Probing Nucleons in the Nuclear Medium

Steffen Strauch
University of South Carolina

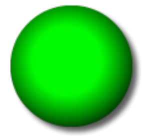
Supported in parts by the U.S. National Science Foundation: NSF PHY-0856010

INT Workshop "Nuclear Structure and Dynamics", February 14, 2013

Nucleons are Modified in the Nuclear Medium

- Conventional Nuclear Physics:
  - Nuclei are effectively and well described as point-like **nucleons** (+ form factor) and interaction through effective forces (**meson** exchange).
  - Medium effects arise through non-nucleonic degrees of freedom.
  - 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 changes of fundamental properties of the nucleon.
  - Do nucleons change their quark-gluon structure in the nuclear medium? Yes!

In-Medium Life Time



Free neutron:
τ_n = 15 min

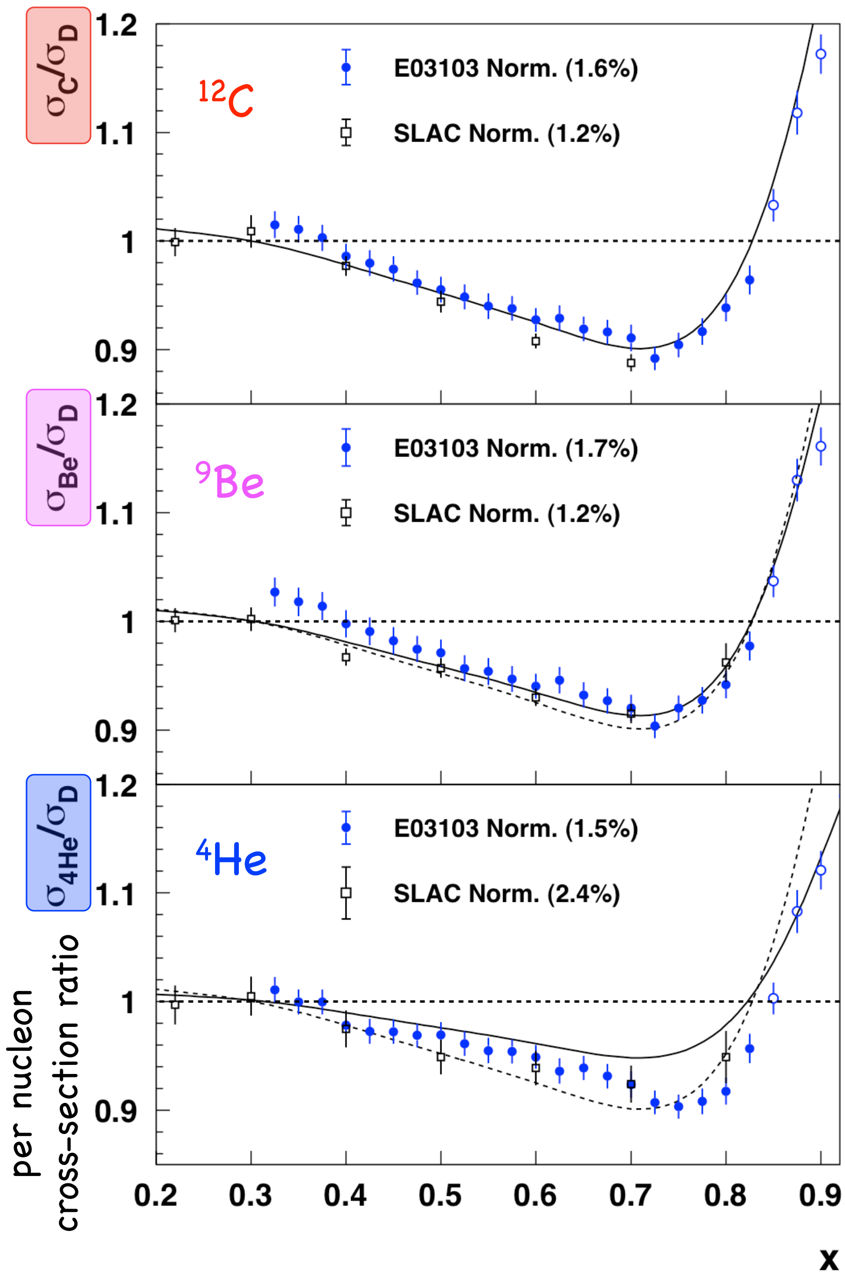
Neutron bound in ^4He does not decay, $\tau_n = \infty$

Probing Nucleons in the Nuclear Medium

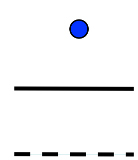
1. Probing structure functions in DIS (e,e′) scattering
2. Probing form factors in QE (**e**,e′**p**) scattering
3. Probing the pp scattering matrix in the QE (p,**pp**) reaction

4. Future experiments and plans:
   - ^{4}He(**e**,e′**p**)^{3}H and ^{2}H(**e**,e′**p**)
   - ^{12}C(**e**,e′**p**)
   - ^{4}He(**e**,e′**n**)^{3}He

EMC Effect in Very Light Nuclei



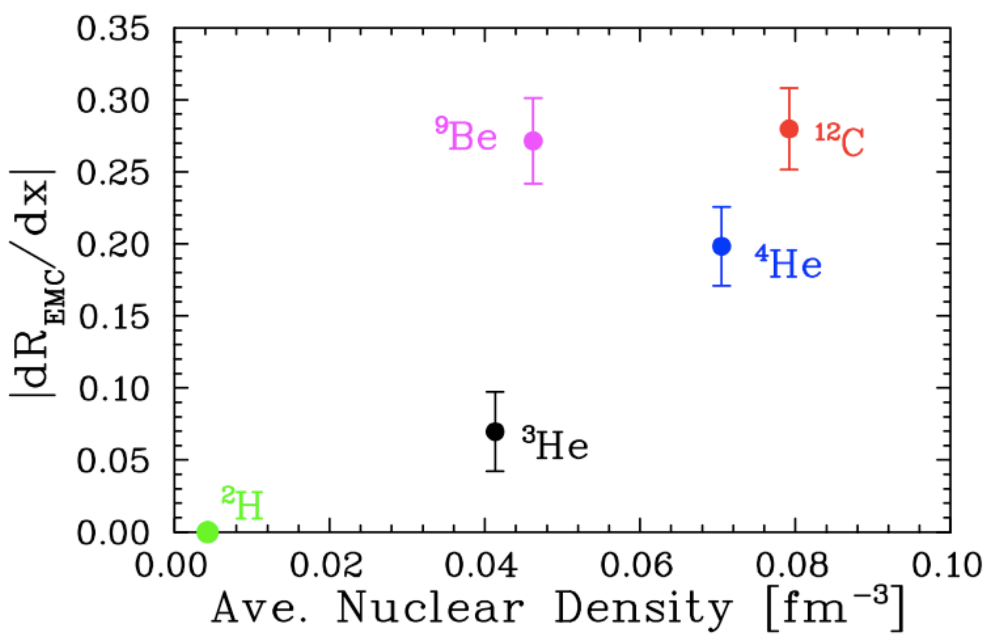
- Few-body nuclei provide the opportunity to test models where the details of the nuclear structure is well understood.
- JLab high-precision measurement of ^{2}H, ^{3}He, ^{4}He, ^{9}Be and ^{12}C for $0.3 < x < 0.9$, $Q^2 \approx 3-6$ GeV^2
- Test scaling models of the EMC effect:
  - Density-dependent (ρ) effect?
  - Mass-dependent (A) effect?

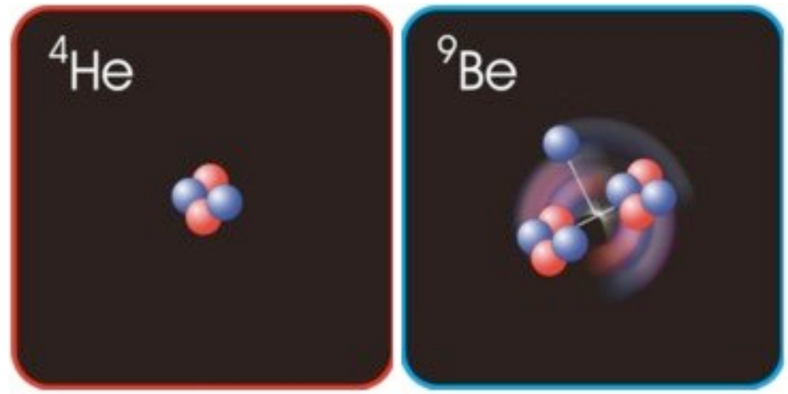


J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009)

