In-Medium Form-Factors and the Coulomb Sum Rule

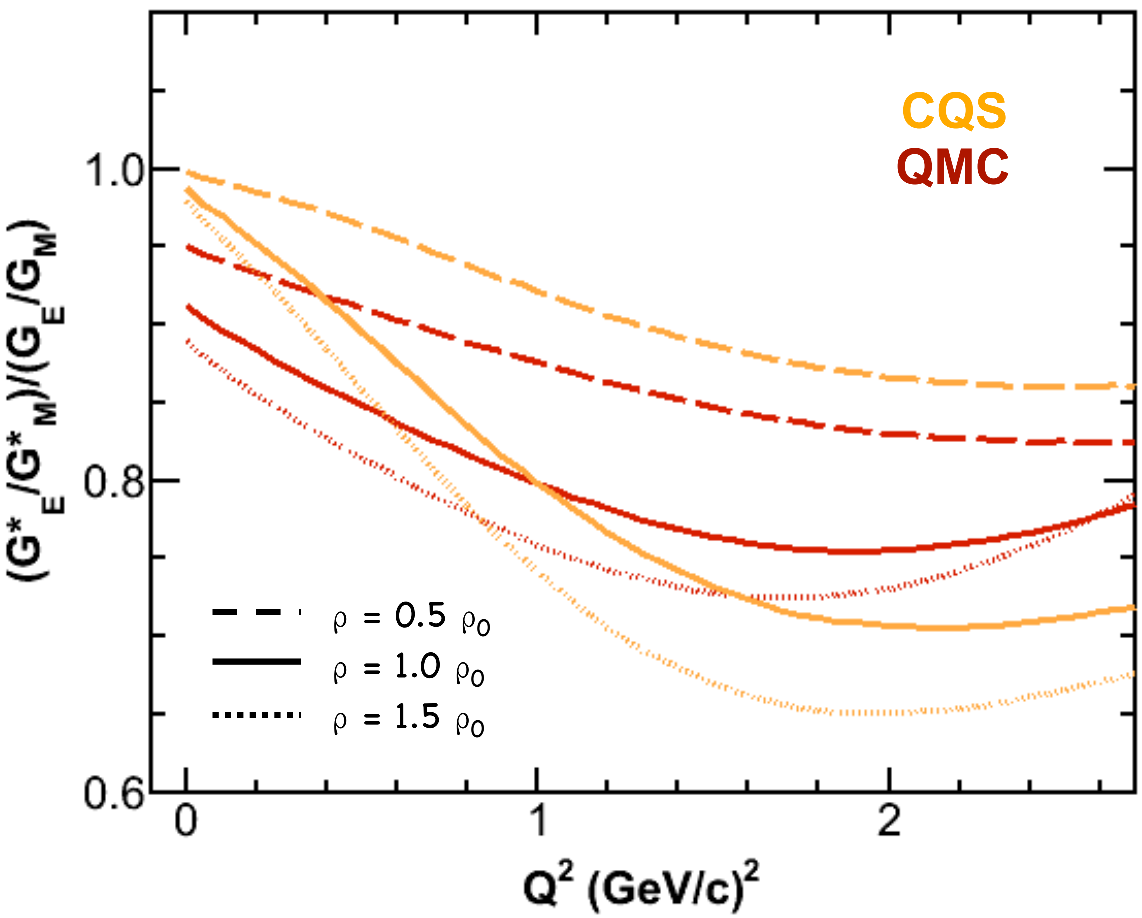
- Models
- Experiments on nuclei that are sensitive to form factors
  - (e,e′**N**) - quasi-elastic proton knockout
  - (e,e′) - quasi-elastic inclusive cross section

Steffen Strauch
University of South Carolina

Supported in parts by the U.S. National Science Foundation: NSF PHY-1505615

Quantitative challenges in EMC and SRC Research and Data-Mining,
MIT, December 2-5, 2016

Models Predict Form-Factor Medium Modifications



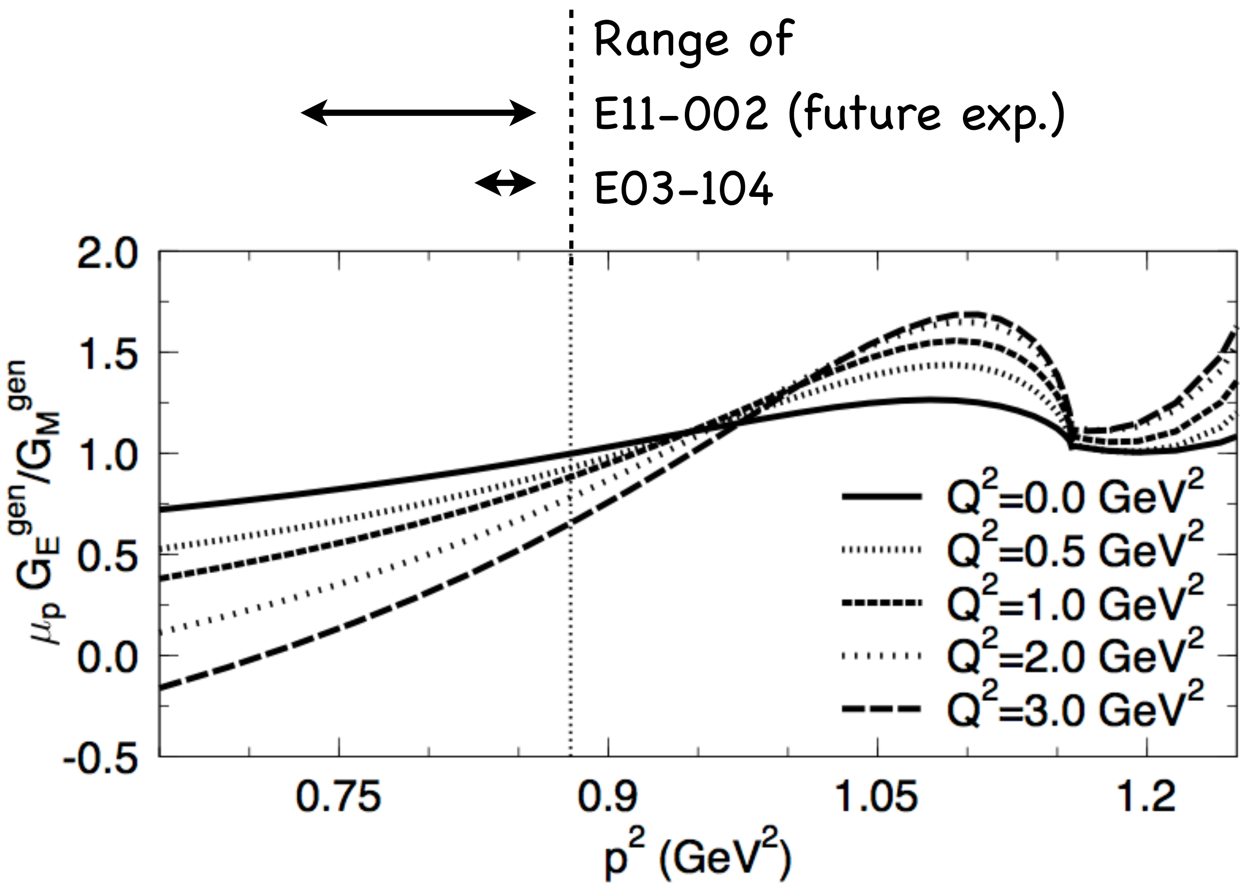
- Changes in the internal structure of bound nucleons result also in **bound nucleon form factors**.
- Chiral Quark Soliton (CQS), Quark Meson Coupling (QMC), Skyrme, Nambu-Jona-Lasinio (NJL), GPD Models.
- Observable effects predicted. Model predictions:
  - are density and Q^2 dependent,
  - show similar behavior,
  - consistent with experimental data (within large uncertainties).

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

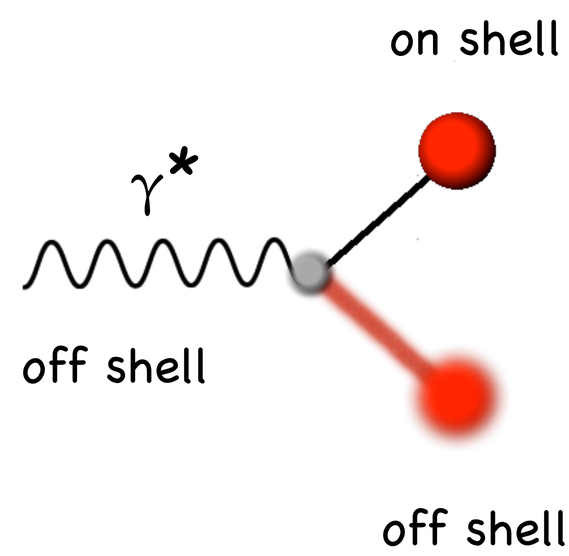
QMC: D.H. Lu et al., Phys. Lett. B 417, 217 (1998)

NJL: I.C. Cloet, W. Bentz, and A.W. Thomas

Form Factors in the Dressed γNN Vertex



photon-nucleon vertex



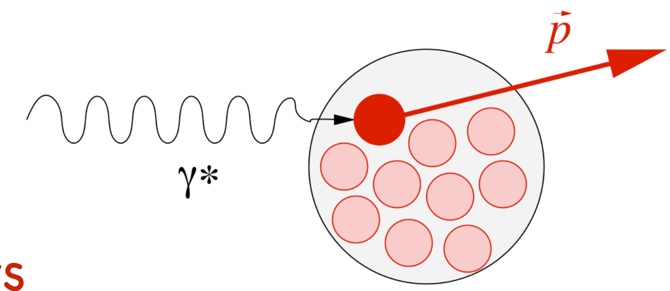
- **Dressed K-Matrix model (DKM)**: dressing the bare vertex with an infinite number of meson loops (π, ρ, σ mesons)

S. Kondratyuk, K. Kubodera, and F. Myhrer, Phys. Rev. C **71**, 028201 (2005).

Polarization-Transfer Technique

$$\frac{G_{Ep}}{G_{Mp}} = -\frac{P'_x}{P'_z}\frac{E_i + E_f}{2m}\tan\frac{\theta_e}{2}$$

- Free nucleon
- Bound nucleon data need evaluation within model
  Reaction-mechanism effects predicted to be small and minimal for
  - Quasi-elastic scattering
  - High Q^2, small missing momenta

