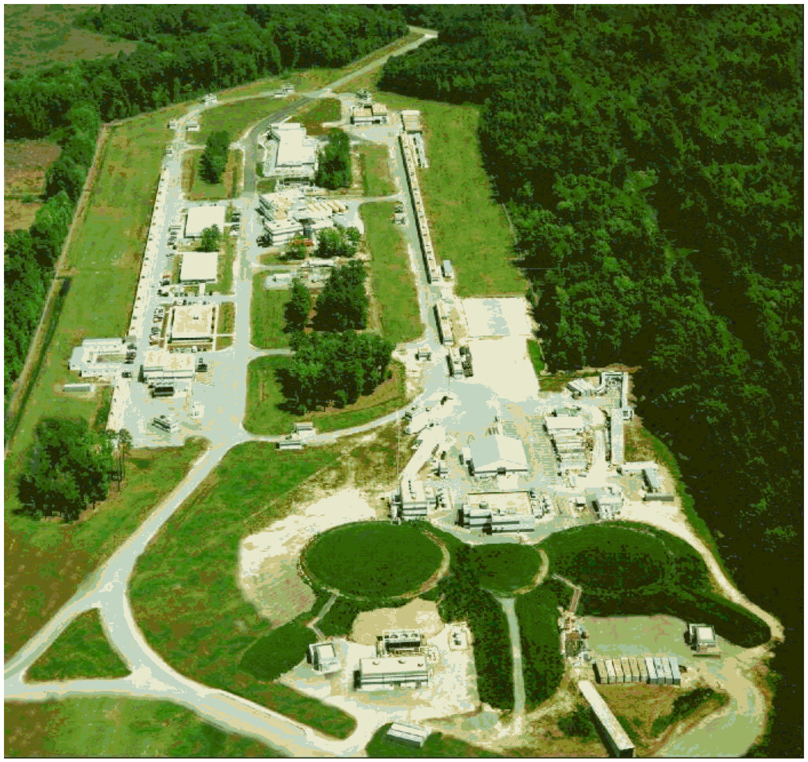


- Polarization-transfer ratio P'_x/P'_z: sensitive to G_E/G_M

$$R = \left(\frac{P'_x}{P'_z}\right)_{\mathrm{bound}} \Big/ \left(\frac{P'_x}{P'_z}\right)_{\mathrm{free}}$$