Local Density Determines Strength of EMC Effect

Slope dR_{EMC}/dx as measure of the EMC-effect magnitude

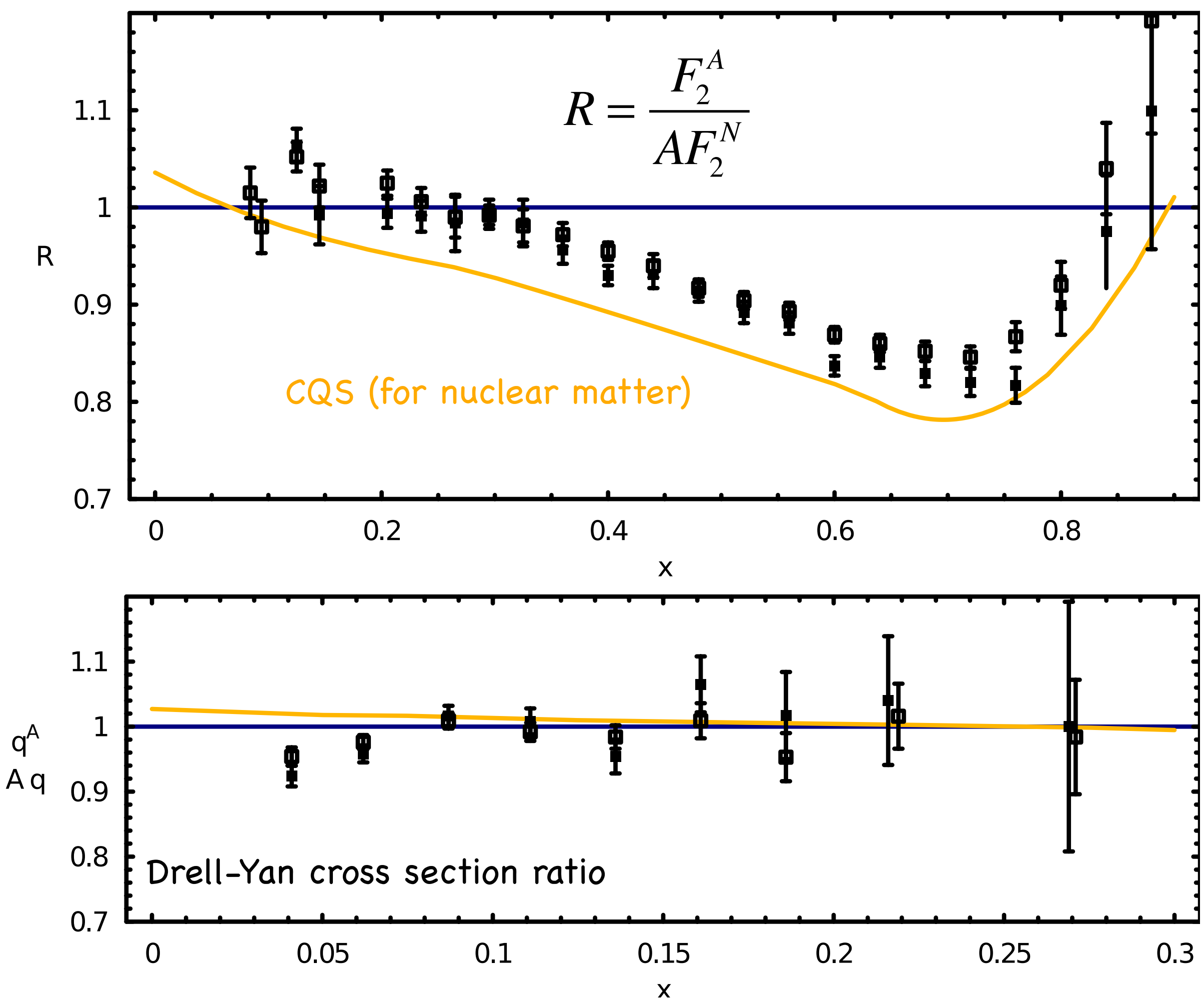




- Sizable nuclear effect in ^{4}He
- Nuclear effects in ^{4}He, ^{9}Be (= 2α+n) comparable to effect in ^{12}C
- Data suggest that **local** density drives the modification

J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009)

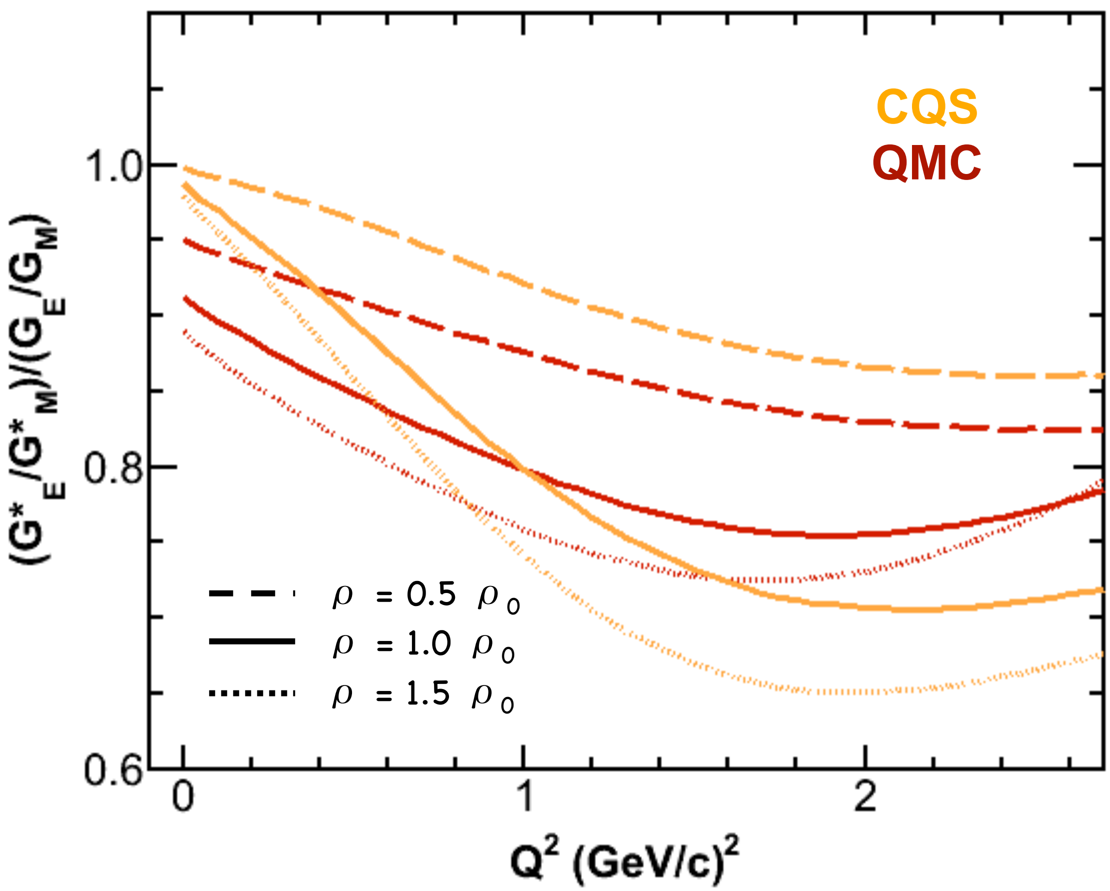
Chiral-Quark-Soliton Model Describes EMC Effect and Drell-Yan Data



- The CQS model is consistent with free nucleon properties, nuclear saturation properties, EMC effect, Drell-Yan experiments.
- EMC Effect is **not** due to conventional nuclear physics.
- Relativistic, quark-level models of nuclear structure, predict fundamental changes in the internal structure of bound hadrons due the mean scalar and vector fields in the medium.
- Medium induced increase of nucleon radius = 2.4%; consistent with A(e,e′p) limit of $G^*/G < 6\%$.

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

Models Predict Form-Factor Medium Modifications



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

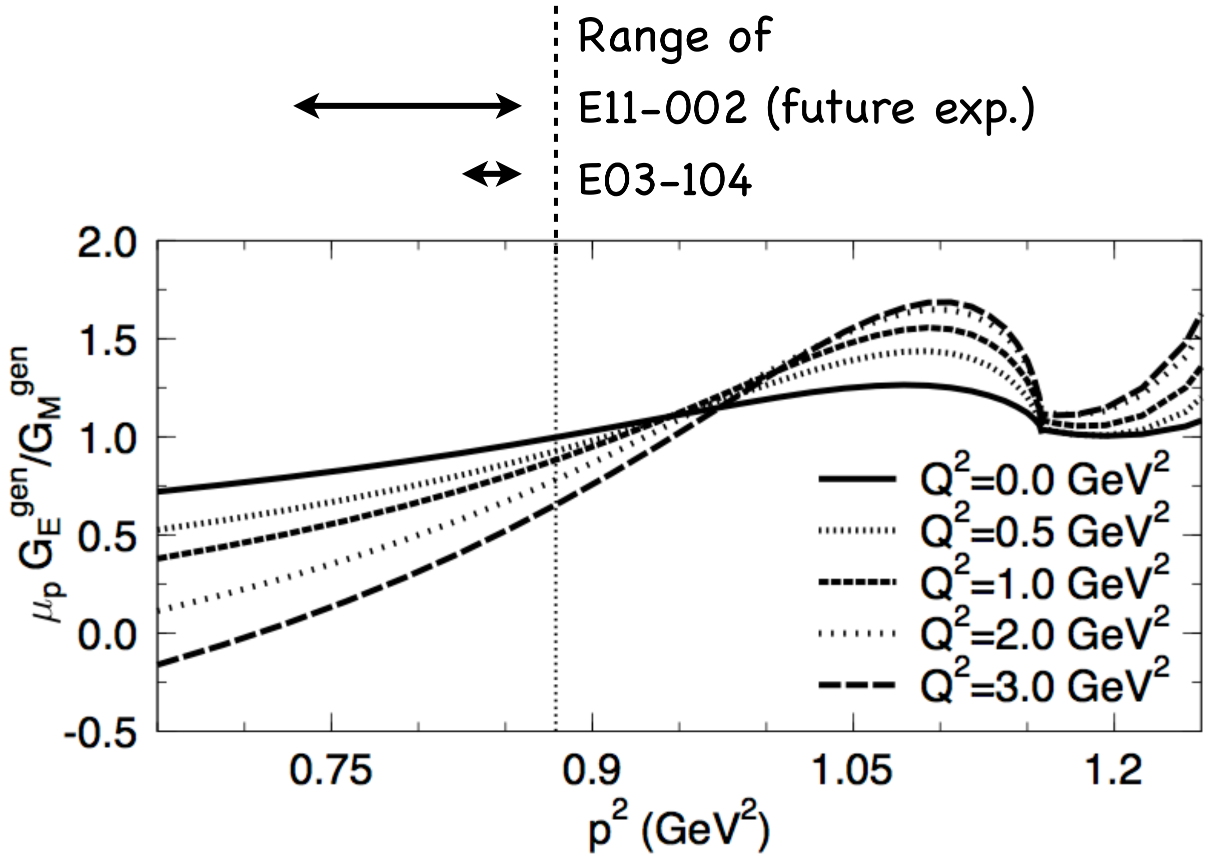
QMC: D.H. Lu et al., Phys. Lett. B 417, 217 (1998)