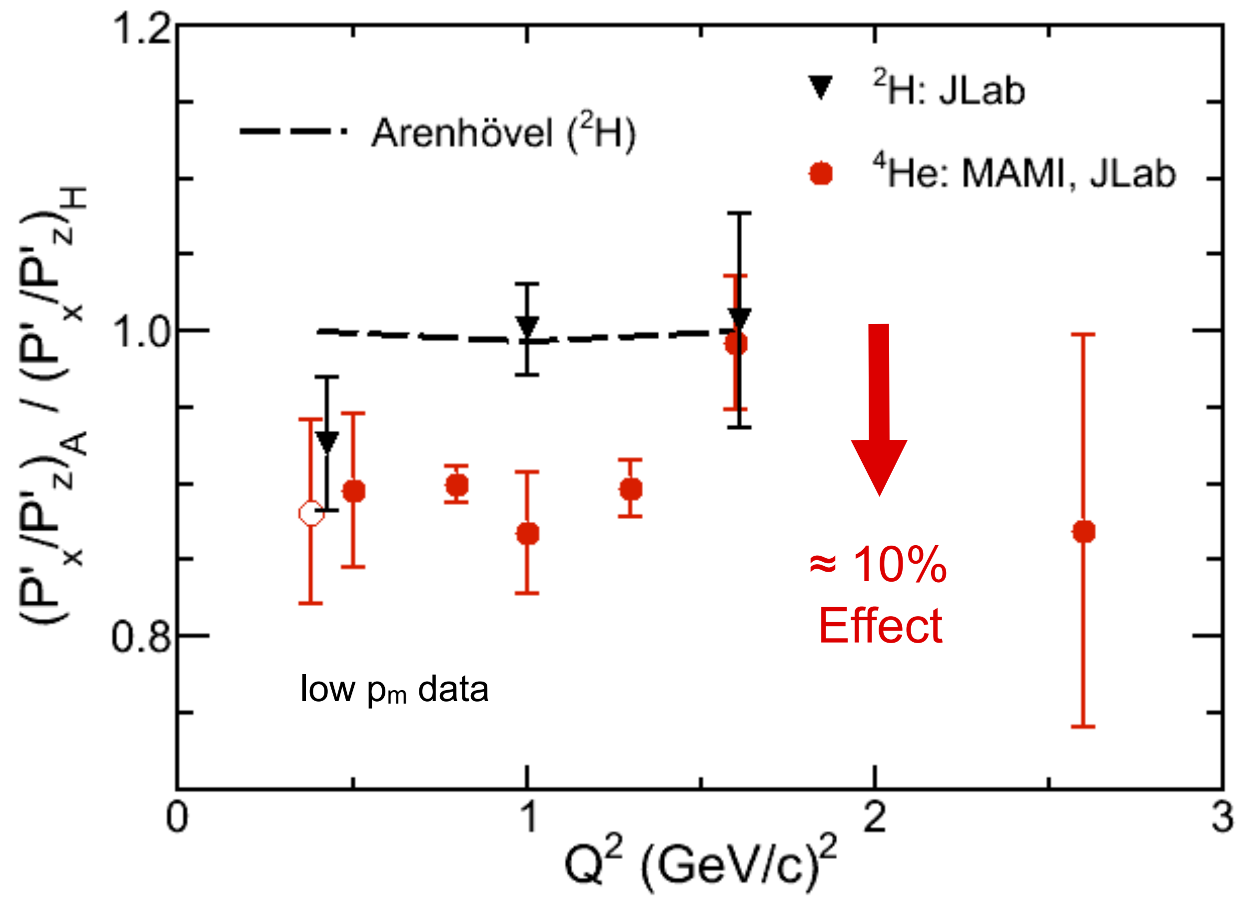


- Compare quasi-elastic and free-proton scattering to study possible medium effects

$$R = \left(\frac{P'_x}{P'_z}\right)_A \Big/ \left(\frac{P'_x}{P'_z}\right)_H$$

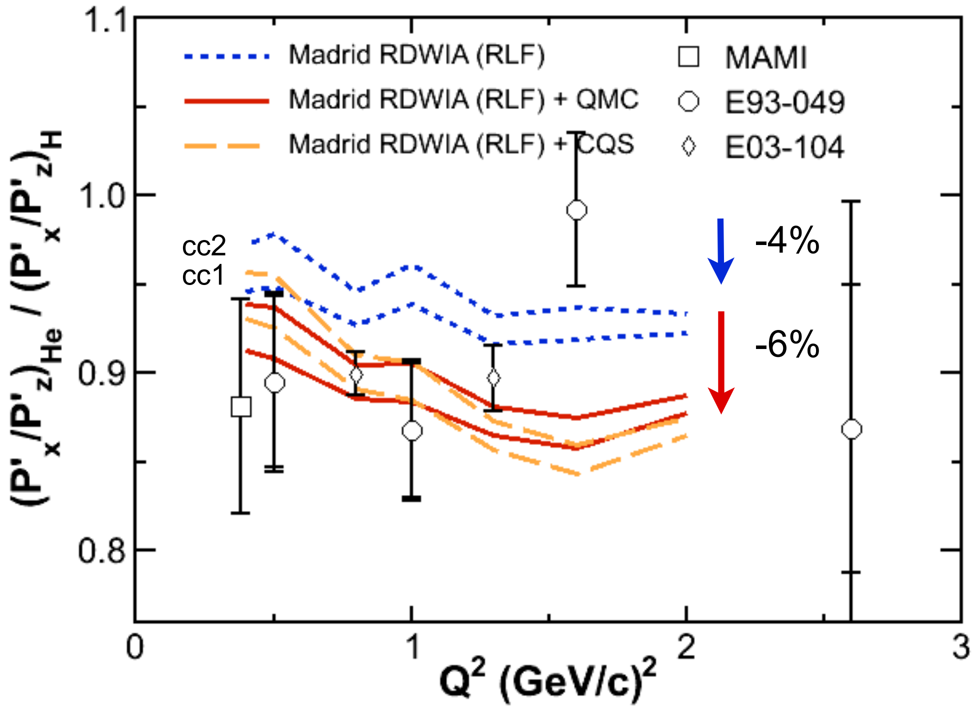
$$^{A}X(\vec{e},e'\vec{p})^{A-1}X$$

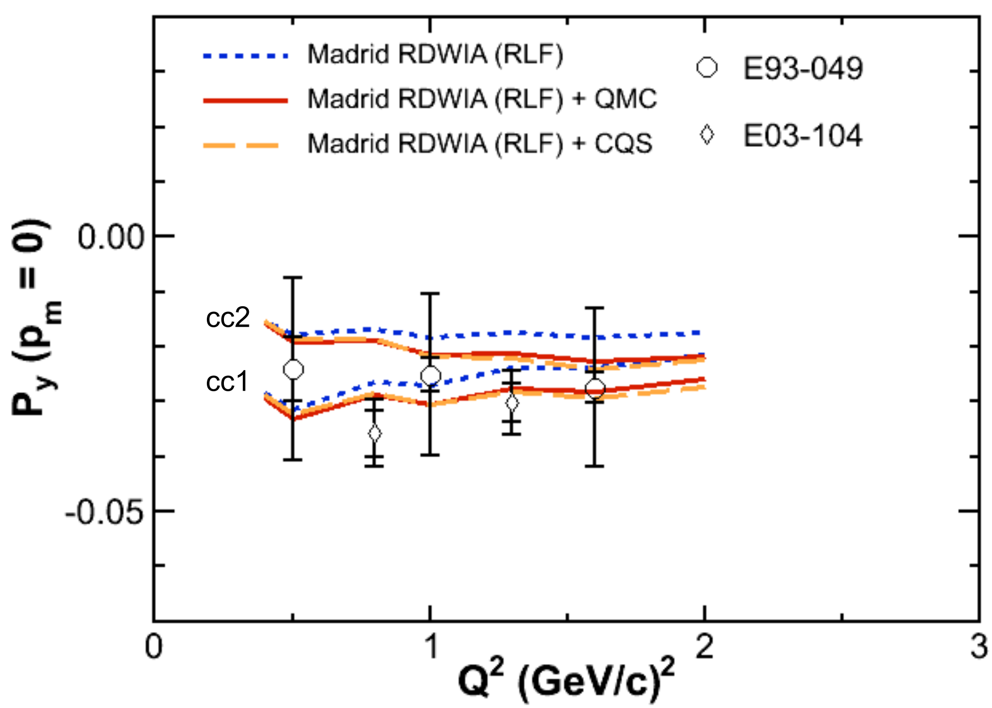
Strong Medium Effects Observed in ^{4}He Polarization-Transfer Double Ratios



- ^{2}H and ^{1}H polarization-transfer data are similar
- ^{4}He data are significantly different than ^{2}H, ^{1}H data

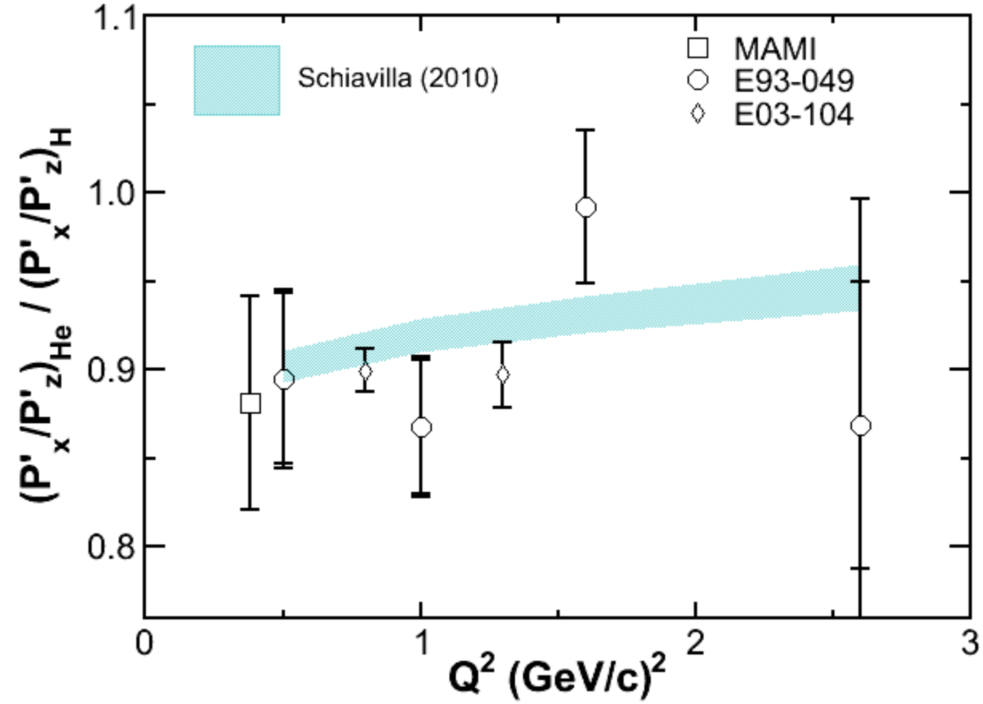
^{2}H: B. Hu et al., PRC **73**, 064004 (2006). **^{4}He**: S. Dieterich et al., PLB 500, **47** (2001); S. S., et al., PRL **91**, 052301 (2003); M. Paolone, et al., PRL **105**, 0722001 (2010); S. Malace et al., PRL **106**, 052501 (2011)