- Induced polarization P_y: sensitive to final-state interactions

Thomas Jefferson
National Accelerator Facility

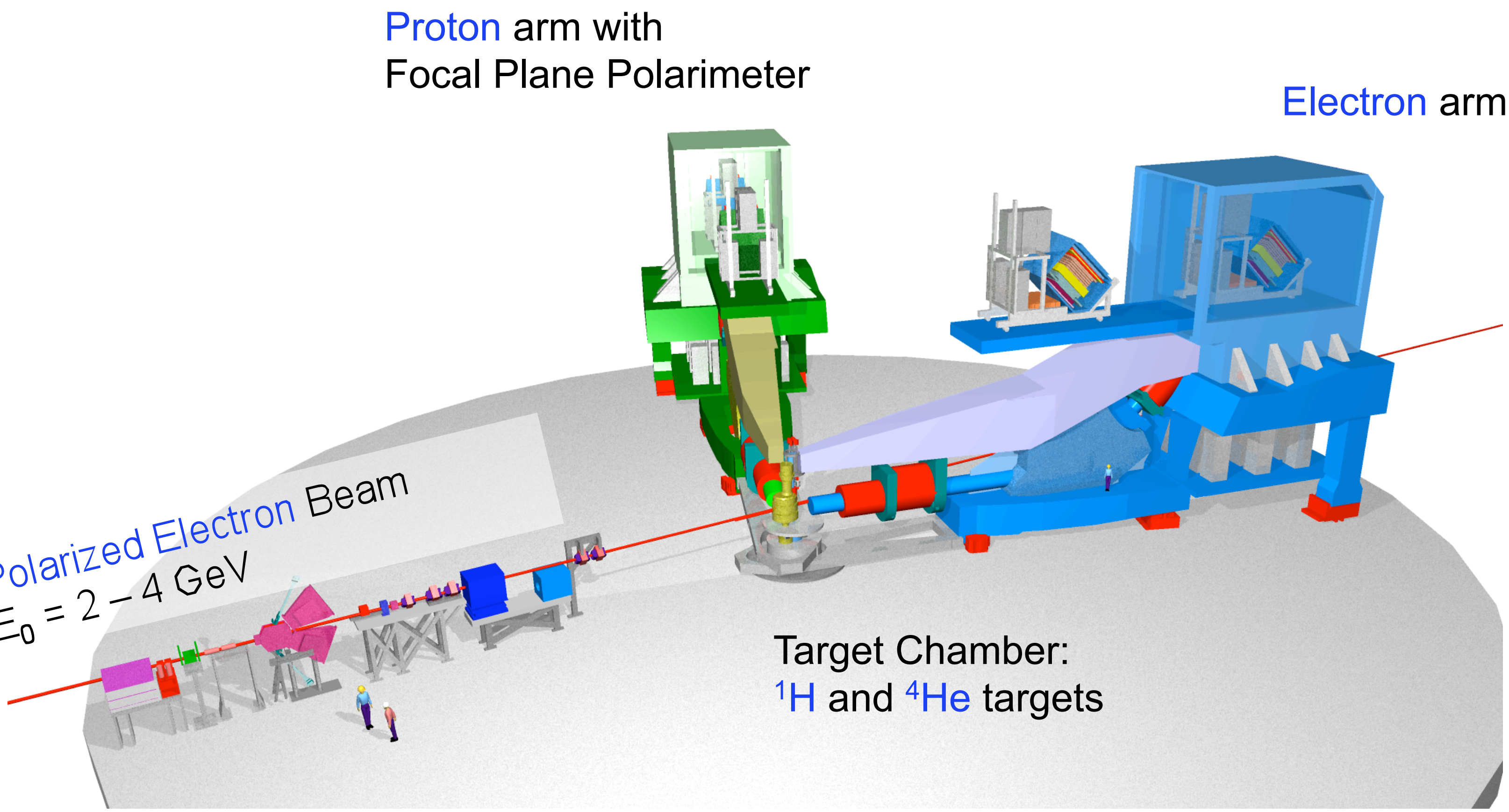


JLab in Newport News, VA

Hall A Counting House

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

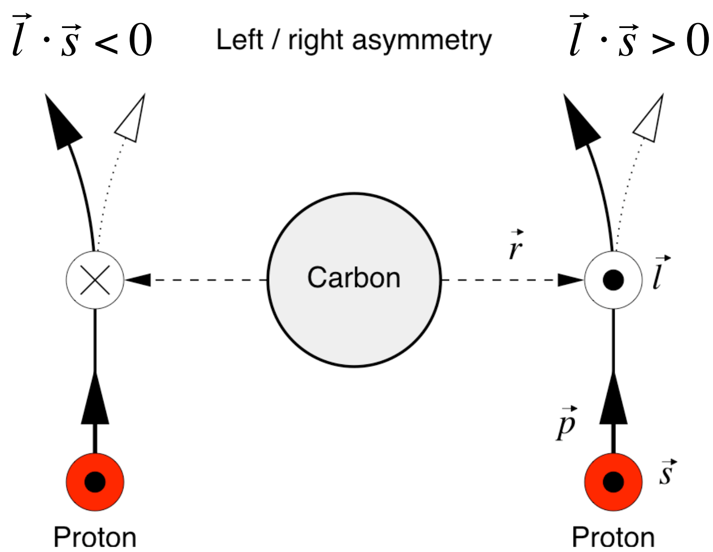
^{4}He(e,e'p)^{3}H in quasielastic kinematics $Q^2 = 0.5 - 2.6$ (GeV/c)^2



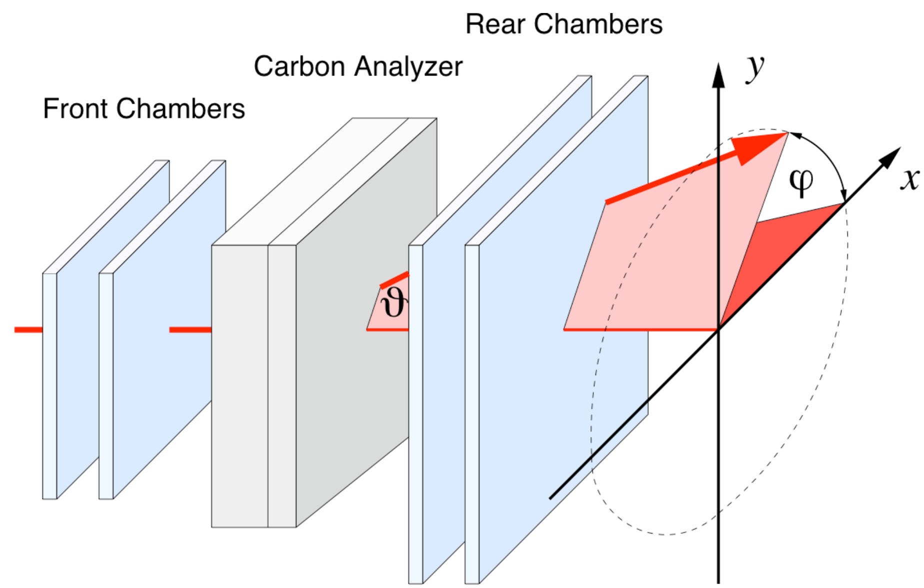
S. Strauch, *et al.*, Phys. Rev. Lett. **91**, 052301(2003);
JLab E03-104, R. Ent, R. Ransome, S. Strauch, P. Ulmer (spokespersons)