NJL: I.C. Cloet, W. Bentz, and A.W. Thomas (to be published)

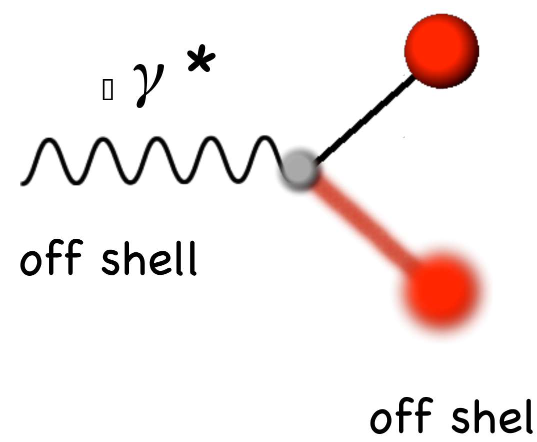
- Changes in the internal structure of bound nucleons result also in **bound nucleon form factors**.
- Observable effects predicted:

  Chiral Quark Soliton (CQS), Quark Meson Coupling (QMC), Skyrme, Nambu-Jona-Lasinio (NJL), GPD Models.
- Model predictions:
  - are density and Q^2 dependent,
  - show similar behavior,
  - consistent with experimental data (within large uncertainties).

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)

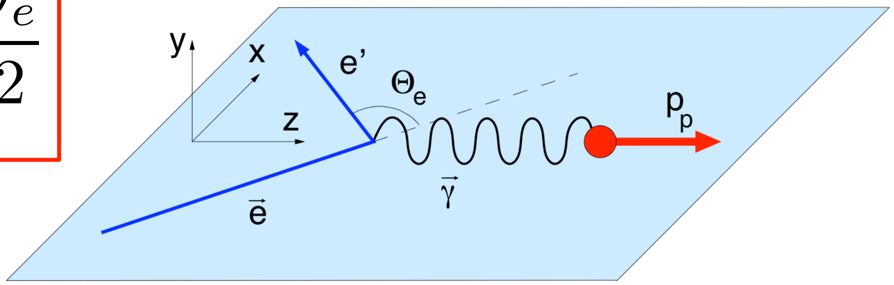
S. Kondratyuk, K. Kubodera, and F. Myhrer, Phys. Rev. C **71**, 028201 (2005).

Form Factor Extraction - Recoil-Polarization

$$P'_x = -2\sqrt{\tau(1+\tau)}\frac{\frac{G_{Ep}}{G_{Mp}}}{(\frac{G_{Ep}}{G_{Mp}})^2+\frac{\tau}{\epsilon}}\tan\frac{\theta_e}{2}$$

$$P'_z = \frac{1}{m}(E_i+E_f)\sqrt{\tau(1+\tau)}\frac{1}{(\frac{G_{Ep}}{G_{Mp}})^2+\frac{\tau}{\epsilon}}\tan^2\frac{\theta_e}{2}$$

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

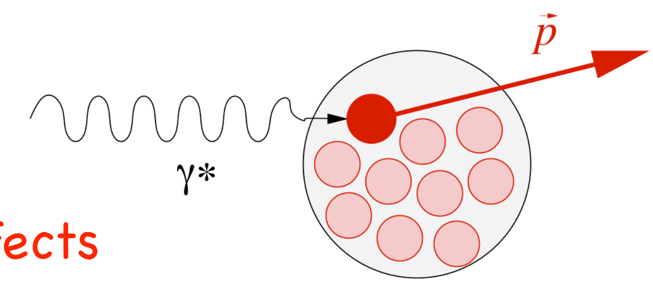


- The ratio G_{Ep}/G_{Mp} is obtained from a single measurement
- Small systematic uncertainties (beam helicity, A_c, ... cancel)
- Minimally affected by radiative corrections

A.I. Akhiezer and M.P. Rekalo, Sov. J. Part. Nucl. **3**, 277 (1974)
R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981)

Polarization-Transfer Technique

- Bound nucleon data need evaluation within model
  Reaction-mechanism effects predicted to be small and minimal for
  - Quasi-elastic scattering
  - Small missing momenta



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

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

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

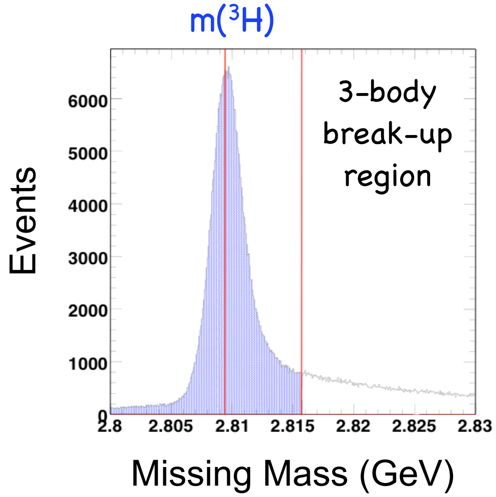
R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981); for reaction-mechanism effects, e.g., J.M. Laget, Nucl. Phys. A **579**, 333 (1994), J.J. Kelly, Phys. Rev. C **59**, 3256 (1999), A. Meucci, C. Guisti, and F.D. Pacati, Phys. Rev. C **66**, 034610 (2002).

Quasi-Elastic $^4He(\vec{e},e'\vec{p})^3H$ at Jefferson Lab Hall A

Experiments:

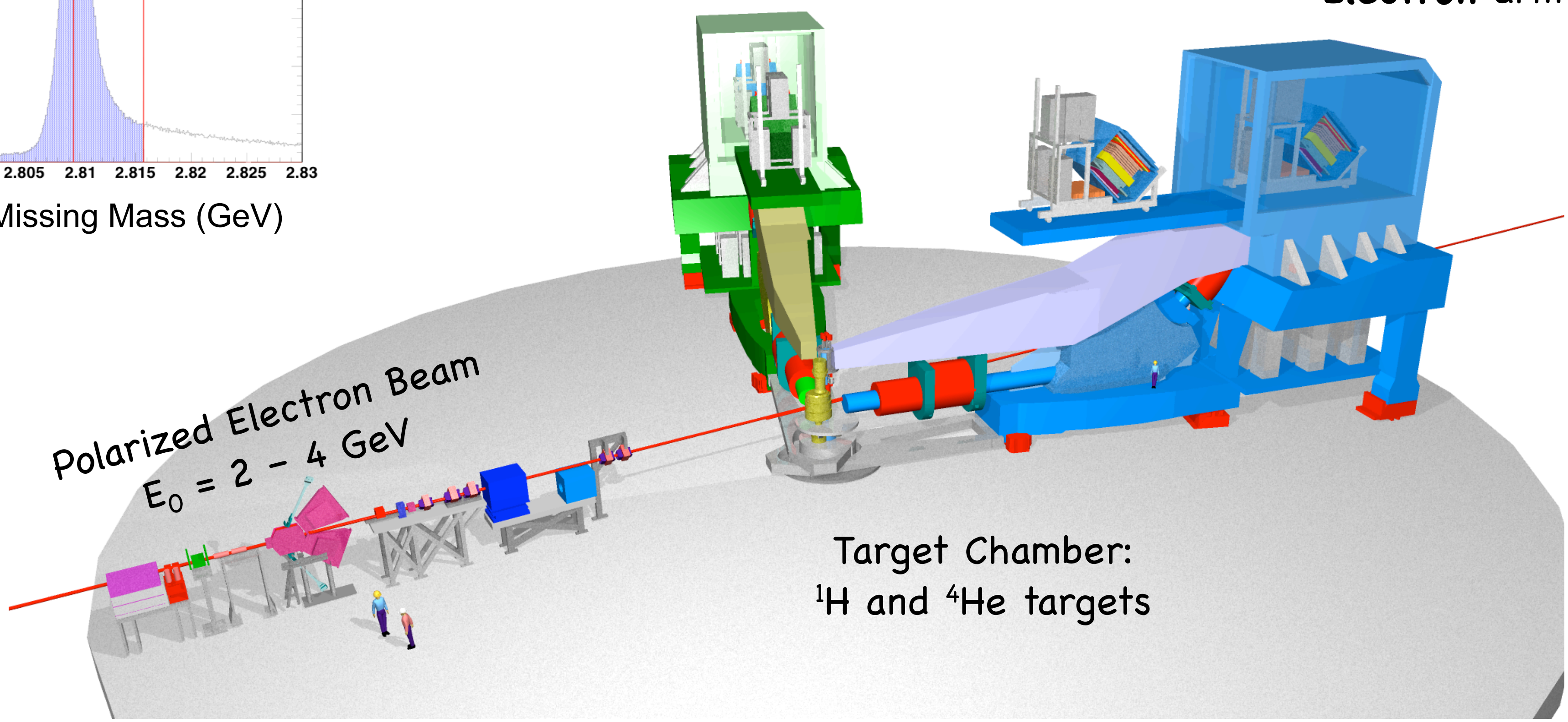
E93-049 and E03-104

Q^2 = 0.5 – 2.6 $(GeV/c)^2$



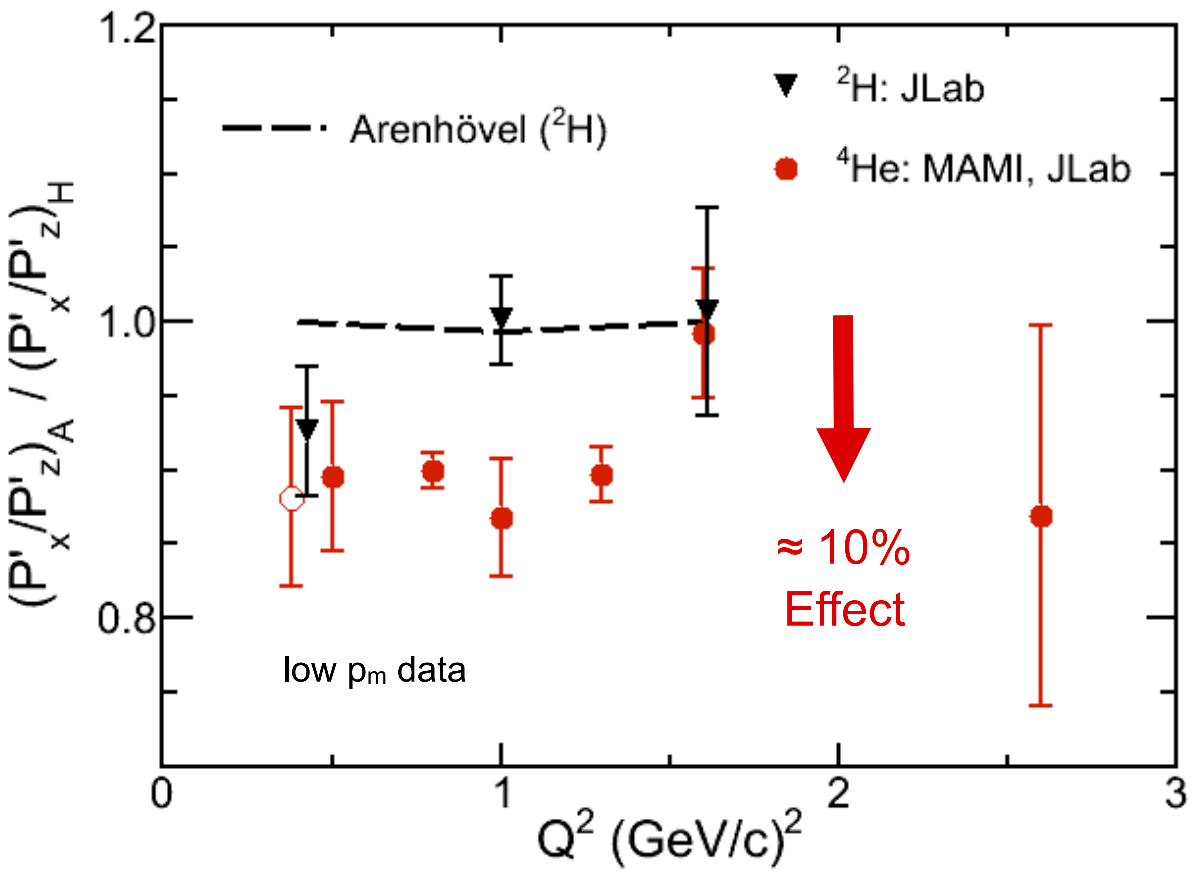
Proton arm with
Focal Plane Polarimeter
Extract: P'_x, P'_z, and P_y

Electron arm



S. S., et al., PRL. **91**, 052301 (2003); M. Paolone, et al., PRL. **105**, 0722001 (2010); S. Malace et al., PRL **106**, 052501 (2011)

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

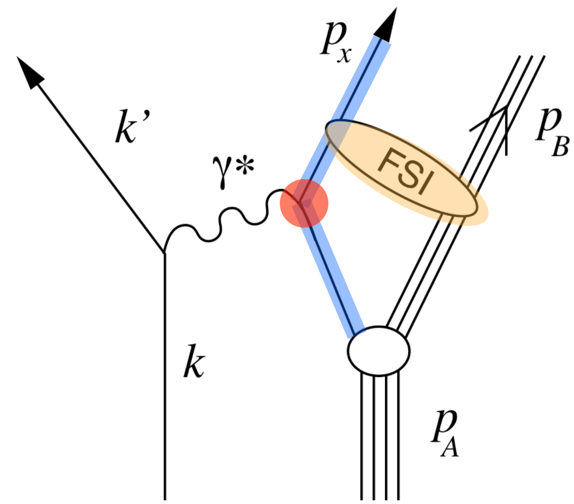


- ^{2}H and ^{1}H polarization-transfer data are similar
- ^{4}He data are significantly different than ^{2}H, ^{1}H data

^{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)

Quasi-Elastic Scattering from Bound Nucleons

Madrid Model: Nucleon one-body current in relativistic distorted-wave impulse approximation (RDWIA)



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

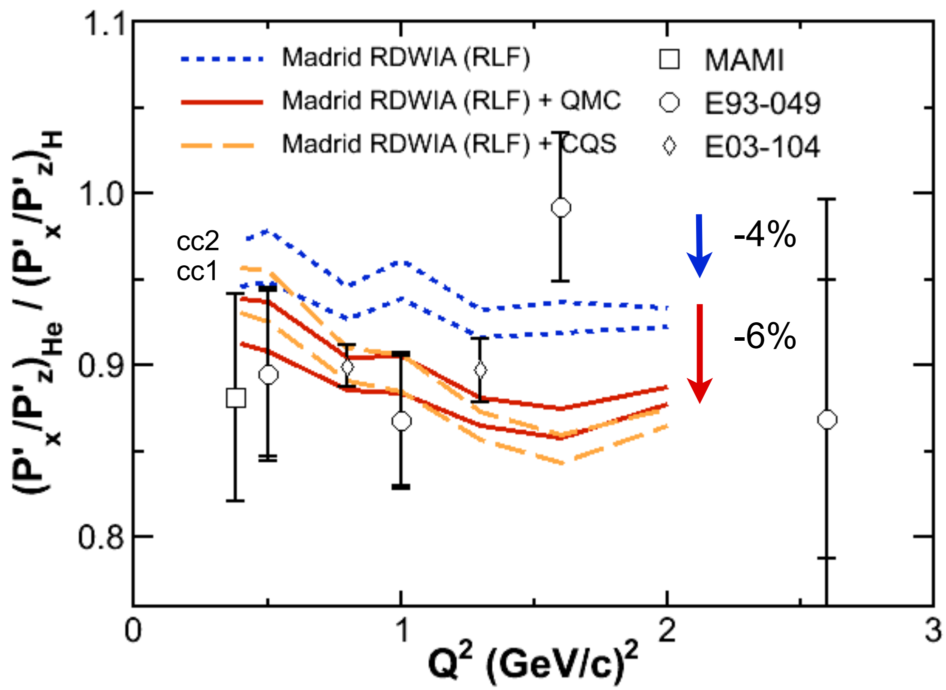
- Wave functions for initial bound, ψ_B, and