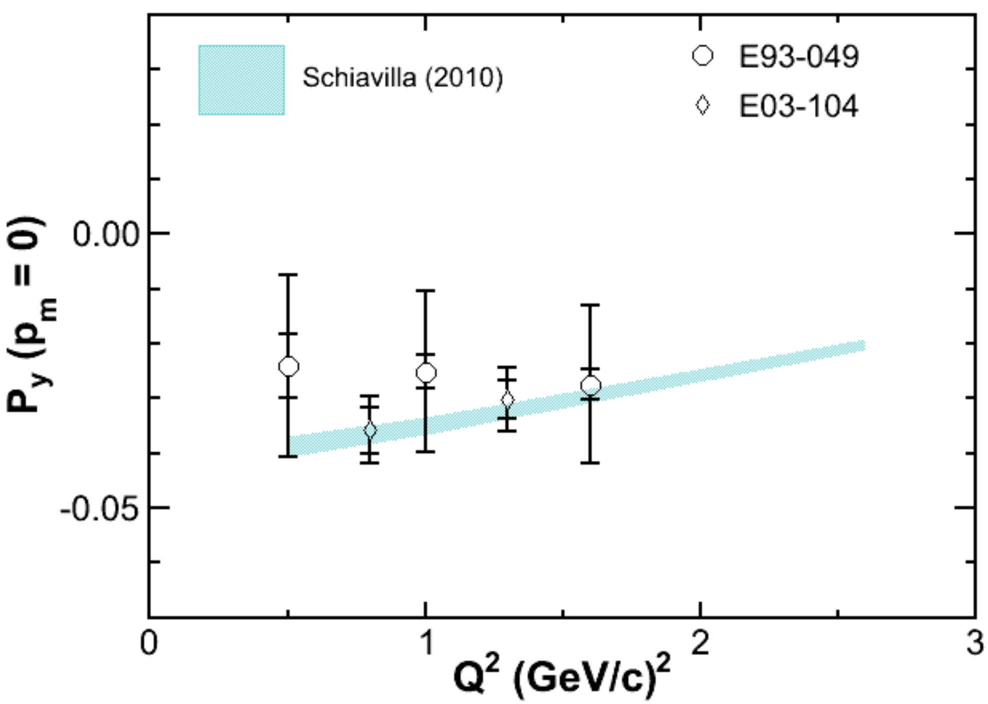




Madrid RDWIA

- Relativistic calculation in distorted-wave impulse approximation **(RDWIA)** overestimates R
- Both, the **QMC** and **CQS** models give reduction in R by about 6% and are in very good agreement with data
- Induced polarization, P_y, is almost exclusively sensitive to FSI
- **RLF optical potential** along with cc1 current operator results in excellent description of P_y within the Madrid model





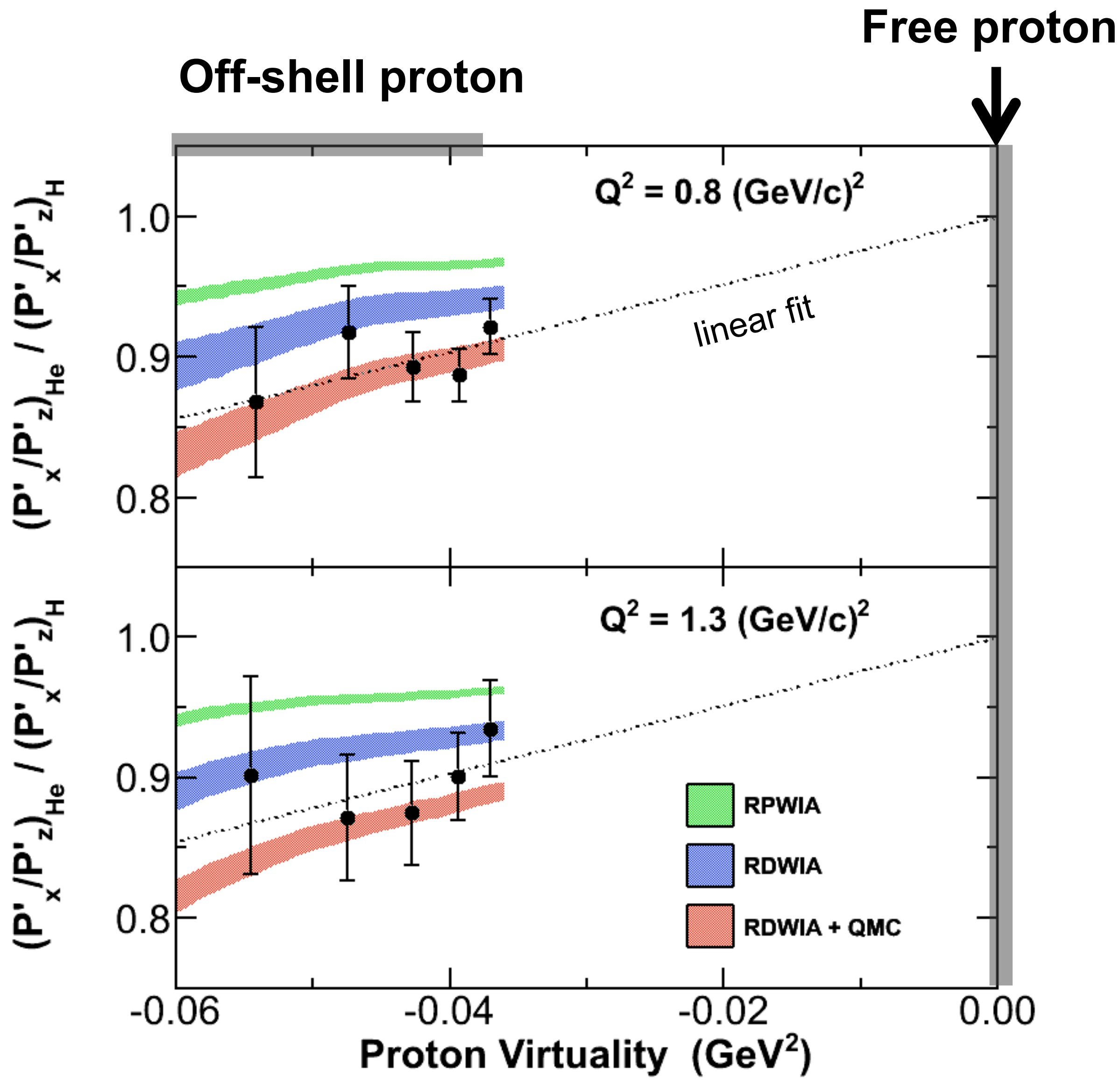
Schiavilla (2010)

- Variational wave functions for the bound three- and four-nucleon systems + nonrelativistic MEC
- Optical potentials include additional charge-exchange terms which are not all well constrained.
- The charge-exchange **in**dependent spin-orbit component of the optical potential was reduced to describe the P_y data (2010).
- Very good agreement with the data after fitting FSI parameters to the induced polarization of E03-104.

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

Within the **Madrid model** P_y seems unaffected by charge exchange to a large degree.

Medium Effect Increases with Proton Virtuality



- $^4He(e,e'p)^3H$ polarization-transfer double-ratio data and calculations show dependence on proton virtuality

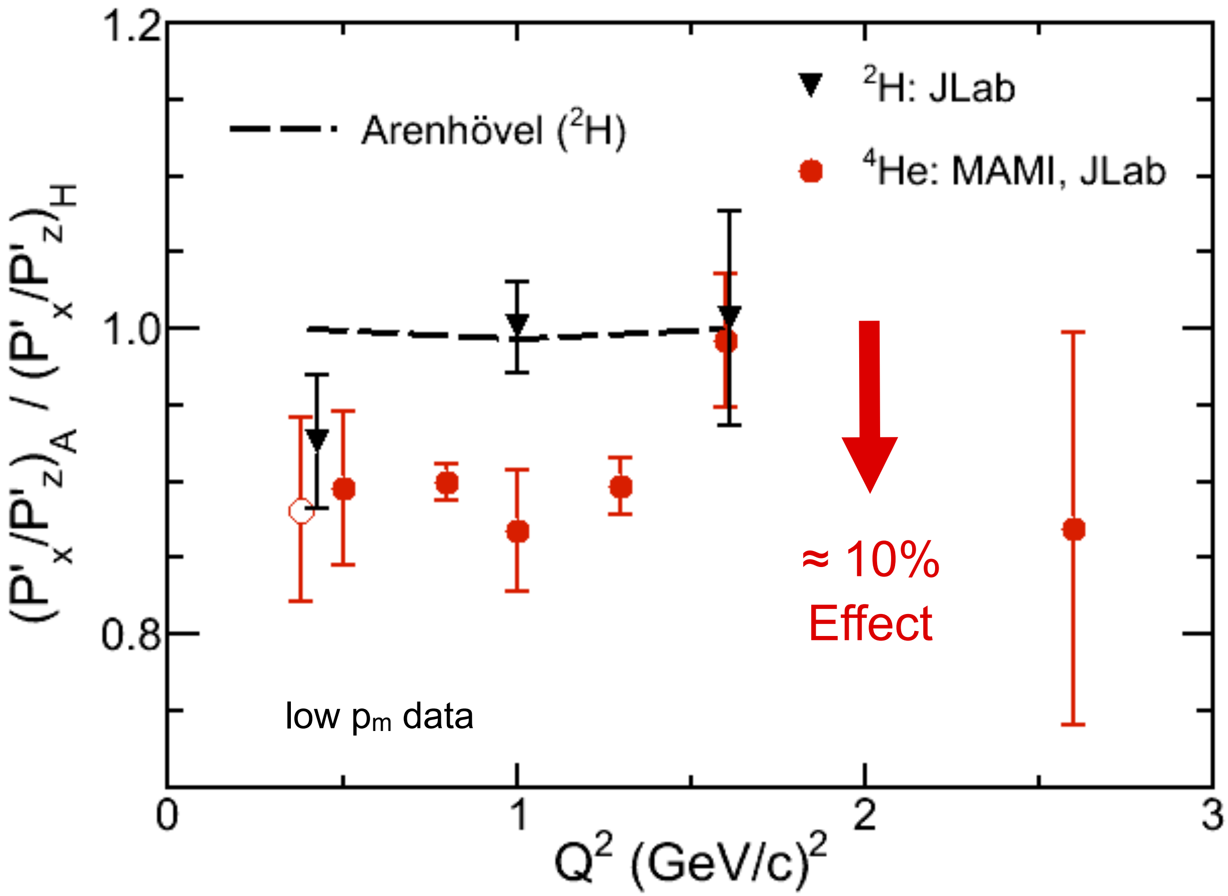
$$v = p^2 - m_p^2$$

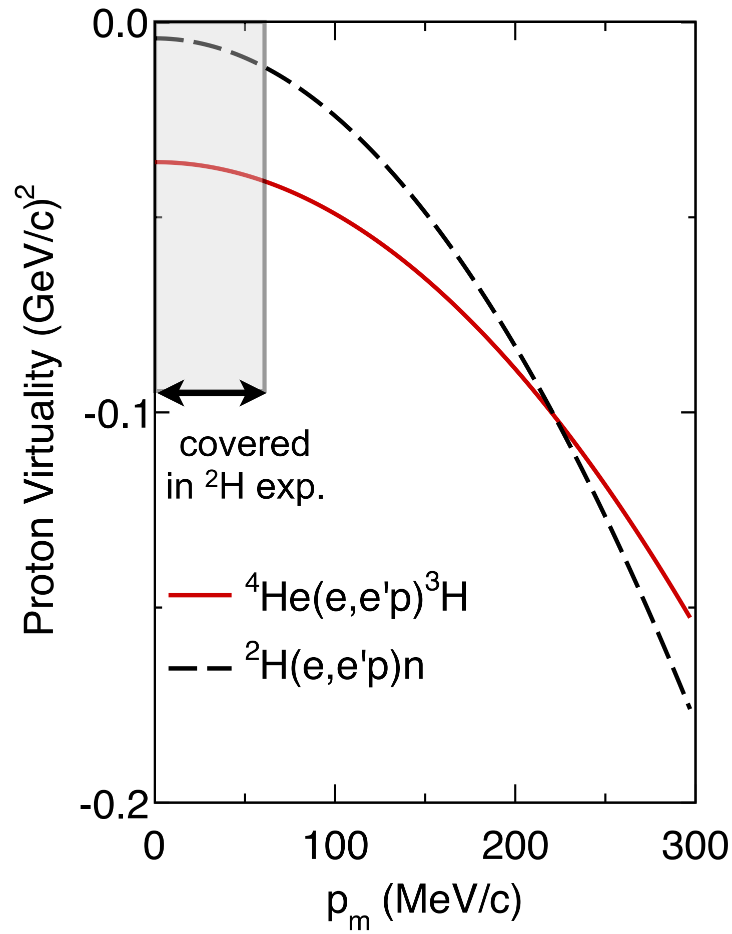
with the trend of $R \approx 1$ for $p^2 = m_p^2$; as it should be.