Polarization Measurement

Spin-dependent scattering



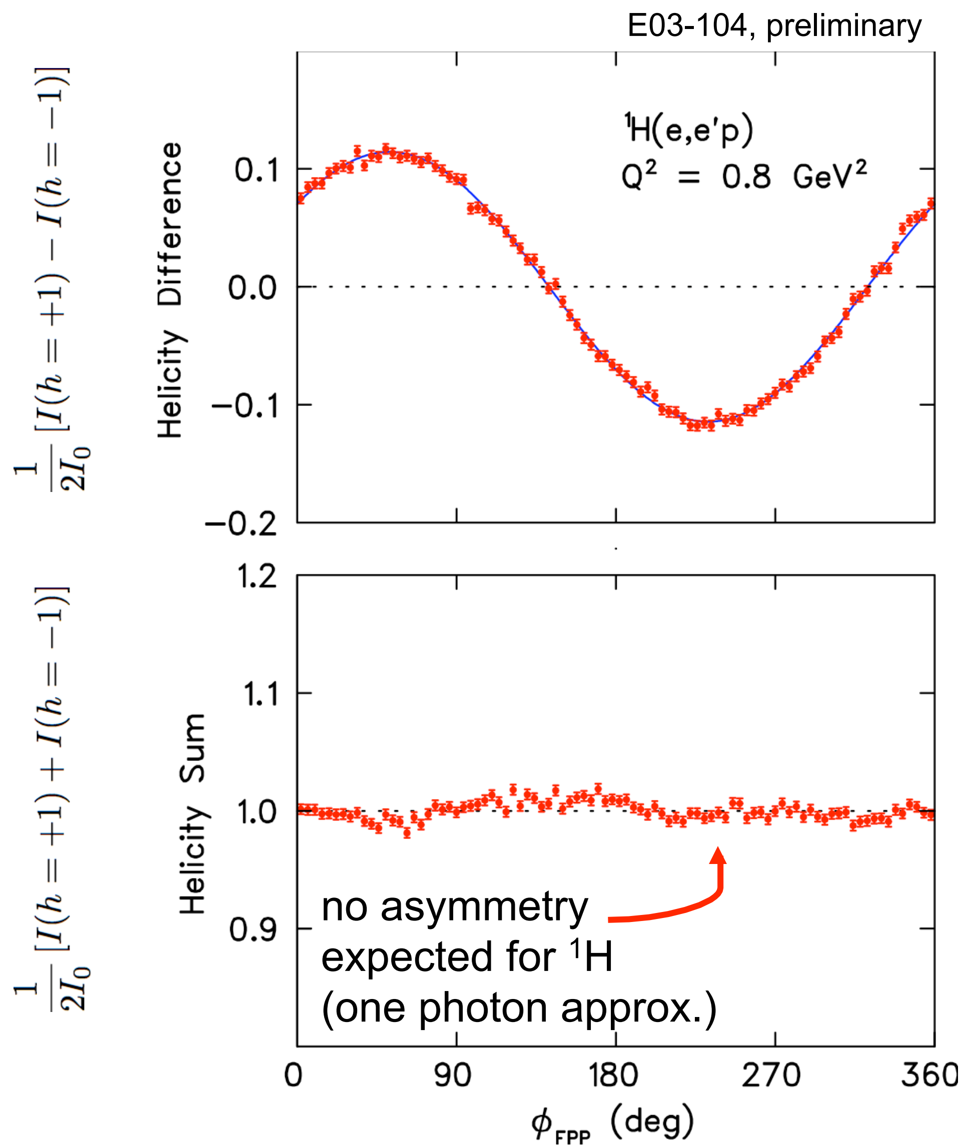
Focal-Plane Polarimeter



Observed angular distribution

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

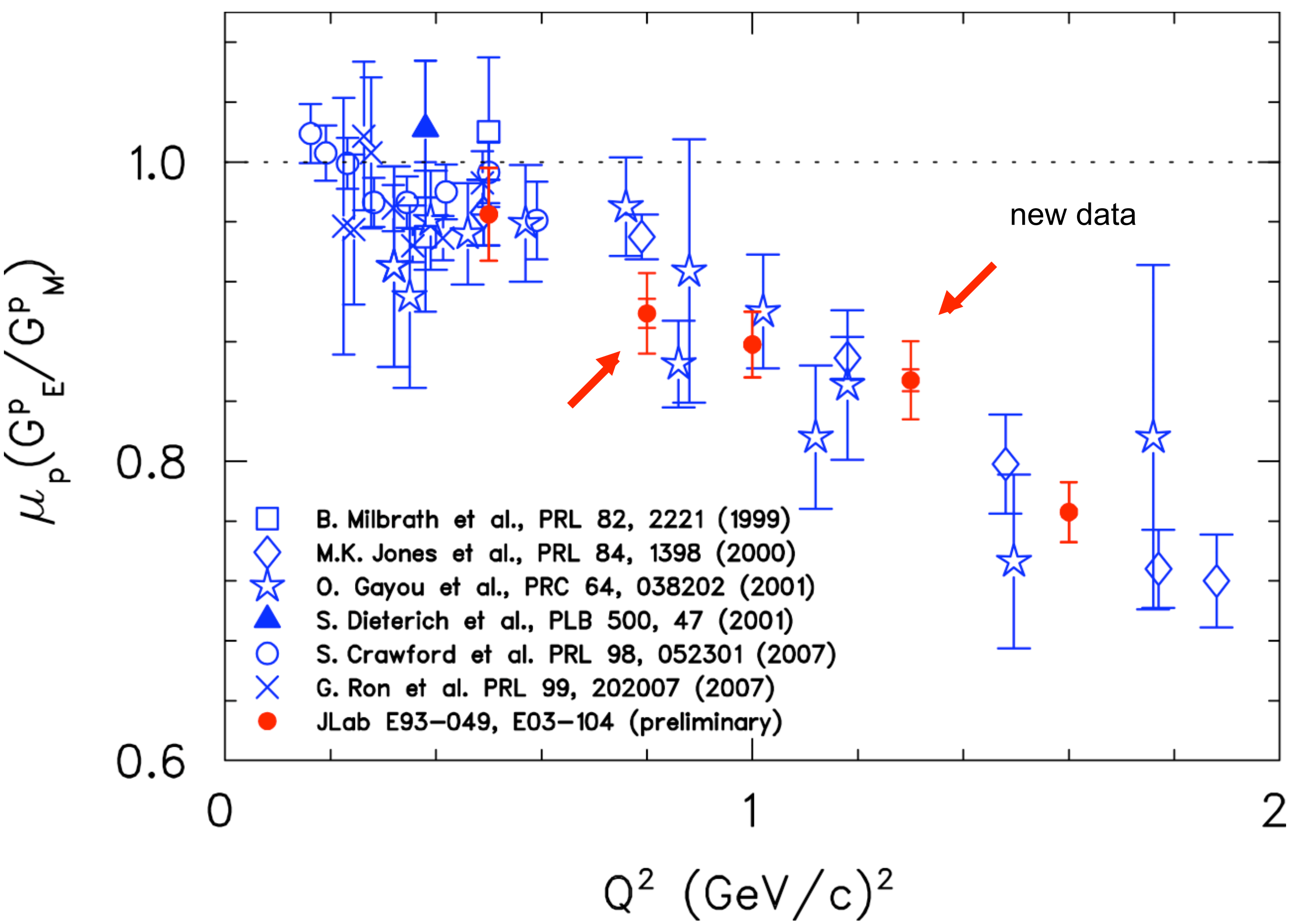
Observed Angular Distribution



- Excellent control of systematic uncertainties for polarization transfer
- Instrumental asymmetries complicate the extraction of induced polarization
  - Detector misalignment
  - Detector inefficiencies
  - Tracking problems