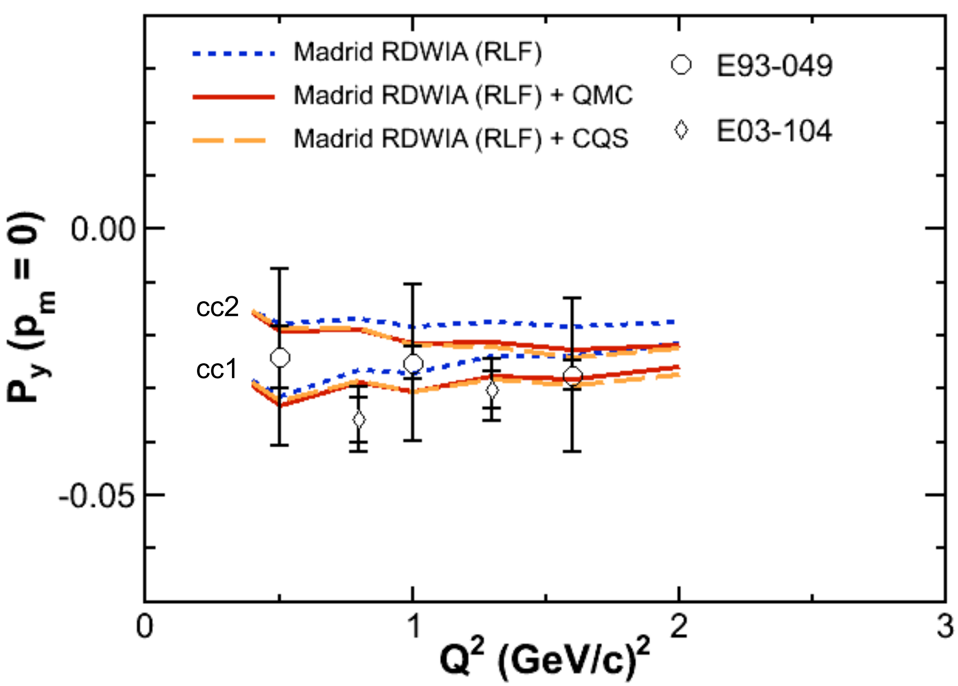
  final outgoing, ψ_F, nucleons (final state interactions, FSI)

- Relativistic nucleon current operator of cc1 or cc2 forms
- Density-dependent in-medium form factors, G^*_E and G^*_M, were evaluated at the local density, ρ(r)

$$G(Q^2,\rho) = G(Q^2)\frac{G^*(Q^2,\rho)}{G^*(Q^2,\rho=0)}$$

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





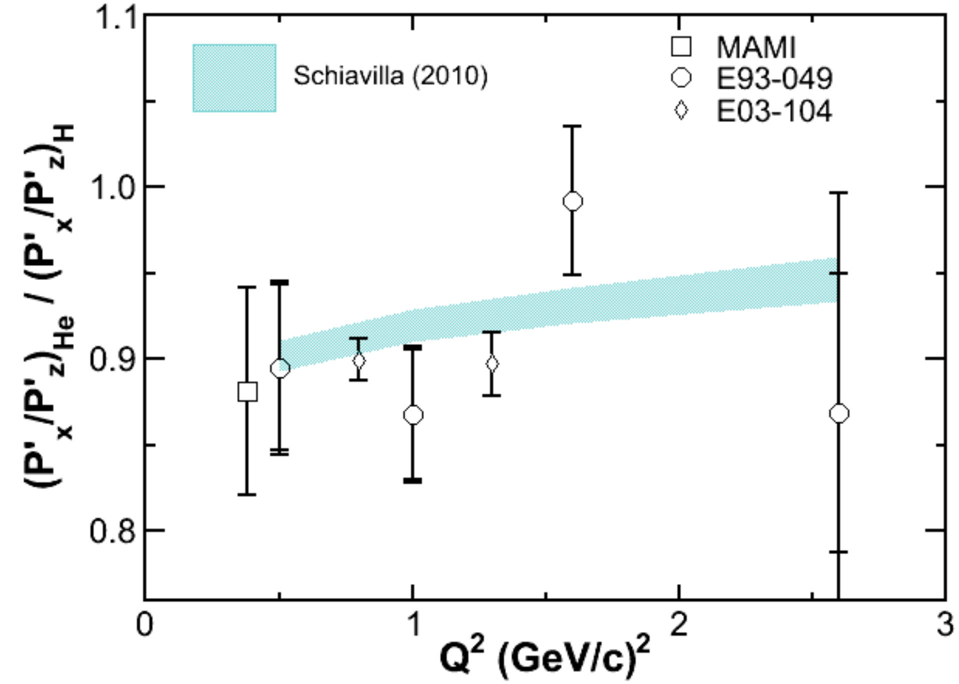
Madrid RDWIA

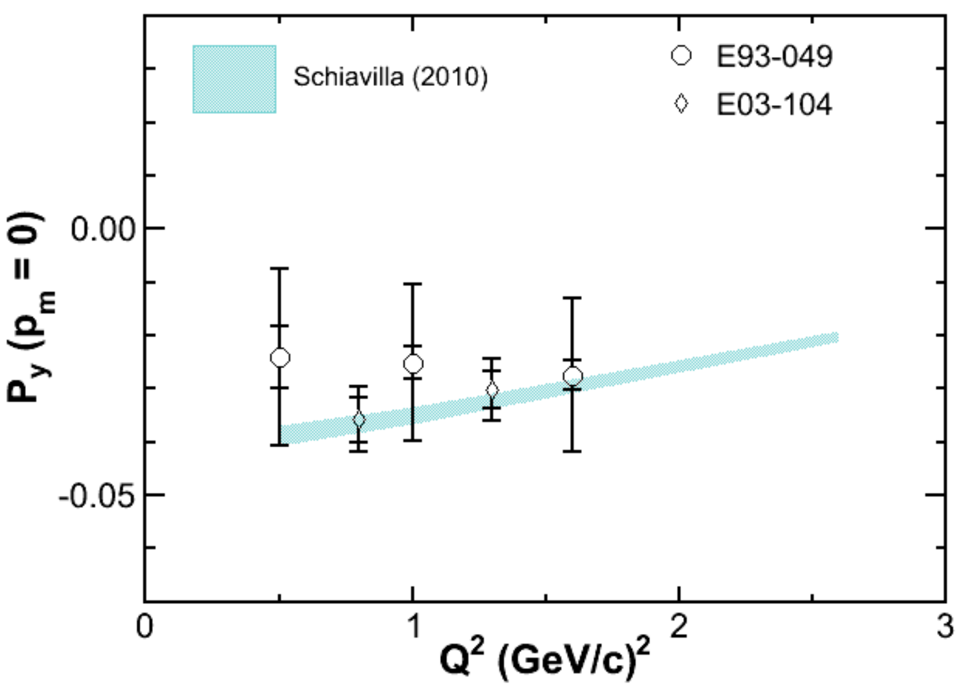
- Relativistic calculation in distorted-wave impulse approximation (RDWIA) overestimates R

- 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





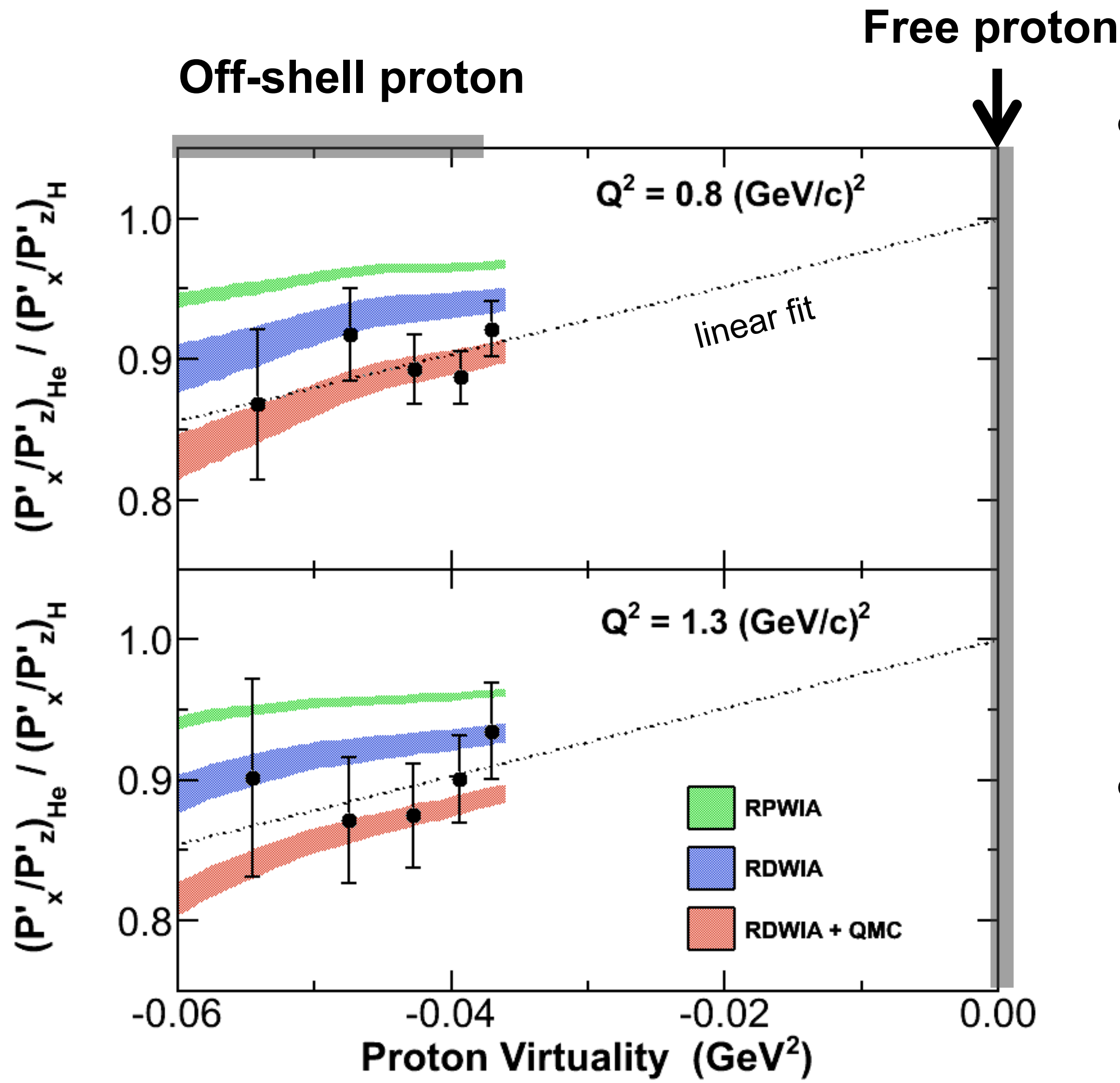
Schiavilla (2010)