- Increase of medium effects with proton virtuality; 4% to 10% over the range covered.

see: C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)

What Generates the Large Medium Effect?



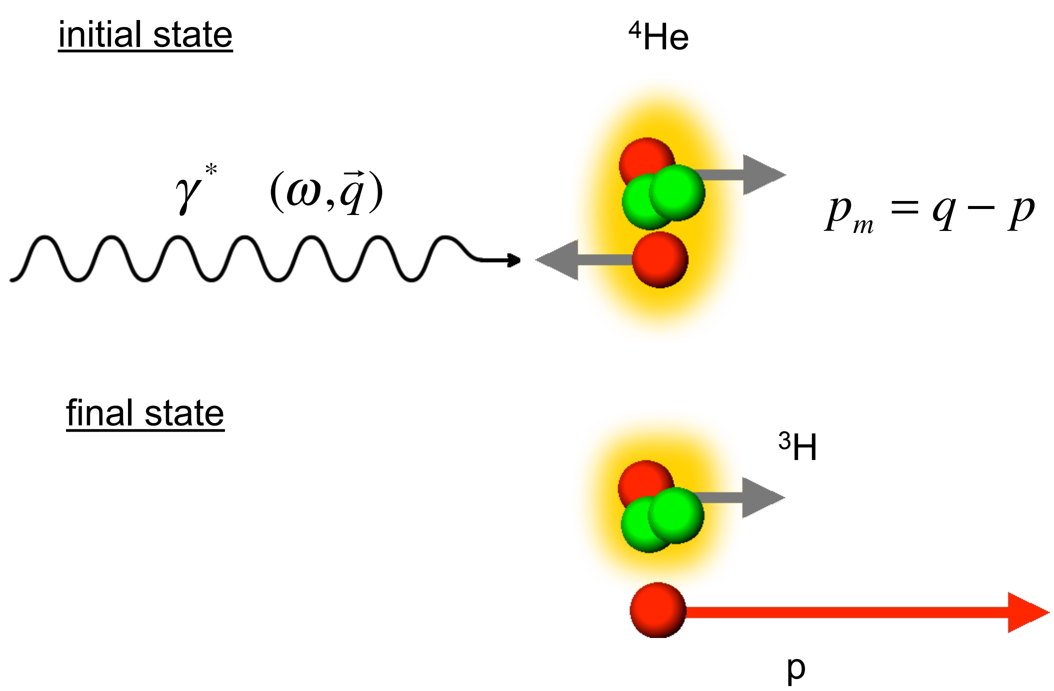


- The nuclear density or
- the larger proton virtuality probed in the ^{4}He experiments?

^{2}**H**: B. Hu et al., PRC **73**, 064004 (2006). ^{4}**He**: S. Dieterich et al., PLB 500, **47** (2001); S. S., et al., PRL **91**, 052301 (2003); M. Paolone, et al., PRL **105**, 0722001 (2010); S. Malace et al., PRL **106**, 052501 (2011)

New experiment in Hall C will measure ^1H, ^2H, ^4He

- Quasielastic scattering
- Parallel kinematics
- x > 1, spectator forward to reduce inelastic channels (Δ production) and probe the genuine quasielastic channel*
- The off-shellness can be quantified as nucleon virtuality:

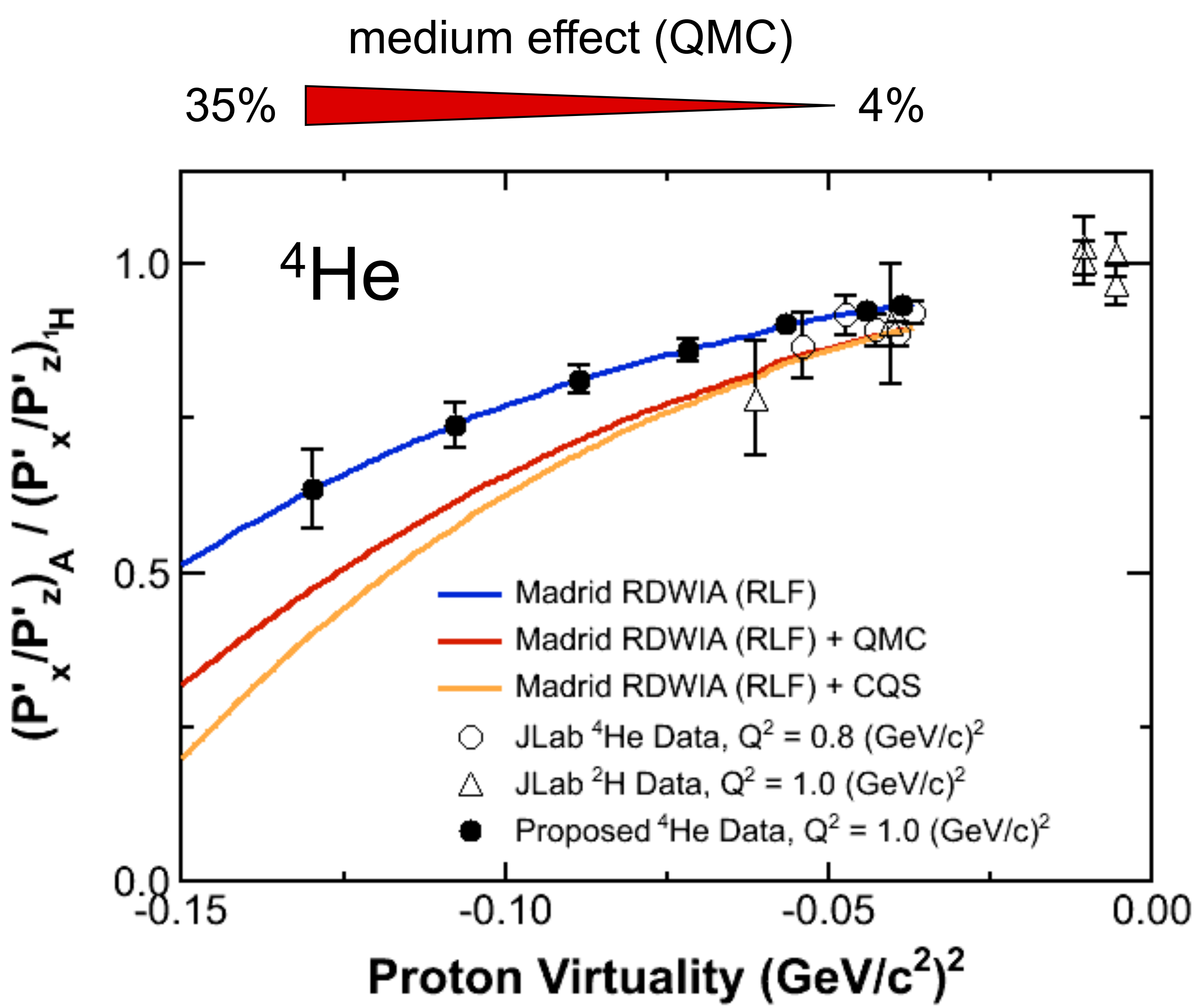


$$v = p^2 - m_p^2$$
$$= \left(M_A - \sqrt{M_{A-1}^2 + \vec{p}_m^{\,2}}\right)^2 - \vec{p}_m^{\,2} - m_p^2$$

Q^2 $(GeV/c)^2$	p_m (MeV/c)	Targets
1.0	0, +140, +220	^4He, ^2H, ^1H
1.8	0	^4He, ^1H

*M. Sargsian, private communication
C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)

1^{st} Feature: Proton-virtuality coverage

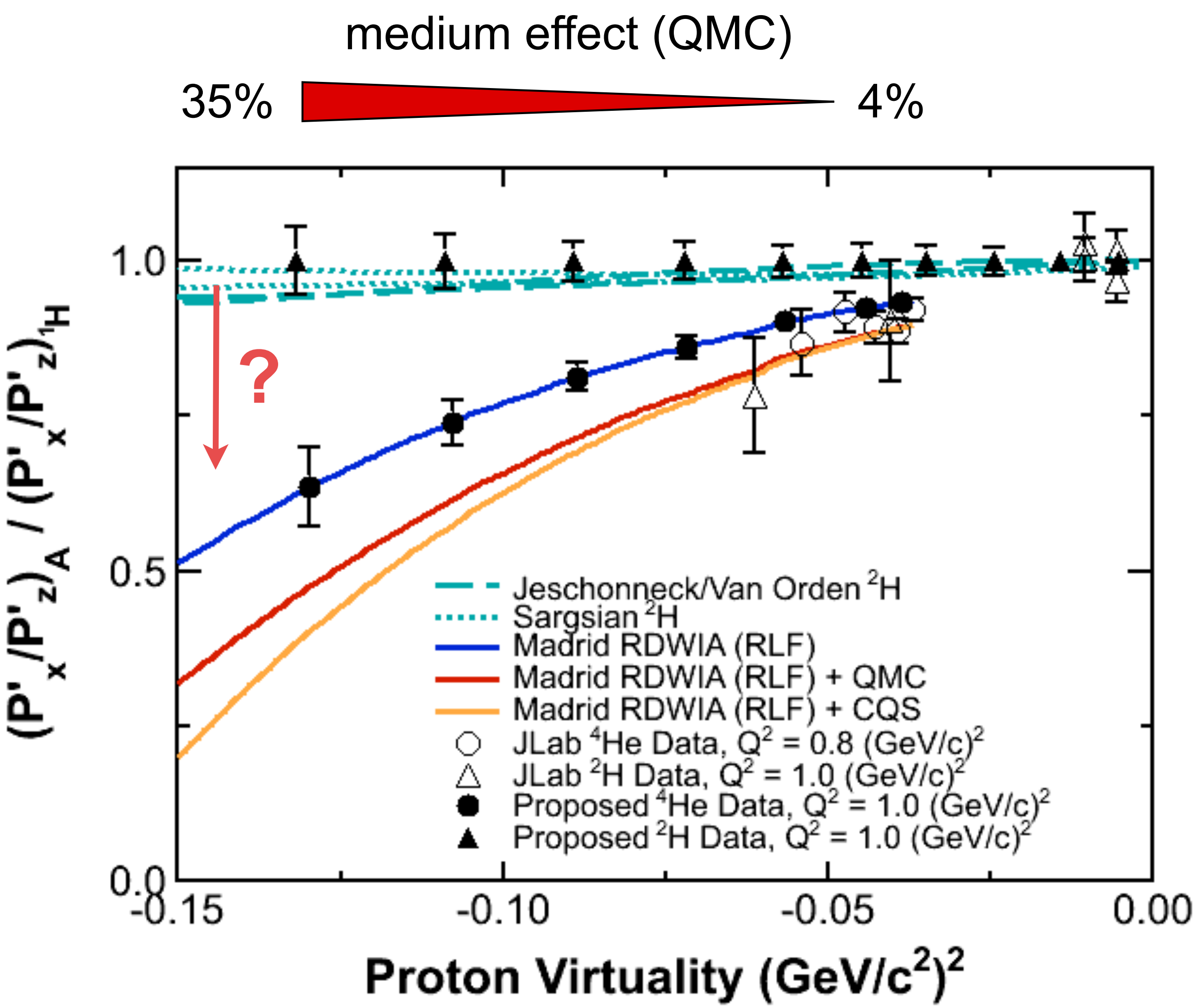


- **E11-002**:
  $Q^2 = 1.0\ (\mathrm{GeV/c})^2$
  p_m = 0, 140, 220 MeV/c

- Study the expected strong dependence of medium effects on the **momentum** of the bound nucleon.