(Simona Malace)

Free Proton Form-Factor Ratio $\mu_p G_E/G_M$

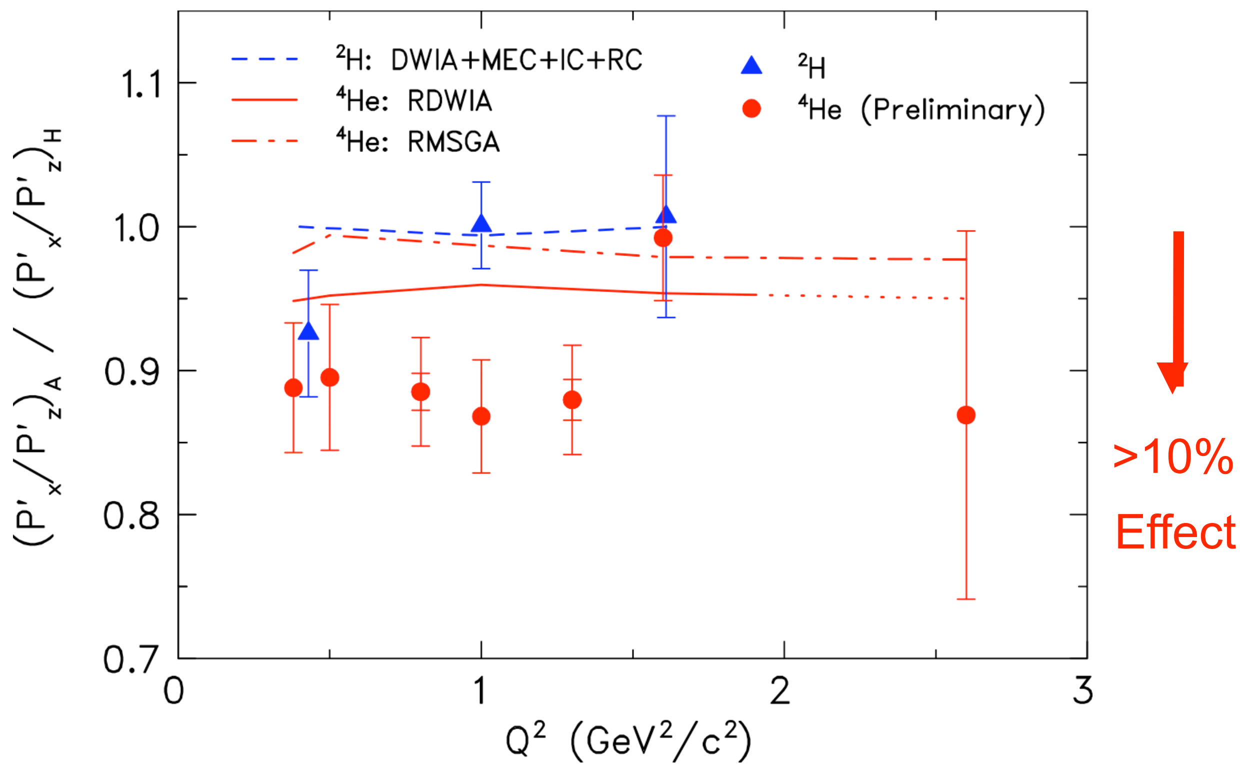


- Preliminary results from E03-104 in good agreement with previous data.
- Small statistical uncertainties 0.7% form E03-104.
- Final data will have reduced systematic uncertainties.

^{2}H and ^{4}He(e,e'p) Polarization-Transfer Ratios

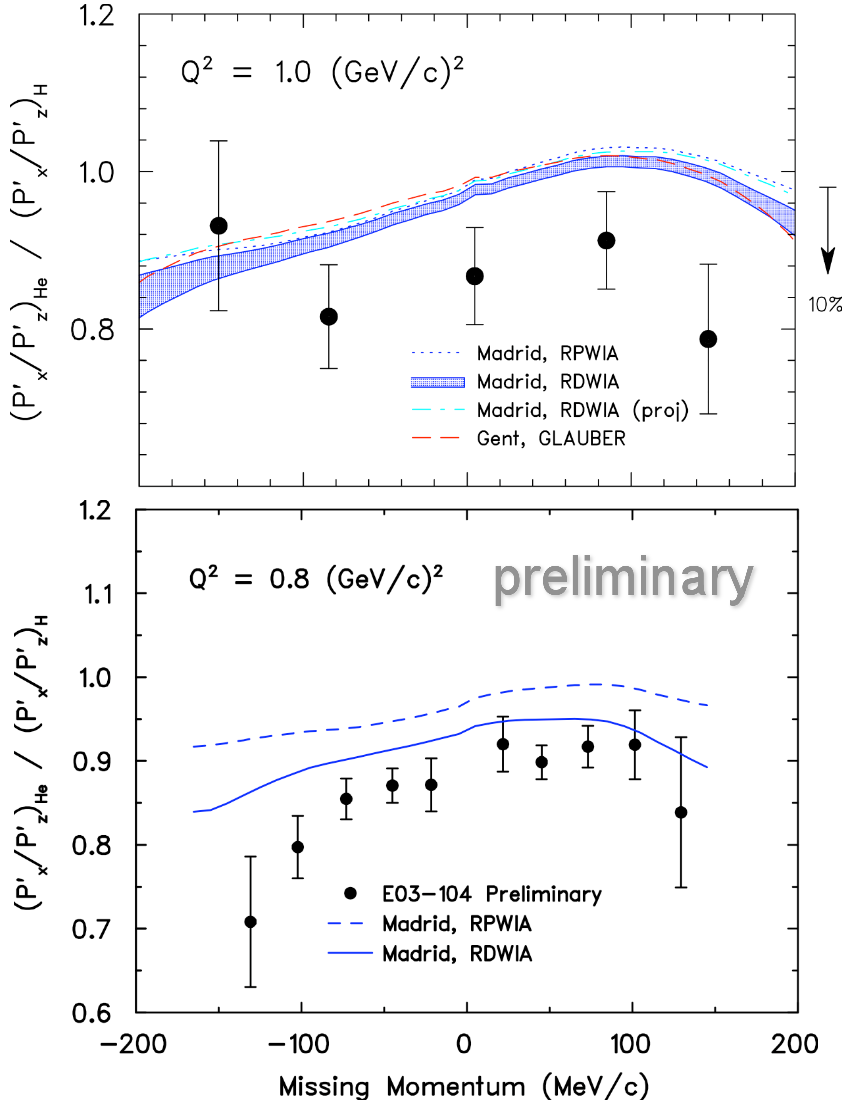
$$R = \left(\frac{P'_x}{P'_z}\right)_{\text{bound}} \Big/ \left(\frac{P'_x}{P'_z}\right)_{\text{free}}$$