- 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

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

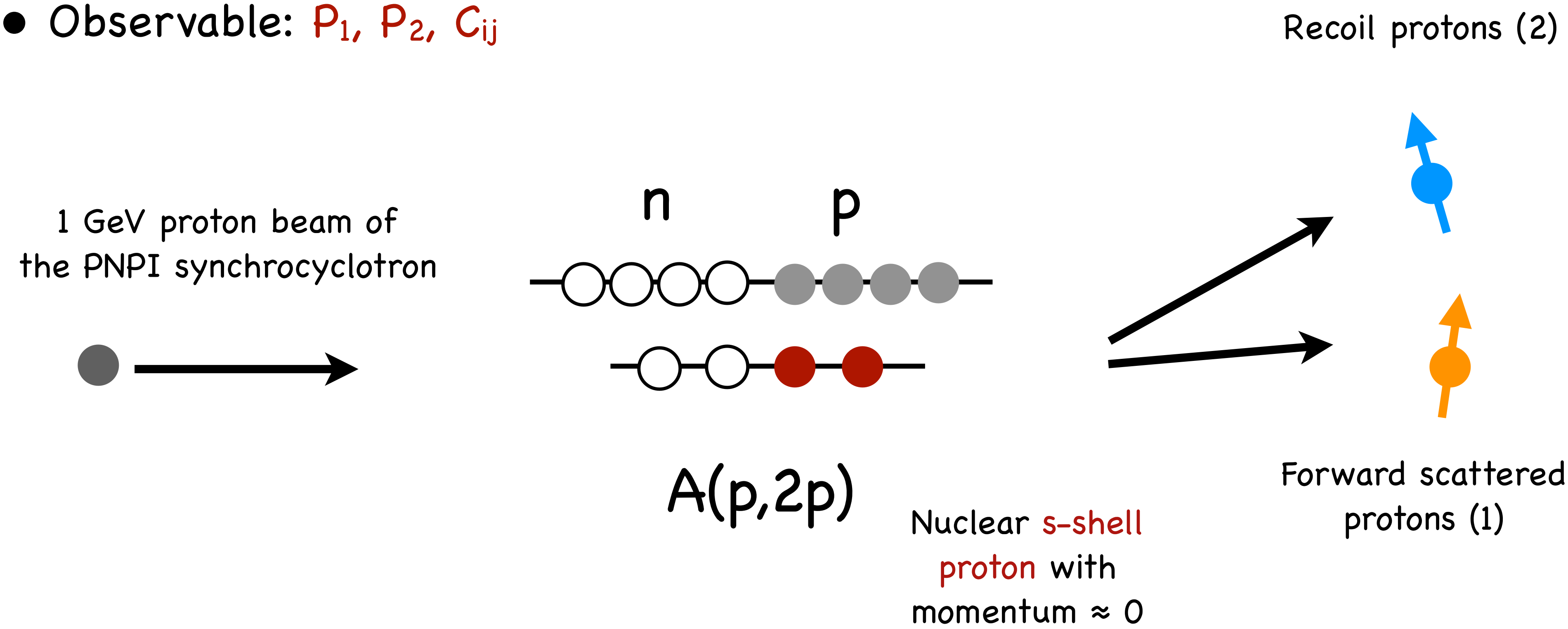
with the trend of $R \approx 1$ for $p^2 = m_p^2$; as it should be.

- 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)

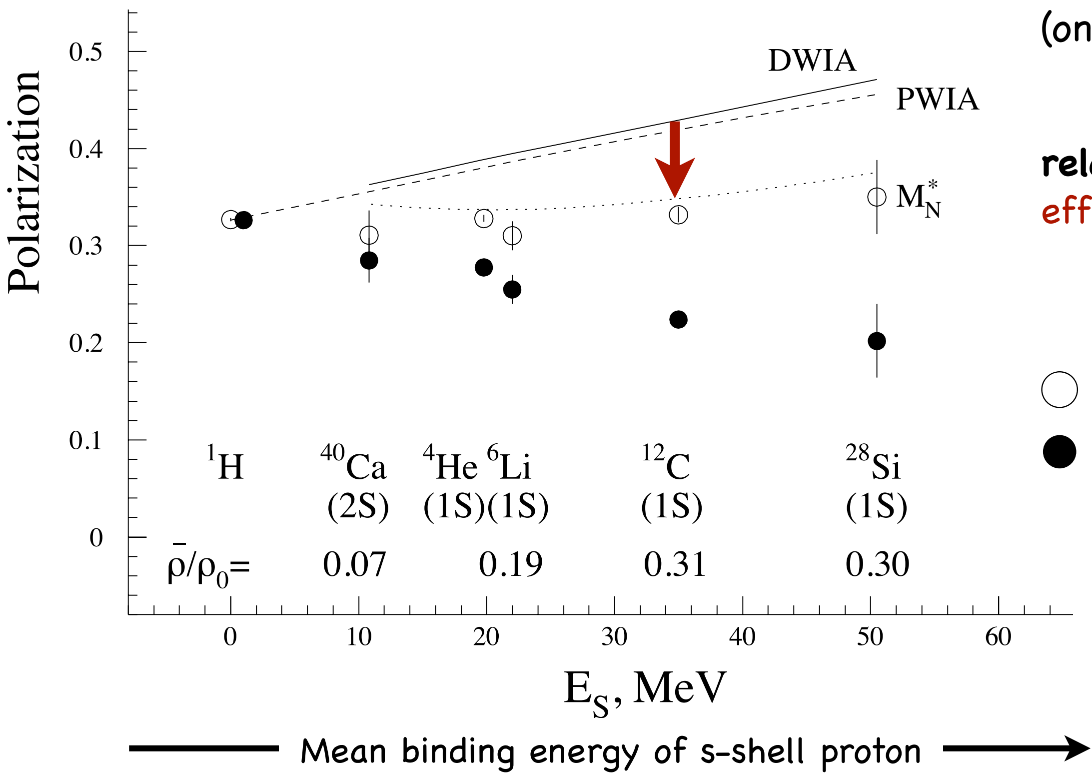
Quasi-Elastic ^{4}He, ^{6}Li, ^{12}C, ^{28}Si, ^{40}Ca(p,2p)

- "Polarization effects in the quasi-elastic (p,2p) reaction with the nuclear s-shell protons at 1 GeV"
- Kinematics close to elastic proton-proton scattering
- Observable: P_1, P_2, C_{ij}



O. V. Miklukho, et al. (Gatchina); arXiv:1301.6487 [nucl-ex]

Medium Effect Increases with Mean Nuclear Density



non-relativistic PWIA, DWIA
(on-shell factorized approximation)

relativistic effect (incl. distortion of nucleon spinor)
effective nucleon mass $M_N^* = M_N - \Delta M$; $\Delta M \propto \rho$