- Previous ^{2}H data (△) follow suggestively close the virtuality dependence of the ^{4}He data (○).

2^{nd} Feature: ^{4}He and ^{2}H targets



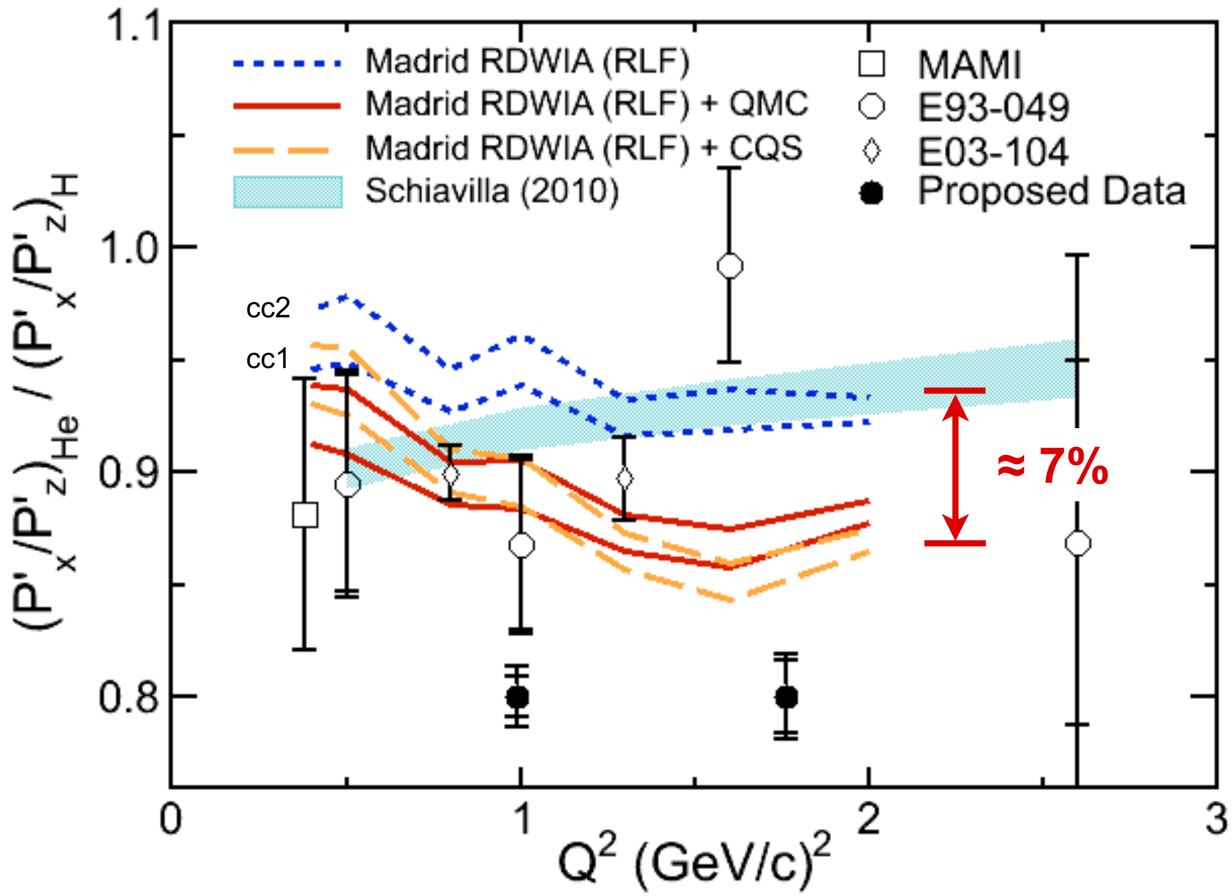
- **E11-002**:
  Compare proton knock-out from dense and thin nuclei:
  ^{4}He(e,e'p)^{3}H and ^{2}H(e,e'p)n

- Modern, rigorous ^{2}H(e,e'p)n calculations show reaction-dynamics effects
  and FSI will change the ratio up to 5% (maximum 8%) in this kinematics

- Any larger effects (35%?)should be attributed to something else …

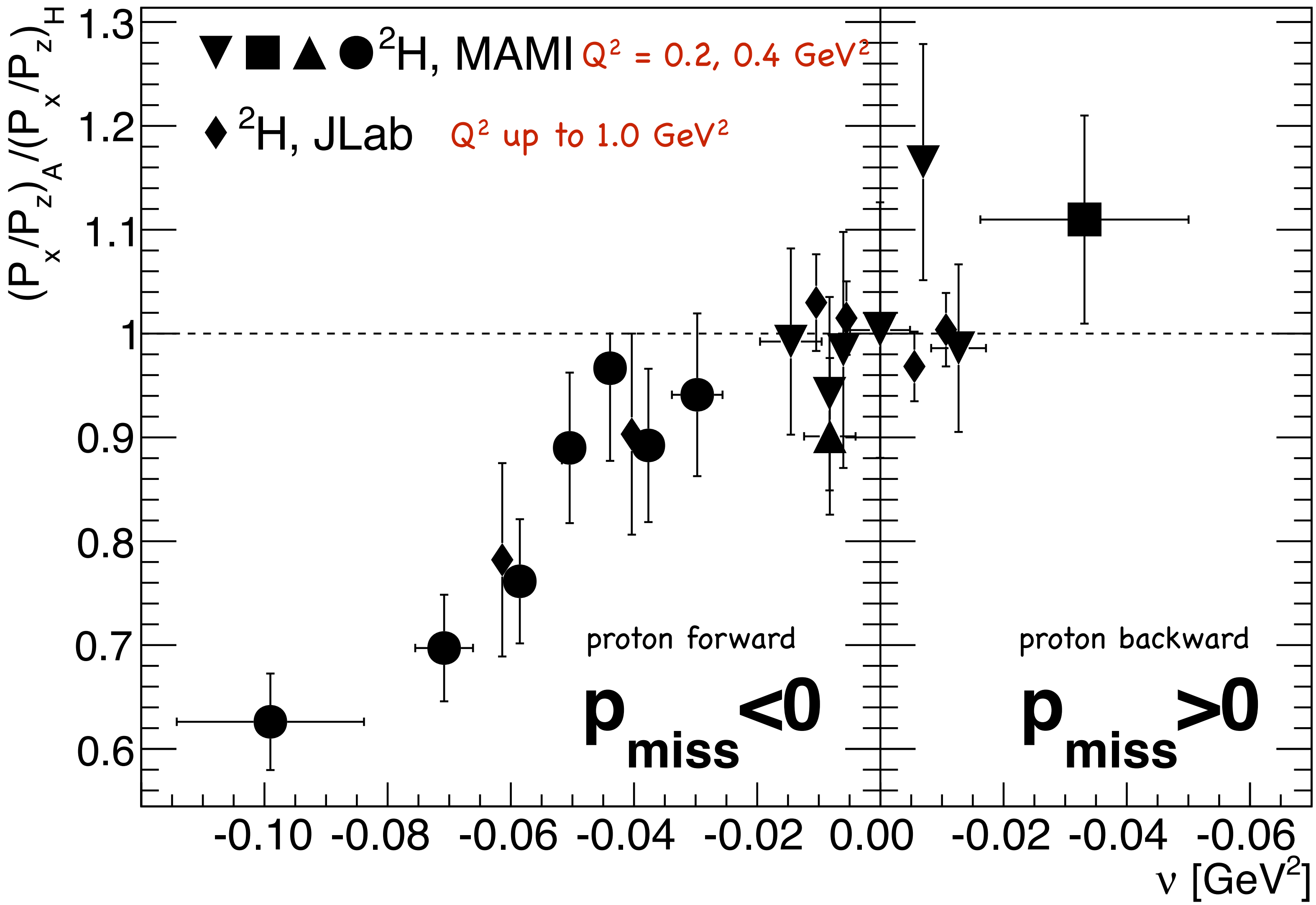
S. Jeschonnek and J.W. Van Orden, Phys. Rev. C **81**, 014008 (2010) and
Phys. Rev. C **78**, 014007 (2008); M.M. Sargsian, Phys. Rev. C**82**, 014612 (2010)

3rd Feature: High-Q^2 point



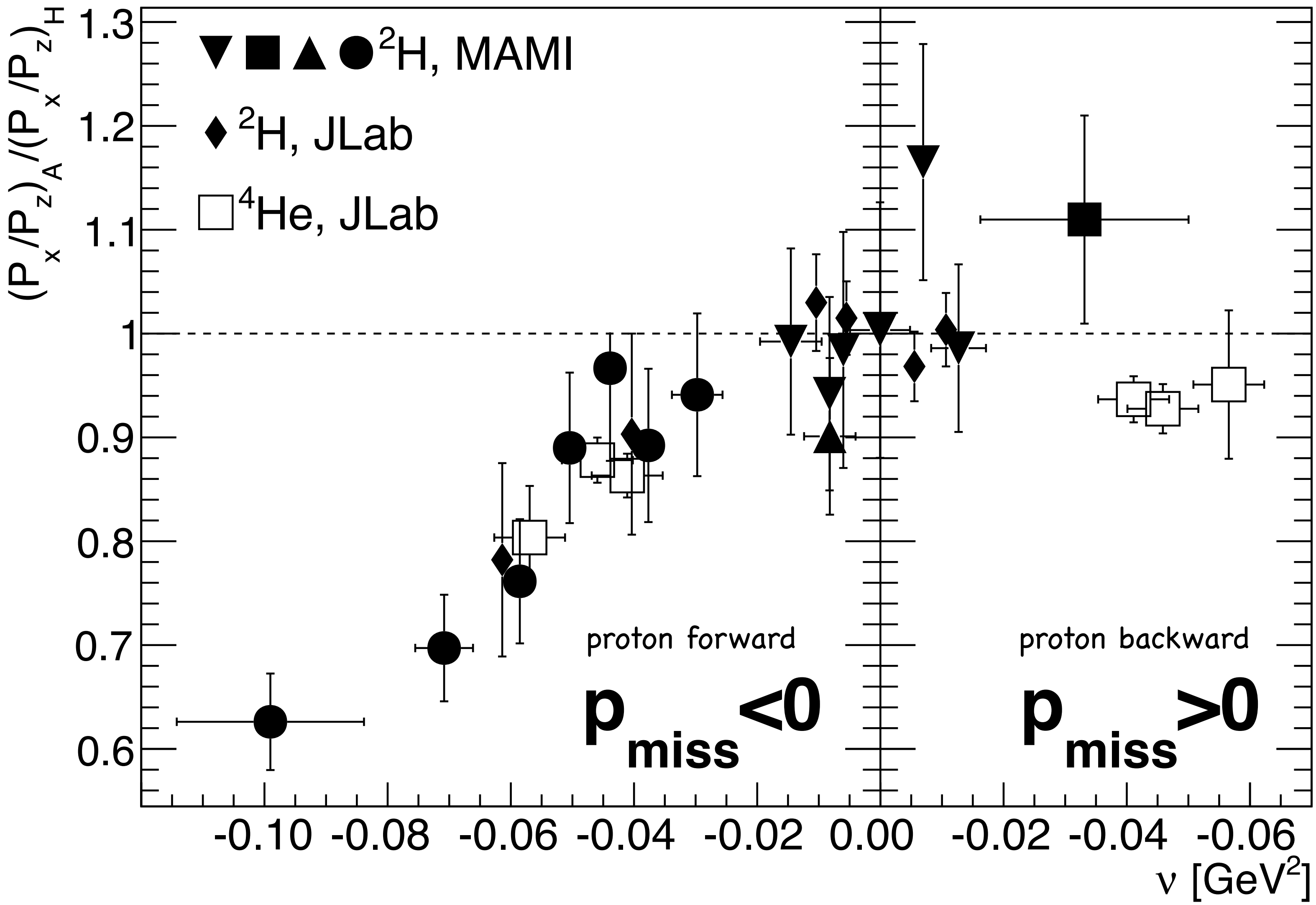
- Polarization-transfer data effectively described by in-medium electromagnetic form factors or charge-exchange FSI.
- For $Q^2 \geqslant 1.3$ (GeV/c)^2 Madrid RDWIA and Schiavilla (2010) results seem to agree.
- Additional data needed
  - **E11-002** will measure one new high-precision data point of the ^{4}He polarization-transfer double ratio at $Q^2 = 1.8$ (GeV/c)^2.
  - Will it be reduced by 7% with respect to Madrid RDWIA/Schiavilla?