- ^{2}H and ^{1}H polarization-transfer data are similar.
- ^{4}He data are significantly different than ^{2}H, ^{1}H data.
- Small effect for less dense nucleus, larger for denser.
- RDWIA and RMSGA models cannot describe ^{4}He data.



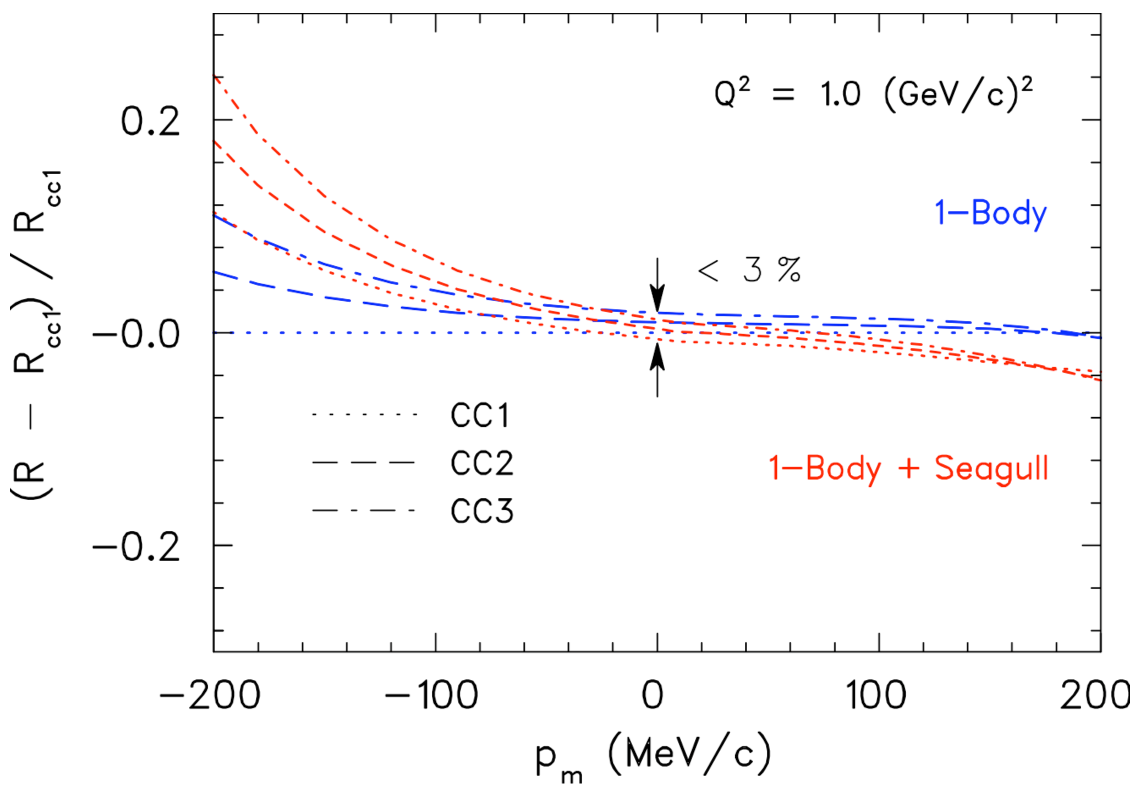
^{2}H Model: H. Arenövel; see: B. Hu *et al.*, Phys. Rev. C **73**, 064004 (2006).
RDWIA: J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999).
Relativistic Multiple-Scattering Glauber Approximation (RMSGA):
P. Lava *et al.*, Phys. Rev. C **71**, 014605 (2005), D. Debruyne *et al.*, Phys. Rev. C **62**, 024611 (2000).

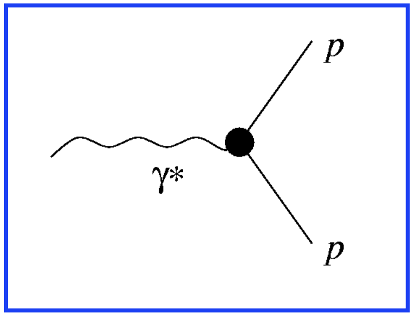
$^4He(e,e'p)^3H$ - Polarization-Transfer Ratio



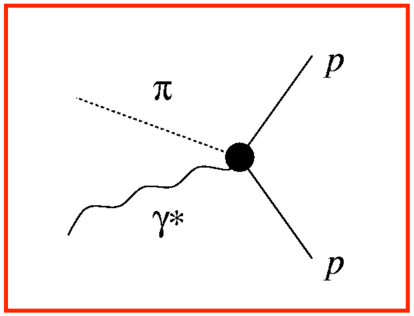
- Previous and preliminary high-statistics data from E03-104 are also low compared to RDWIA
- R^{RDWIA} reduced by 3% compared to R^{RPWIA} due to Enhancement of lower components (spinor distortions) in RDWIA
- Small sensitivity to
  - bound-state wave function
  - current operator
  - optical potential (not including charge exchange terms)