○ – P_1 forward scattered protons
● – P_2 recoil protons

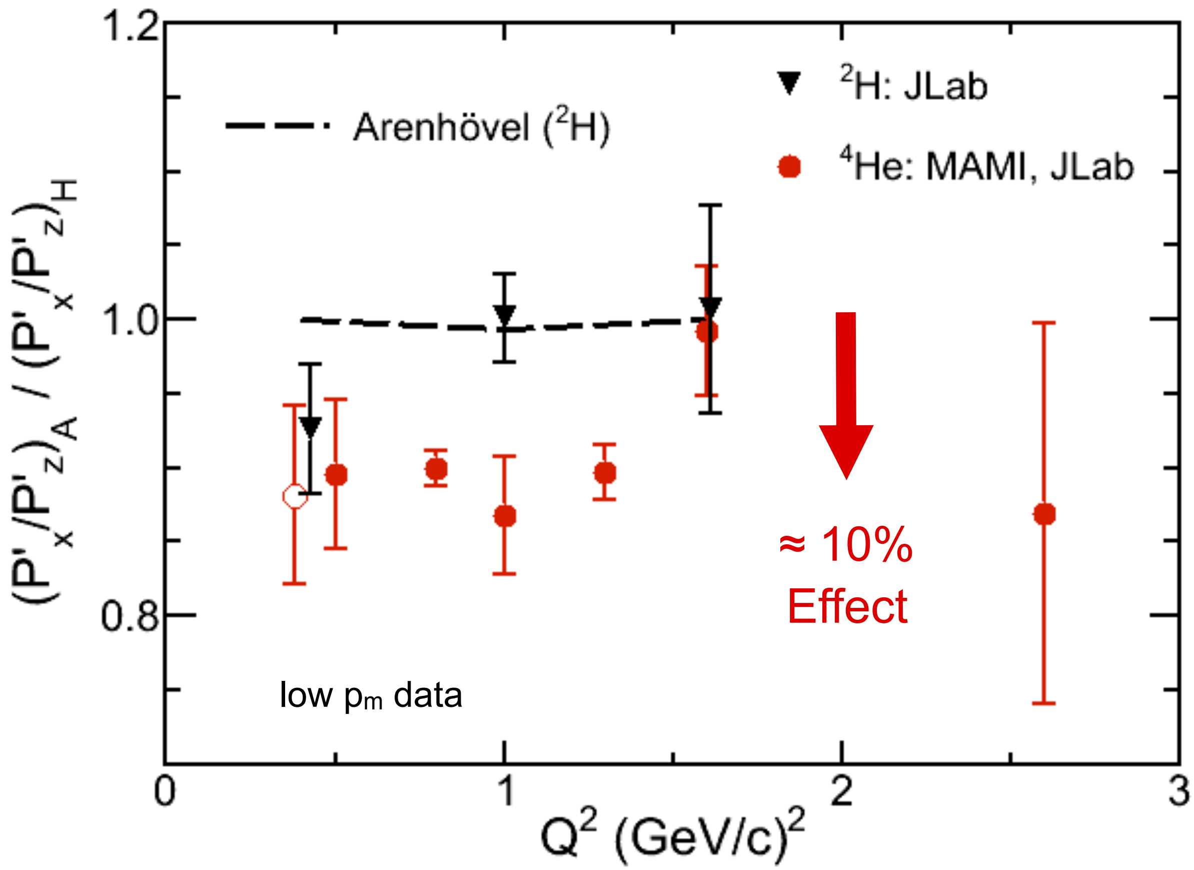
O. V. Miklukho, et al. (Gatchina); arXiv:1301.6487 [nucl-ex]

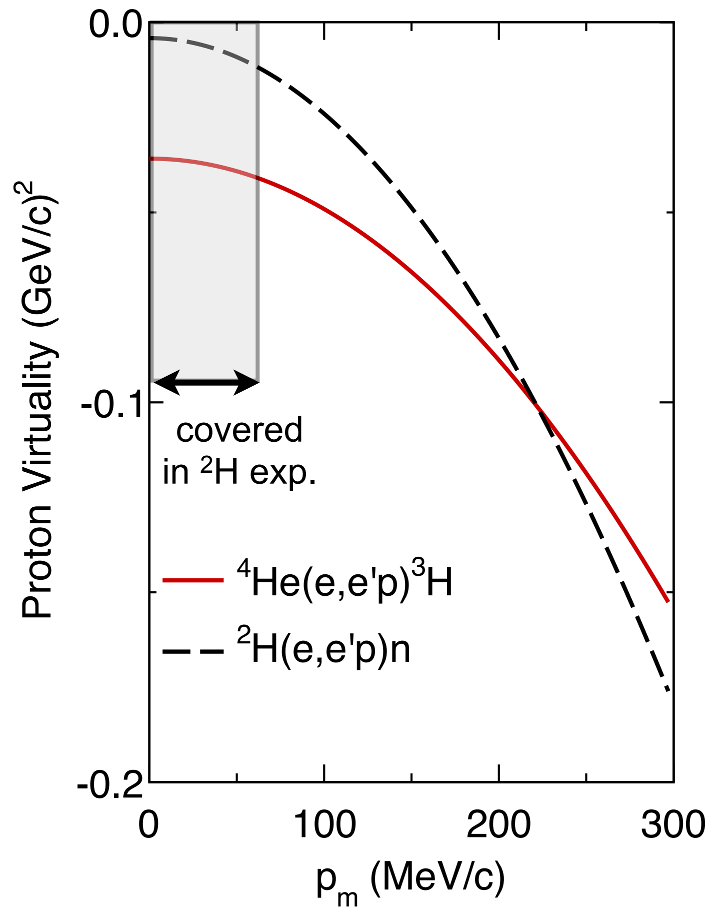
- Medium effect is related to the effective mean nuclear density.
  Also determined by the mean binding energy of the s-shell proton of a nucleus; A < 12.
- Indication of a modification of the proton-proton scattering matrix in the nuclear medium.

What are the Driving Parameters for the Observed Medium Effects?

Reaction	Observable	Medium effect	Driving parameter
$(e,e')_{DIS}$	σ_A	depletion of the nuclear structure function F_2	local density
$(e,e'p)_{QE}$	P'_x/P'_z	decrease of the polarization-transfer ratio, G_E/G_M(?)	proton virtuality (?)
$(p,pp)_{QE}$	P_1, P_2, C_{ij}	reduction of magnitude of proton polarization; p-p scattering amplitude	effective mean nuclear density; mean binding energy of s-shell proton

What Generates the Large Medium Effect?

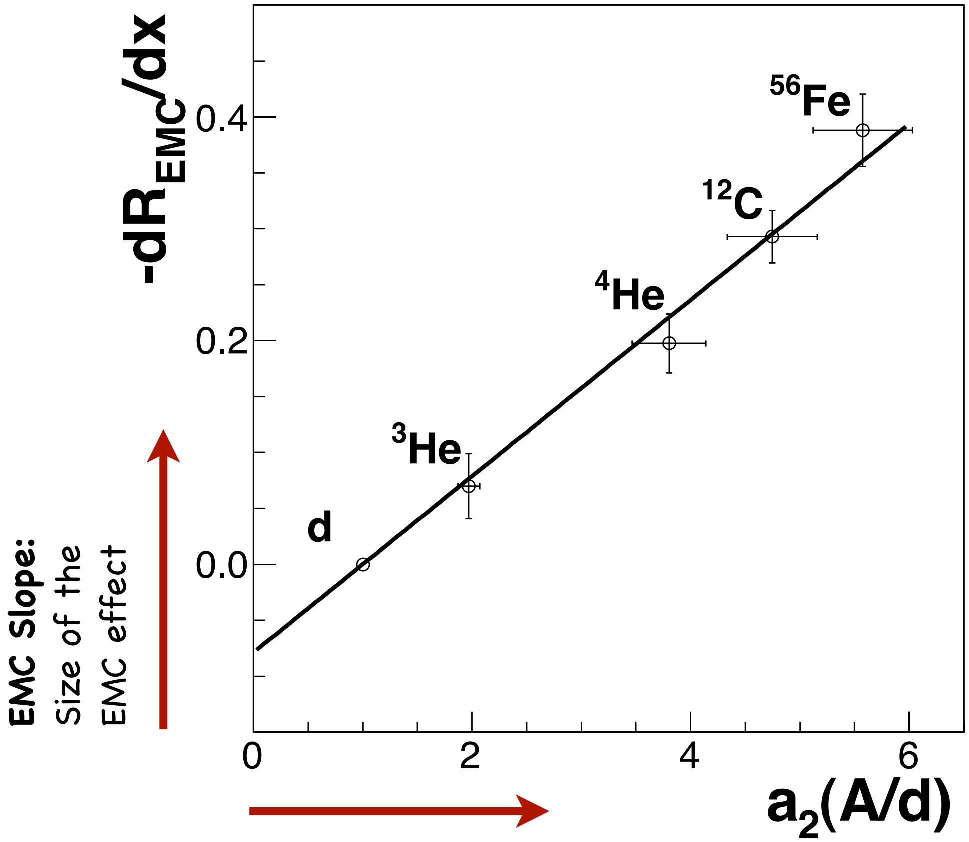




- the nuclear density or
- the larger proton virtuality probed in the ^{4}He experiments?

^{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)

Momentum Dependence of the EMC Effect



SRC Scaling Factor:
Probability to find SRC pairs (low c.m., high relative momentum) in the nucleus

- The observed EMC-SRC linear correlation supports the hypothesis that the EMC effect is mainly associated with the nucleons at high virtuality.

- New experiment, **E11-002,** will test with ^{4}He(e,e′p) and ^{2}H(e,e′p) data at high proton virtuality if medium effects in previous polarization-transfer measurements depend on:
  - nucleon momentum, off-shellness (virtuality), or
  - mean nuclear density.