New MAMI Data: ^2H data virtuality dependent



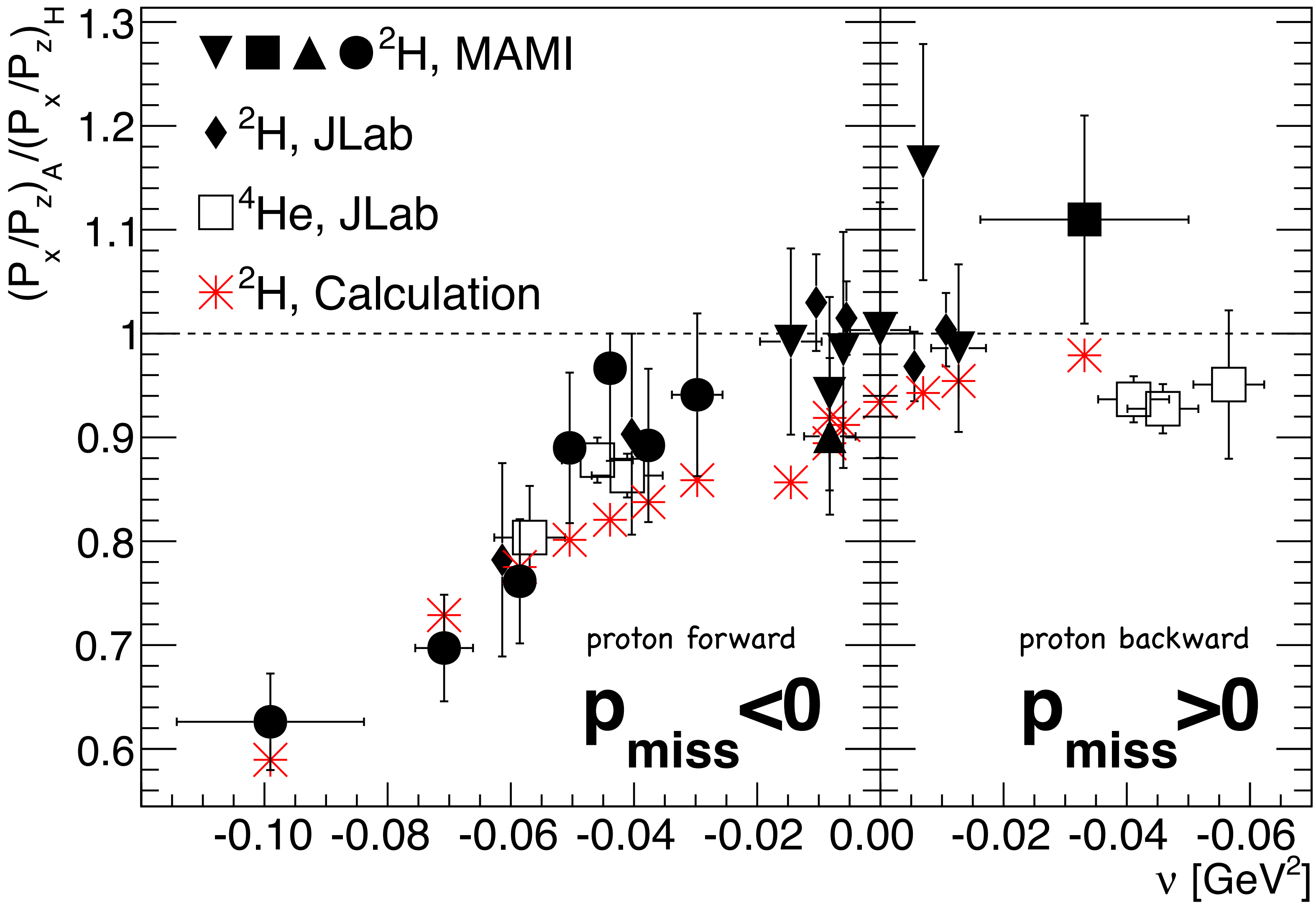
No significant Q^2 dependence

^{2}H data agree with ^{4}He data



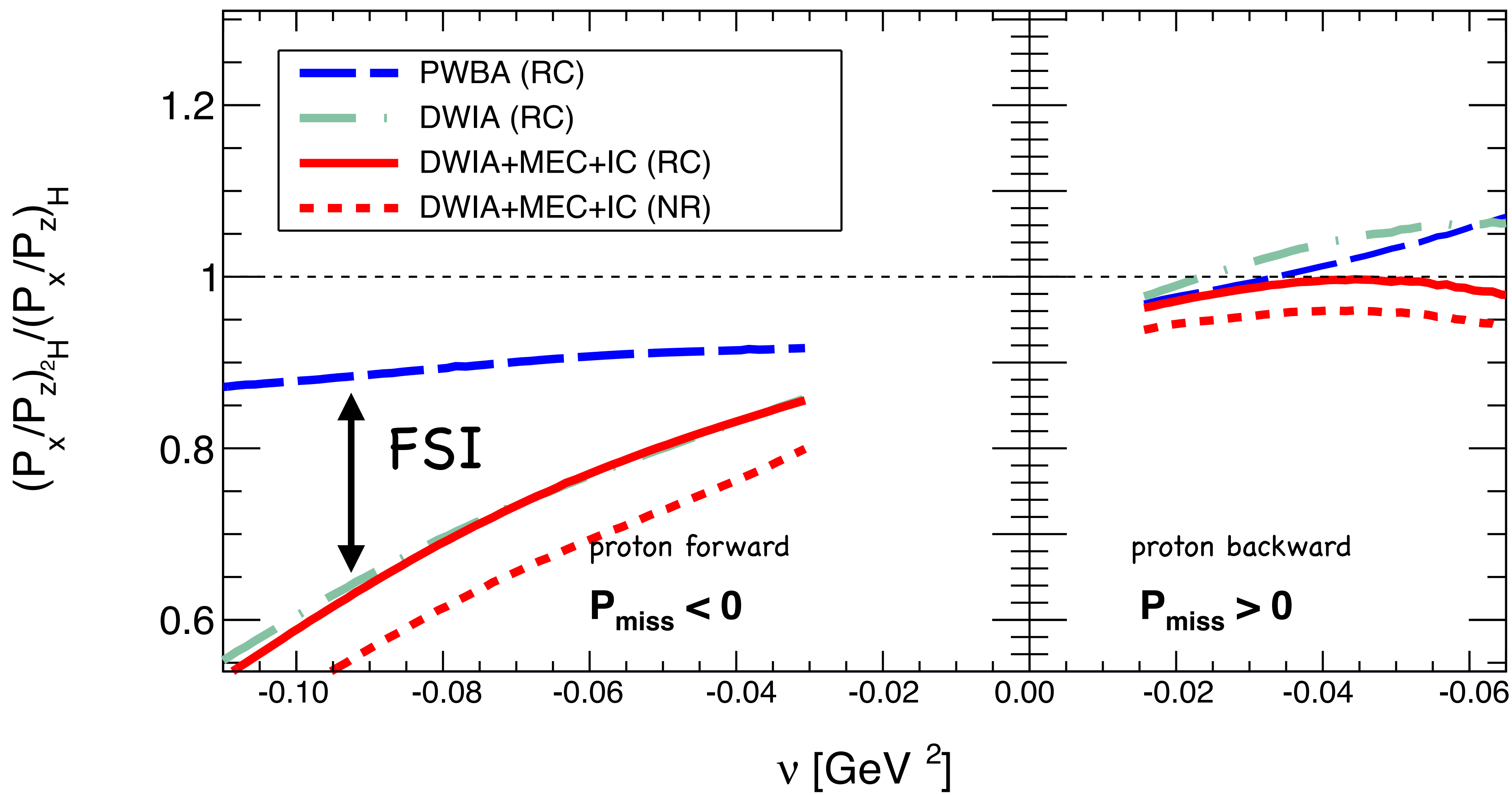
Results do not seem to depend on the nuclear density.

Model calculations on average 10% low



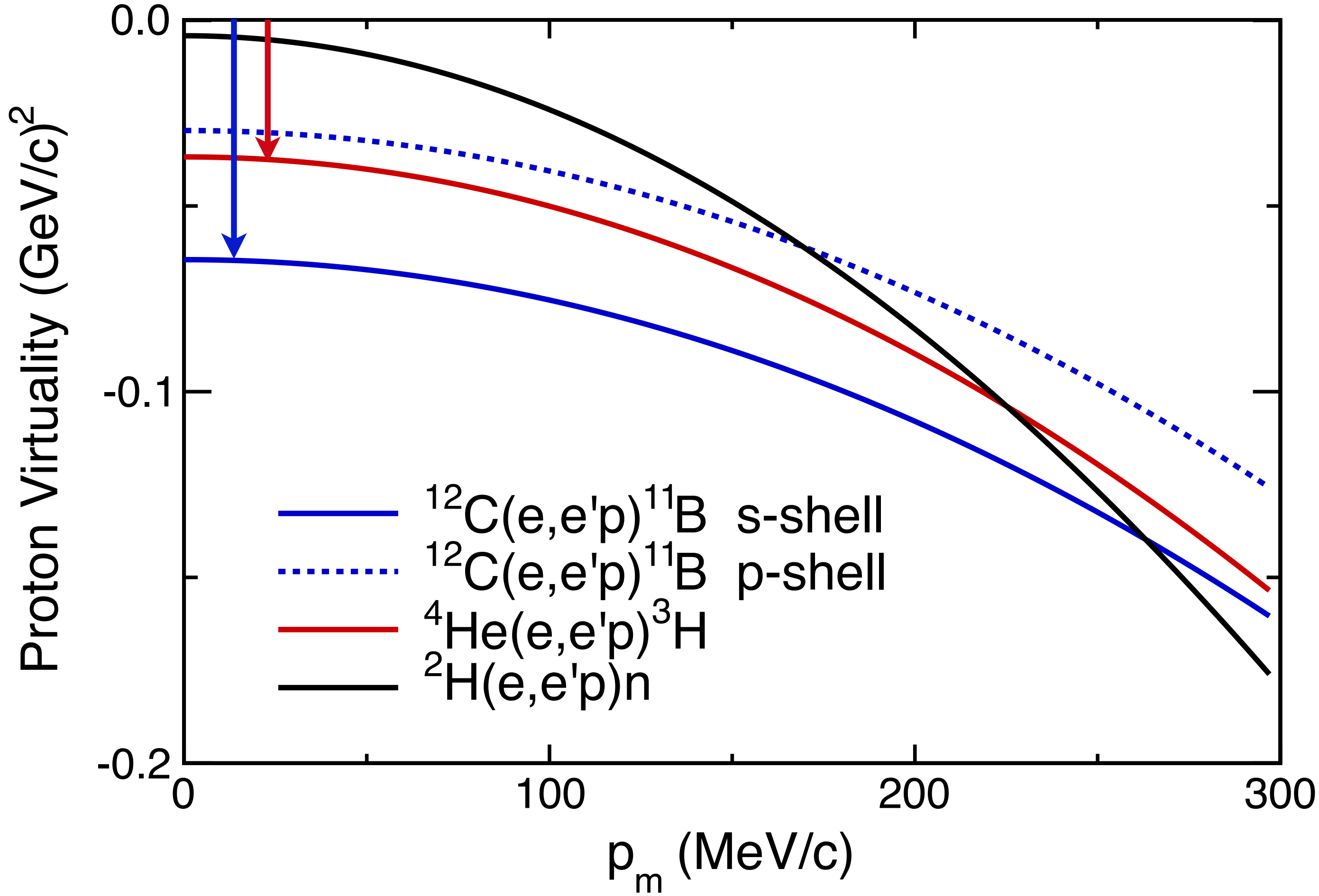
No need for medium-modified form factors, but certainly not excluded.