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





direct knockout contribution

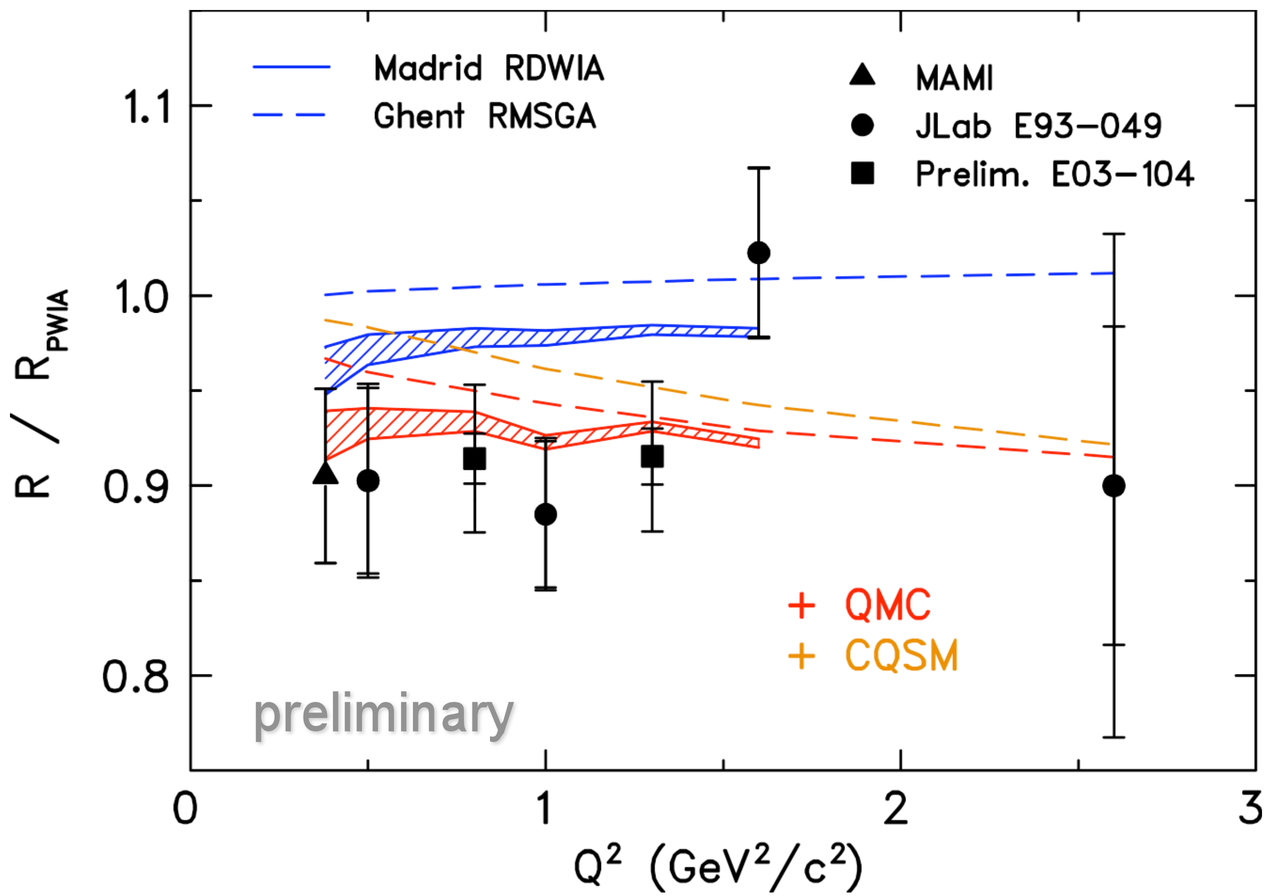


seagull (contact) diagram with one-pion exchange

- The seagull diagram effects generally small and visible only at high missing momenta; MEC expected to give more significant effect in the induced polarization
  Relativistic mean-field calculation: A. Meucci, C. Giusti, and F.D. Pacati, Phys. Rev. C **66**, 034610 (2002)
- R is suppressed by about 4% with respect to that obtained with one-body currents only
  R. Schiavilla, O. Benhar, A. Kievsky, L.E. Marcucci, and M. Viviani, Phys. Rev. Lett. **94**, 072303 (2005)