Results of H. Arenhövel calculations



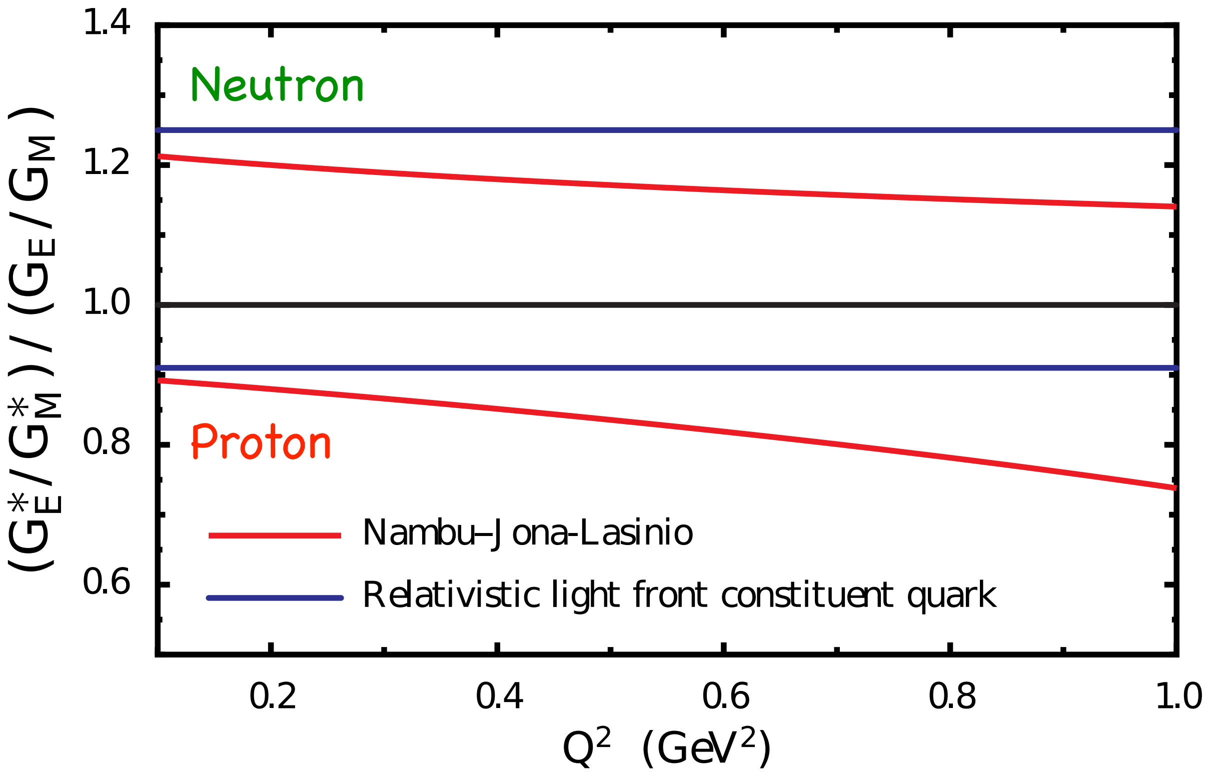
Final-state interactions are the major medium effect in the calculation.
Medium modifications of the proton FF are expected to be small at the MAMI Q^2.

Measurement of the $^{12}C(e,e'p)$ Reaction



- S-shell knockout in the $^{12}C(e,e'p)^{11}B$ reaction allows probing medium modifications of the P'_x/P'_z ratio at high proton virtualities.

Neutron in the Nuclear Medium



Neutron: ≈ +20%

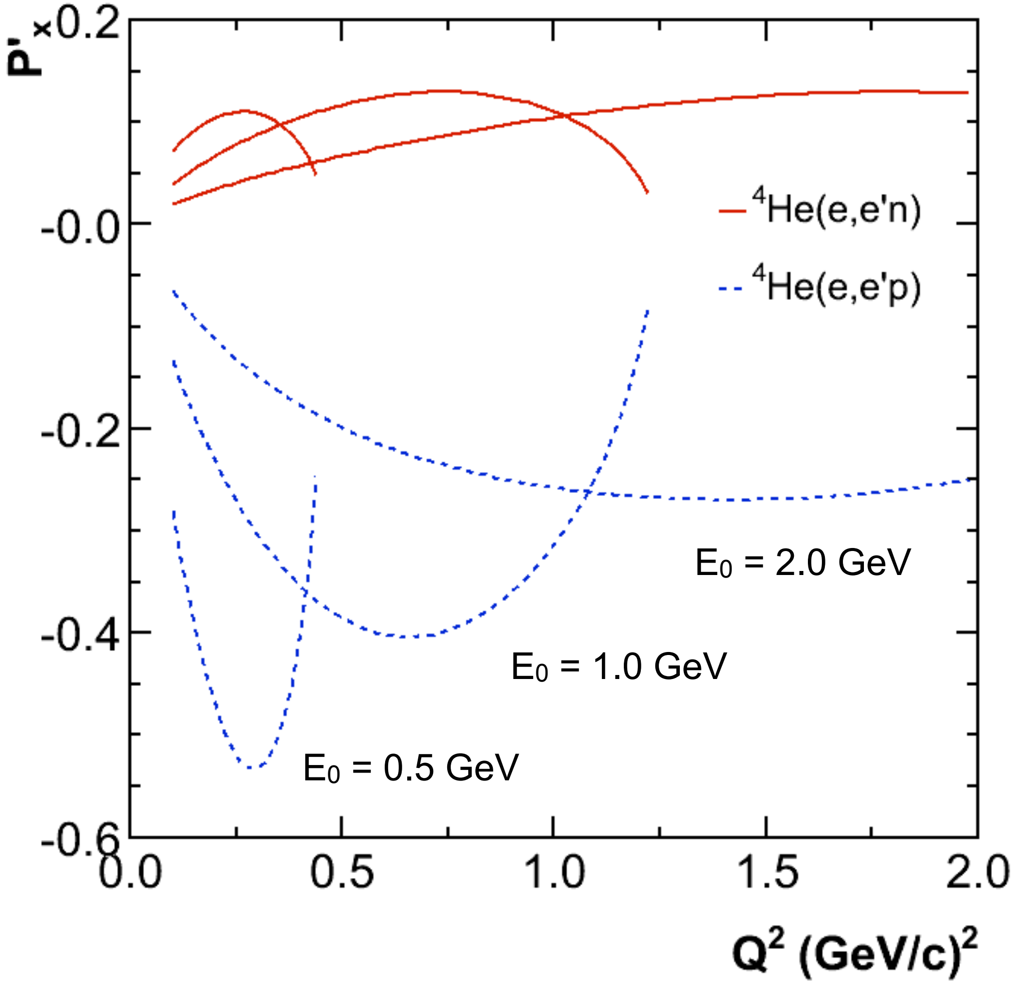
Proton: ≈ -10%

$$\frac{G_{En}}{G_{Mn}} = -\frac{P'_x}{P'_z}\frac{(E_i + E_f)}{2m}\tan\frac{\theta_e}{2}$$

- Different models for medium modification all give same result.
- Effect on neutron form factor ratio **very different** from the proton!
- ^{4}He(**e**,e′**n**)^{3}He: $G_E^n \gtrsim 0$; very difficult measurement.

I. Cloet, G.A. Miller, E. Piasetzky, and G. Ron, Phys. Rev. Lett **103**, 082301 (2009)

$^4He(e,e'n)^3He$: Challenges and Choice of Q^2



$$P_x' = -2\sqrt{\tau(1+\tau)}\,\frac{\frac{G_E}{G_M}}{\left(\frac{G_E}{G_M}\right)^2 + \frac{\tau}{\epsilon}}\tan\frac{\theta_e}{2}$$

- Measure P'_x, P'_z to study possible neutron medium modifications
- Q^2 = 0.1 $(GeV/c)^2$ – Theory calculation* best at low energy
- Q^2 = 0.4 $(GeV/c)^2$ – Highest sensitivity to changes in magnetic FF

MAMI ?

- Q^2 = 0.8 $(GeV/c)^2$, 1.3 $(GeV/c)^2$ – Direct comparison with (e,e'p) results

JLab ?

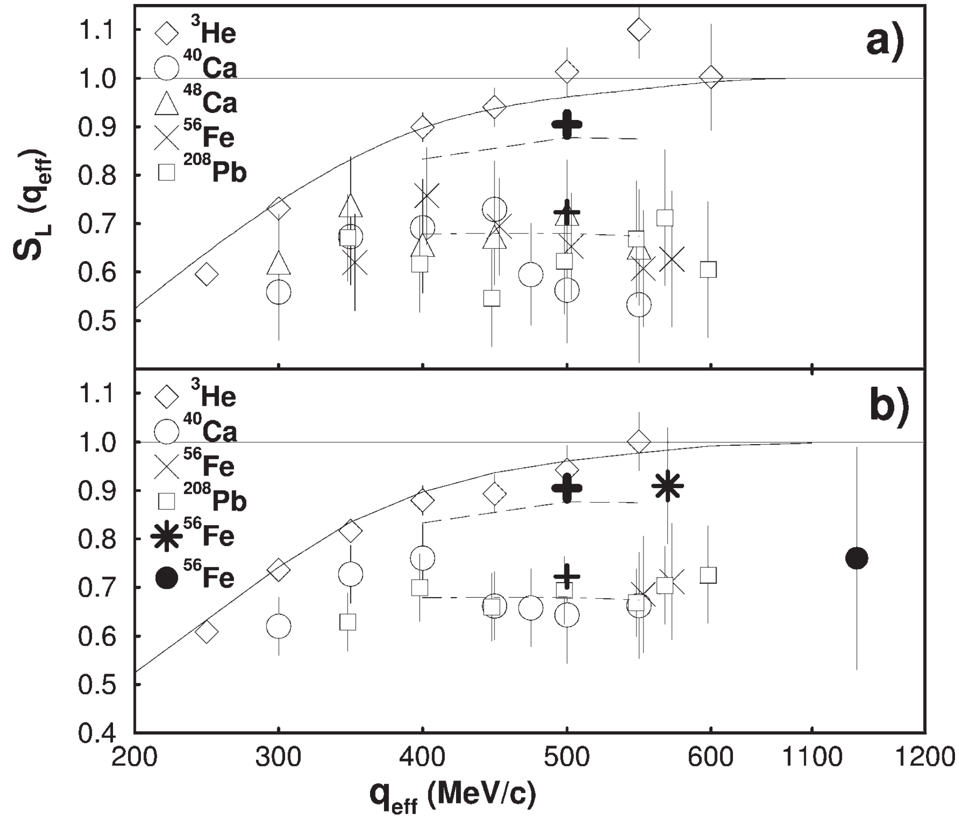
- P_y in $^4He(e,e'n)$ could also provide crucial constraints on charge-exchange FSI

*S. Bacca, N. Barnea, W. Leidemann, and G. Orlandini, PRL **102**, 162501 (2009)

JLab LOI 10-007: G. Ron, D. Higinbotham, R. Gilman, S. Strauch, J. Lichtenstadt

Coulomb Sum Rule in quasi-elastic A(e,e')

$$S_L(|\mathbf{q}|) = \int_{\omega^+}^{|\mathbf{q}|} d\omega \frac{R_L(\omega, |\mathbf{q}|)}{ZG_{Ep}^2(Q^2) + NG_{En}^2(Q^2)}$$



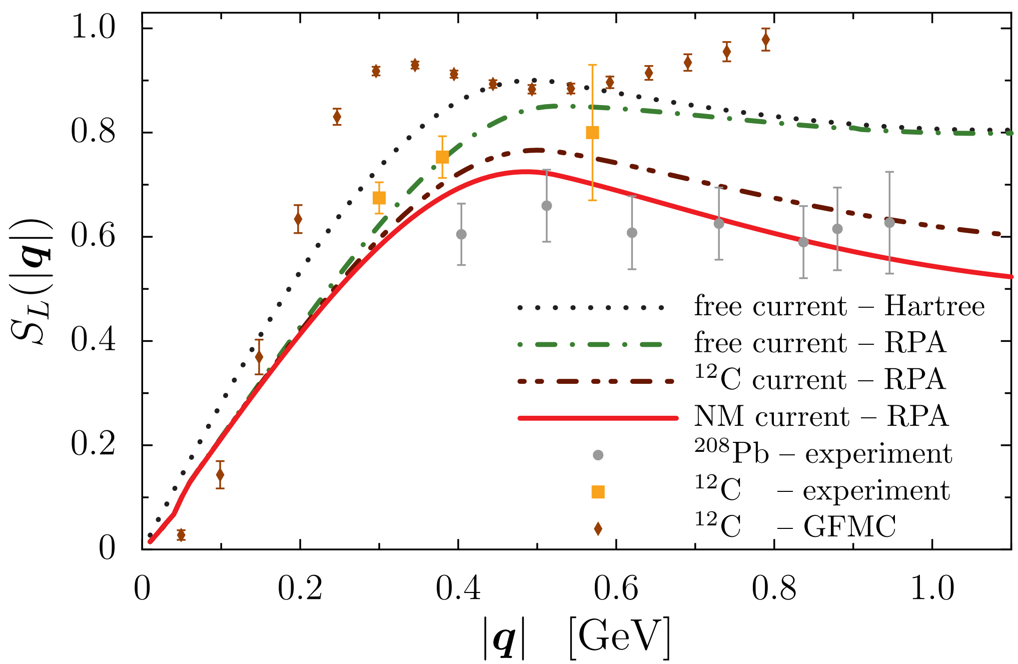
J. Morgenstern, Z.-E. Meziani, Phys. Lett. B 515, 269 (2001)

Nonrelativistic expectation: S_L should approach unity for |q| much greater than the Fermi momentum.

Experimental findings controversial:

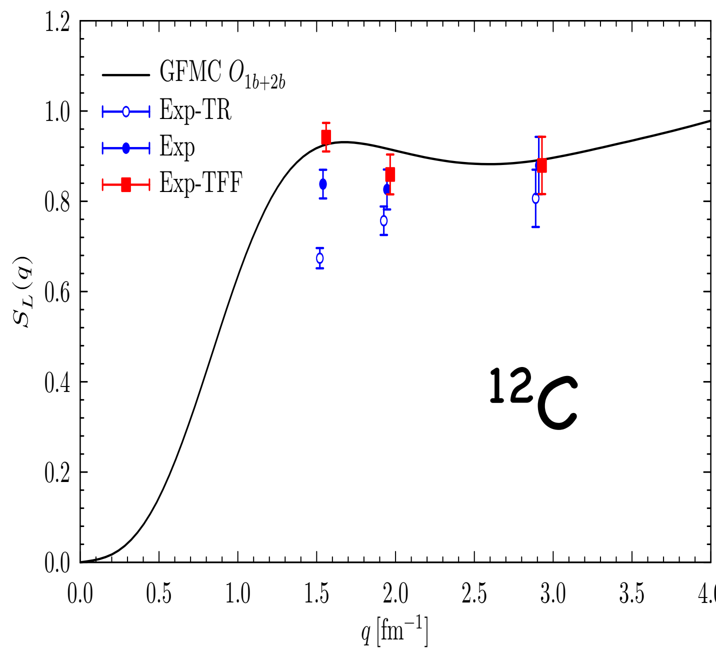
- No quenching in the data observed
  J. Jourdan, Nucl. Phys. A 603, 117 (1996)
- Quenching of S_L is experimentally established
  J. Morgenstern, Z.-E. Meziani, Phys. Lett. B 515, 269 (2001)
- Good agreement between theory and experiment for ^{4}He when using free-nucleon form factors
  J. Carlson, J. Jourdan, R. Schiavilla, and I. Sick, Phys. Lett. B 553, 191 (2003)

Very different recent interpretations



"The observed quenching is directly associated with a softer F_{1p} in medium."

Ian C. Cloët, Wolfgang Bentz, Anthony W. Thomas, Phys. Phys. Rev. Lett. **116**, 032701 (2016)



"The so-called quenching … emerges in this study as a result of initial-state correlations and final-state interactions."

A. Lovato, S. Gandolfi, J. Carlson, Steven C. Pieper, R. Schiavilla, Phys. Rev. Lett. **117**, 082501 (2016)

New Data are coming from Hall A E05-110

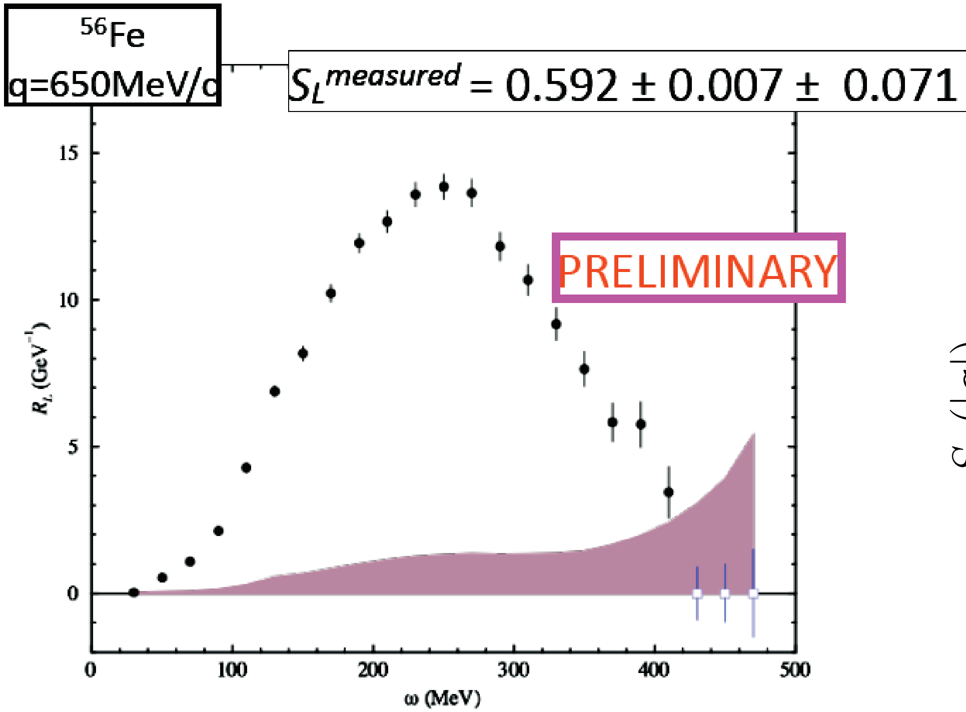
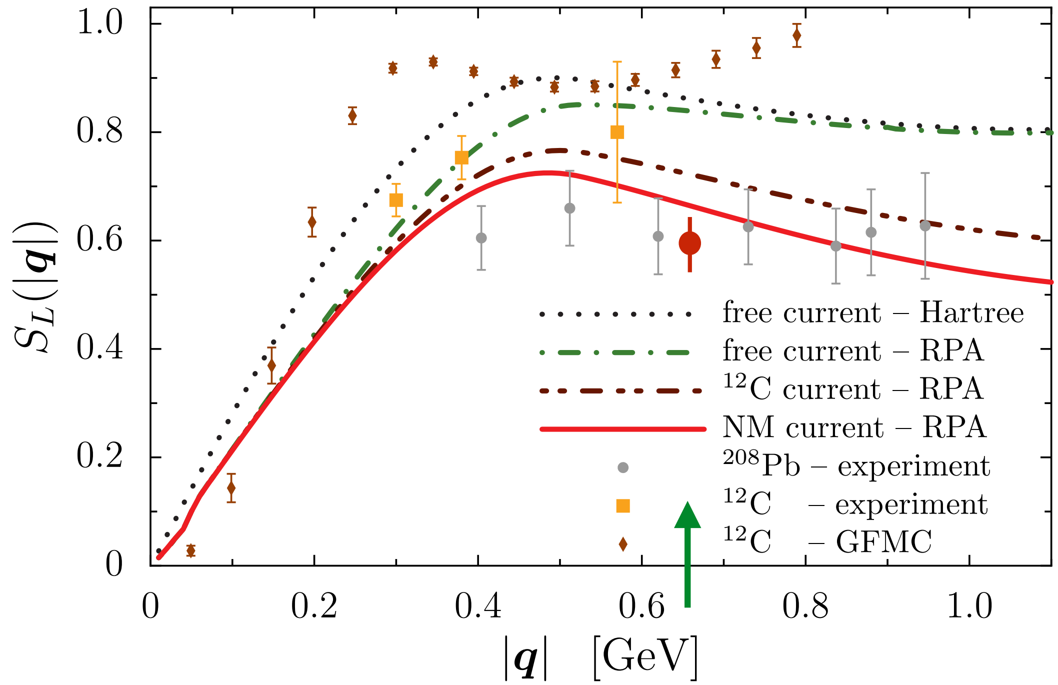


Figure from M. Paolone, HALL A/C SUMMER COLLABORATION MEETING 2016



- Four nuclei: ^{4}He, ^{12}C, ^{56}Fe, ^{256}Pb
- high momentum: q = 650 MeV/c
- "Final results are just around the corner"

Ian C. Cloët, Wolfgang Bentz, Anthony W. Thomas, Phys. Phys. Rev. Lett. **116**, 032701 (2016)
E05-110: Choi, Chen, and Meziani spokespeople

Future Steps

$A(e,e')$

- Finalize results from Hall A Coulomb Sum Rule experiment

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

- Finalize MAMI ^{2}H and ^{12}C data analysis
- Re-defend Hall C ^{4}He, ^{2}H, ^{1}H polarization-transfer experiment
- Propose to include ^{12}C in Hall C experiment?

$A(e,e'\vec{n})$

- at MAMI?
- at JLab?