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

$$G(Q^2,\rho) = G(Q^2)\frac{G_{\mathrm{QMC}}(Q^2,\rho)}{G_{\mathrm{QMC}}(Q^2)}$$



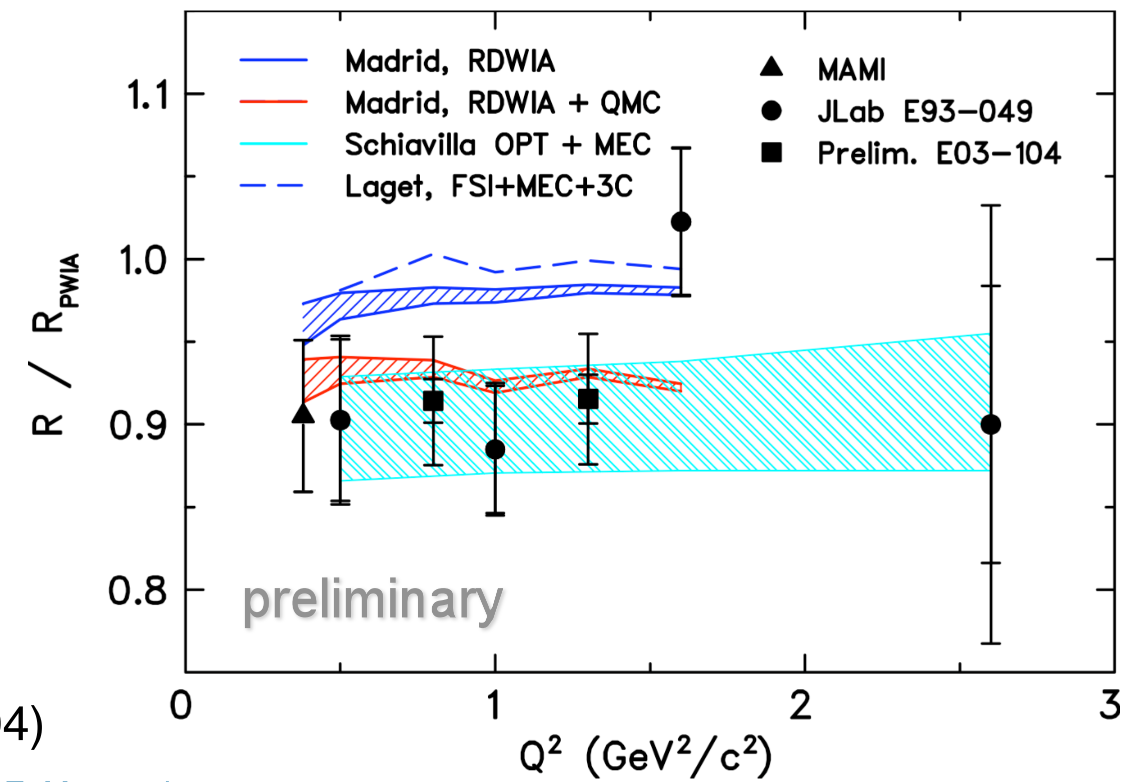
- In-medium form factors: density-dependent form factors are evaluated at the local density $\rho(r)$.
- R is reduced by an additional 6% (QMC).
- Data effectively described by proton medium modified form factors

Interpretation of Polarization-Transfer Data

- Data consistent with:
  - RDWIA
  - Density-dependent medium modified form factors.

OR

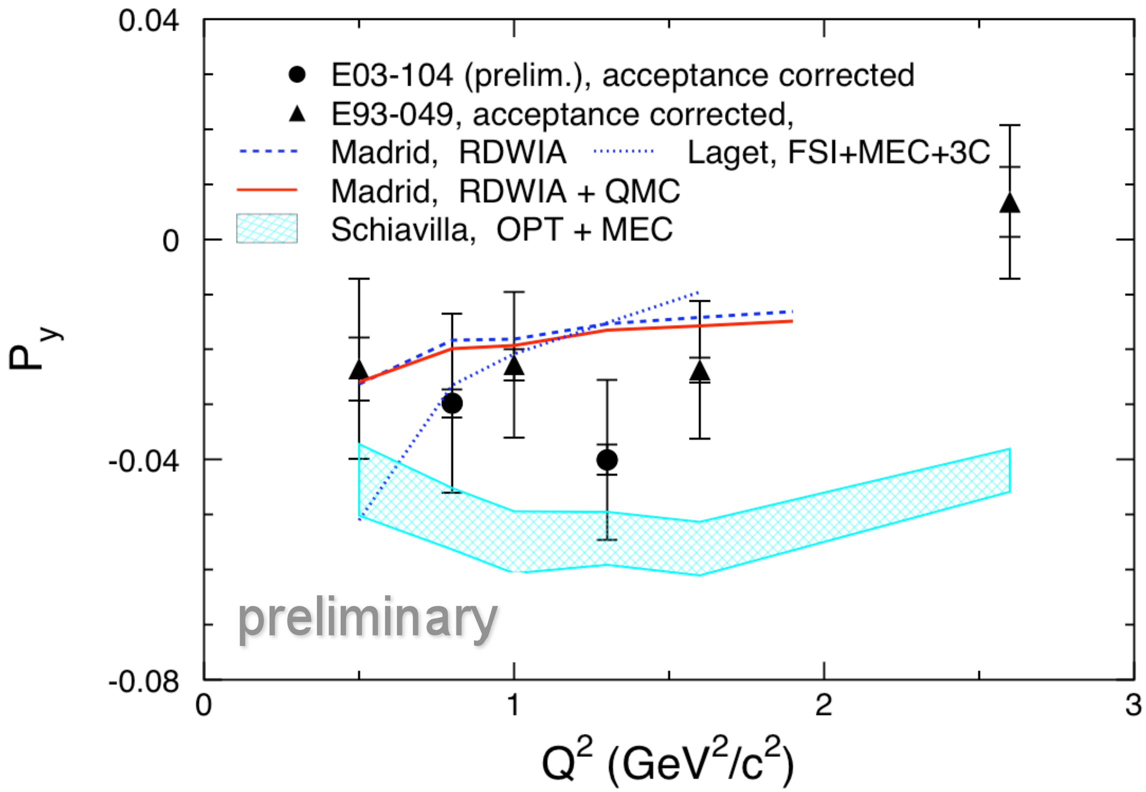
  - Free form factors
  - MEC
  - Spin-dependent charge-exchange FSI (not well constrained $\Rightarrow$ need P_y from E03-104)



R. Schiavilla, O. Benhar, A. Kievsky, L.E. Marcucci, and M. Viviani, Phys. Rev. Lett. **94**, 072303 (2005)

- The modeling of final-state interactions can be tested by measuring the induced polarization, P_y.

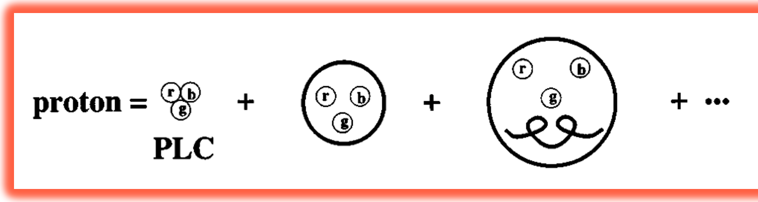
Induced Polarization in $^4\mathrm{He}(e,e'\vec{p})$



Note: Data are acceptance corrected; inner uncertainties are statistical only; full analysis of E03-104 will have reduced systematic uncertainties

- P_y is a measure of final-state interactions (FSI)
- P_y is insensitive to in-medium form factors.
- Observed final-state interaction small and with only very weak Q^2 dependence
- Results from RDWIA and Laget consistent with data
- Spin-dependent charge exchange terms not well constrained by N-N scattering and possibly overestimated

Bound Nucleon Wave Function



Pointlike Configurations (PLC)

- Smaller average interaction strength
- PLC suppressed in the bound state
- Contribution of PLCs exhibit a strong momentum dependence (arising from the reduction of the interaction strength)

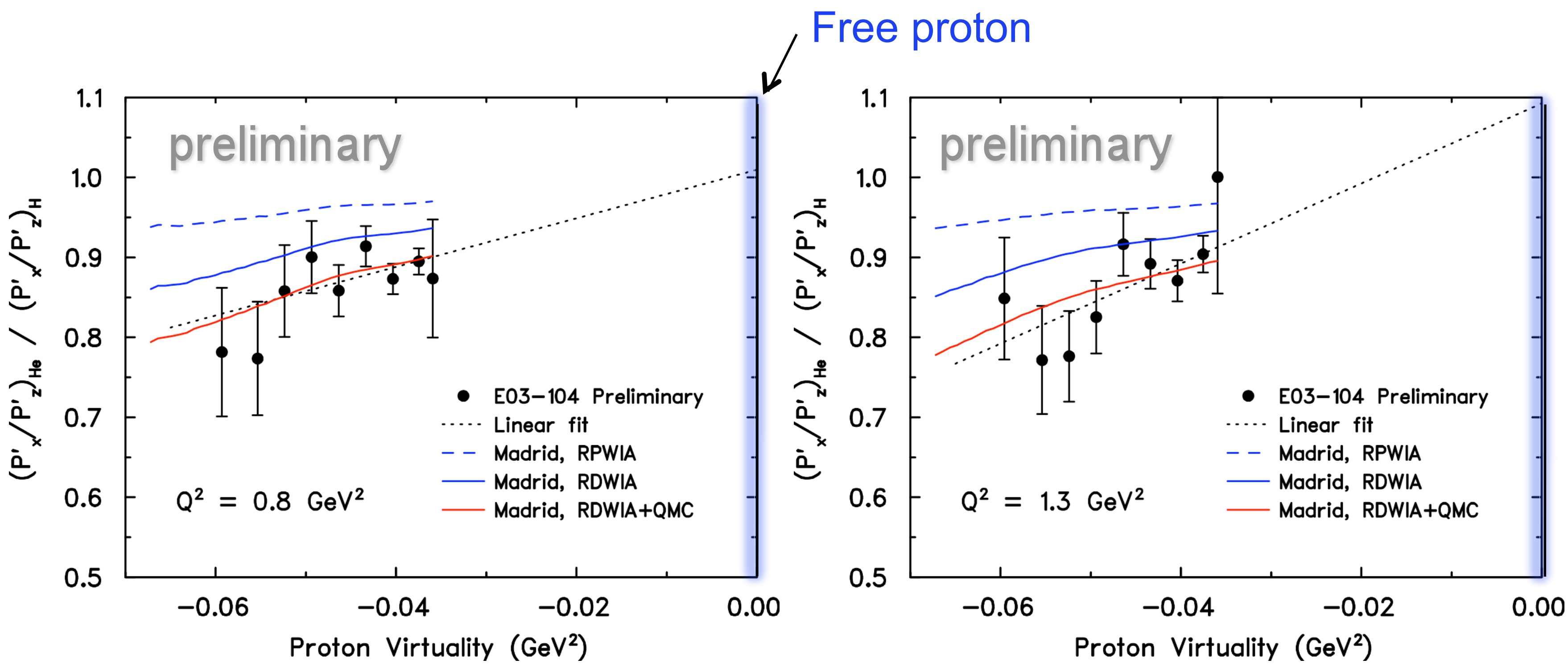
Ciofi degli Atti *et al.* argue that medium modifications should strongly depend on the nucleon momentum (nucleon virtuality)

$$
\begin{aligned}
v &= p^2 - m_N^2 \\
&= \left(M_A - \sqrt{(M_A - m_N + E)^2 + \mathbf{p^2}}\right)^2 - \mathbf{p^2} - \mathbf{m_N^2}
\end{aligned}
$$

- At $v = 0$, 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, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)
M.R. Frank, B.K. Jennings, G.A. Miller, Phys. Rev. C **54**, 920 (1996)

Proton Virtuality – Suppression of PLCs?



- Polarization-transfer double ratio shows (linear) dependence on proton virtuality with the trend of R ≈ 1 for $p^2 = m^2_N$
- Excellent description with the RDWIA + QMC model.

Summary

- **Models predict change of the internal structure of bound nucleon**
- **Recoil-polarization in $^4He(e,e'p)^3H$**
  - Two polarization observables act together to constrain the interpretation of the data
    - Polarization transfer: sensitive to in-medium form factors
    - Induced polarization: sensitive to final-state interactions, not sensitive to in-medium form factors
- **Preliminary results**
  - Data effectively described by in-medium electromagnetic form factors or strong charge-exchange FSI
  - Induced polarization crucial to clarify role of FSI and new results from E03-104 will provide needed constraints