Figure from: L.B. Weinstein et al., Phys. Rev. Lett. **106**, 052301 (2011)

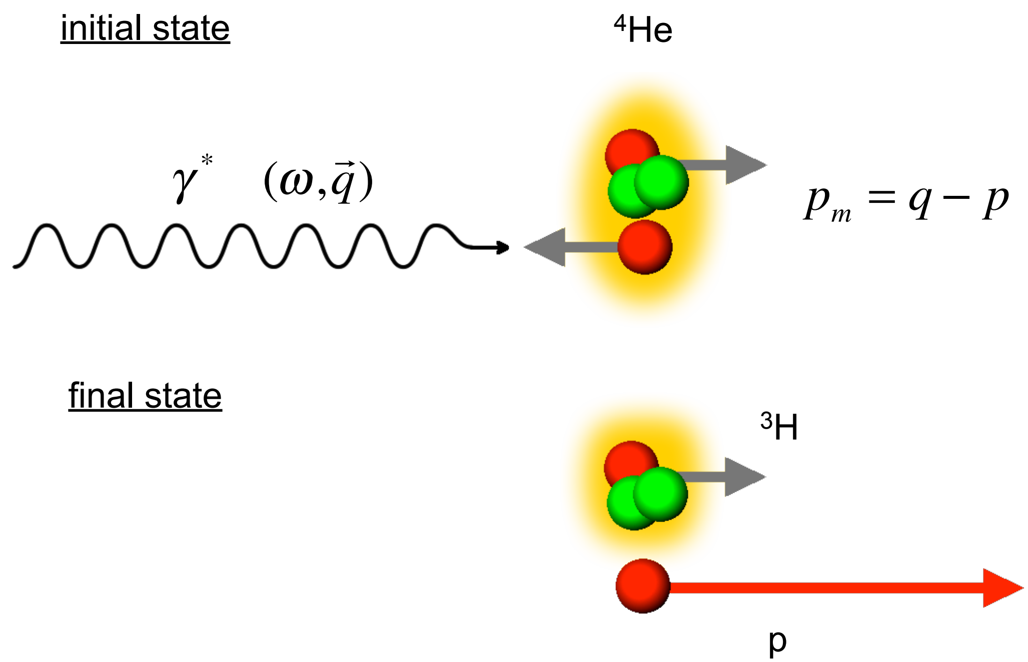
C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)

E11-002: Kinematics

- 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:

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

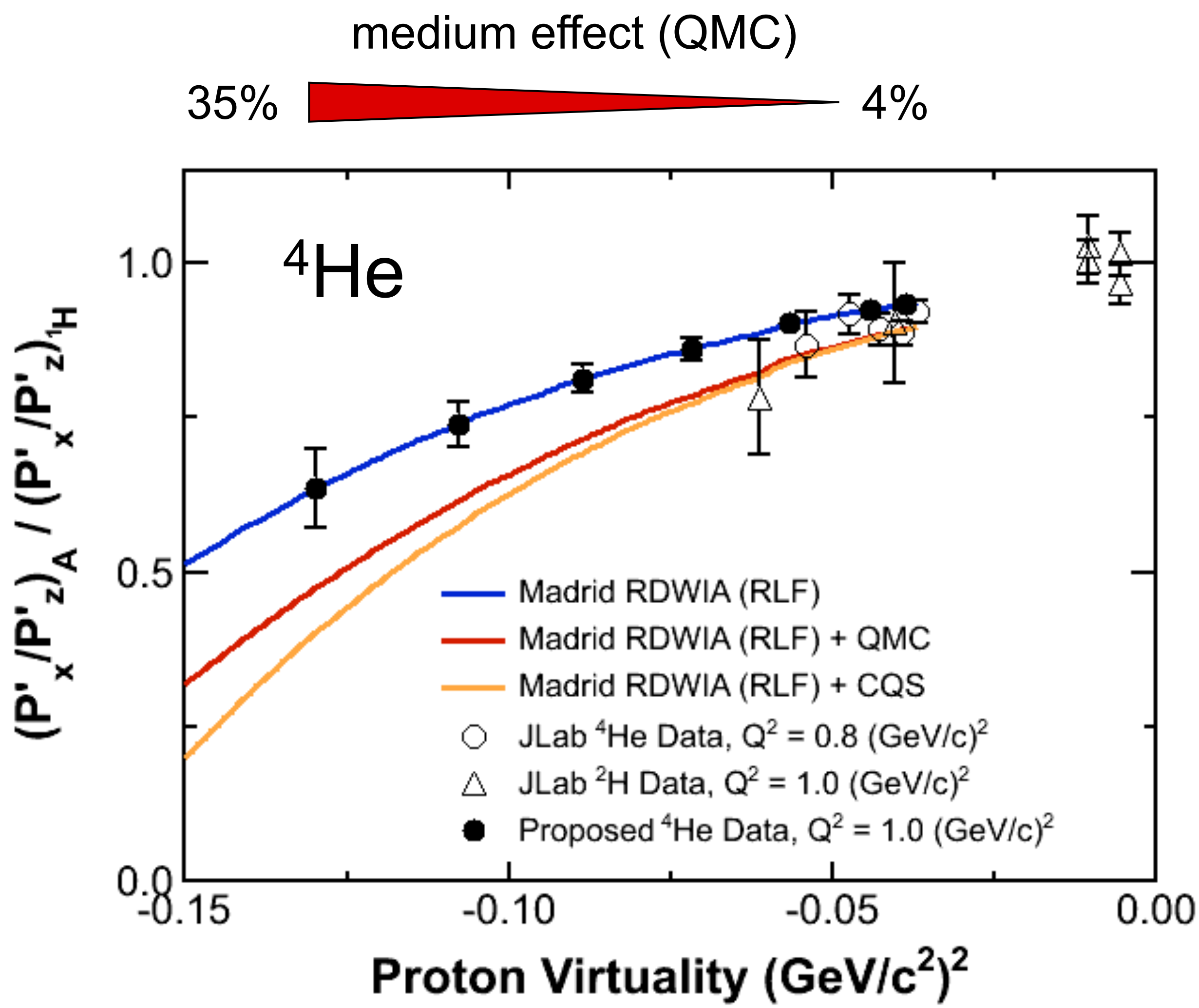
$$= \left(M_A - \sqrt{M_{A-1}^2 + \vec{p}_m^{\,2}}\right)^2 - \vec{p}_m^{\,2} - m_p^2$$



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

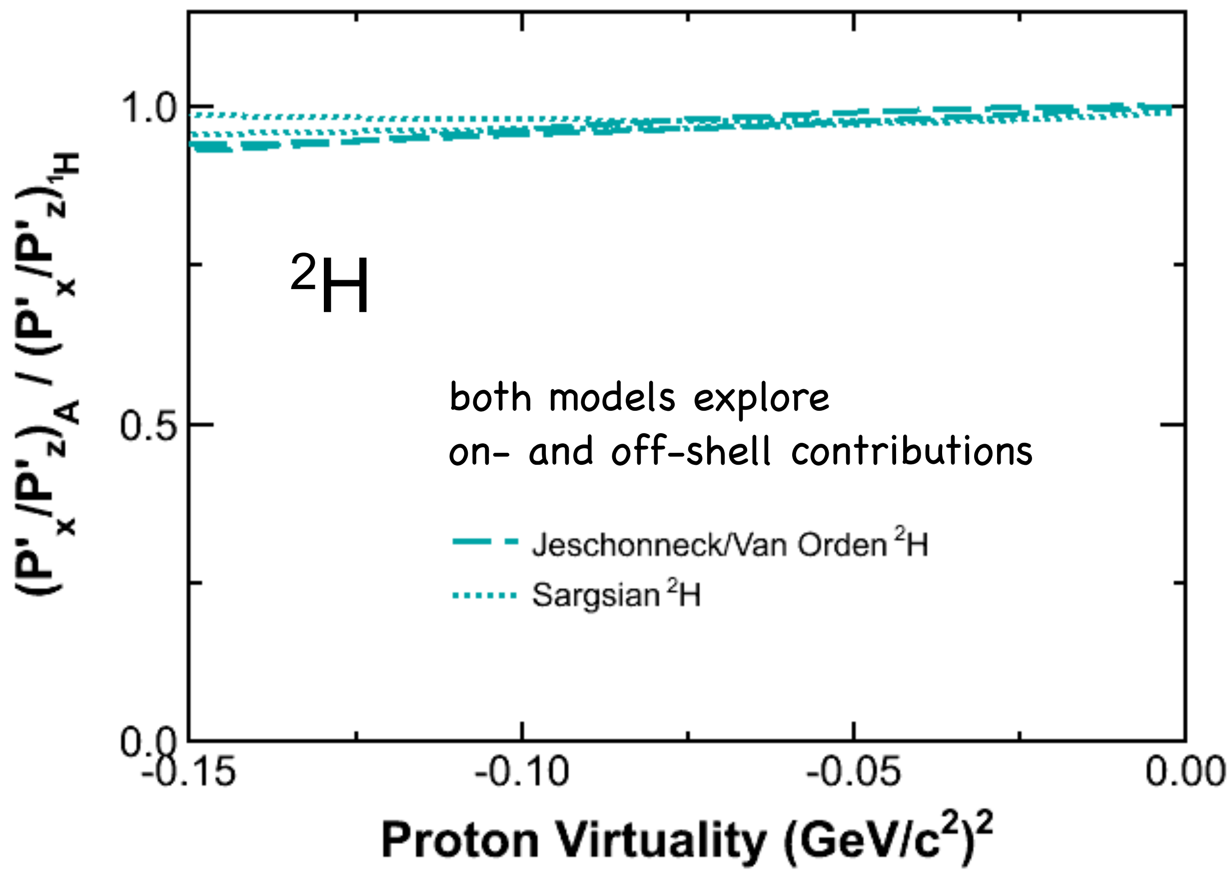
*M. Sargsian, private communication
C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)

1st Feature of E11-002



- **E11-002**:
  Q^2 = 1.0 (GeV/c)^2
  p_m = 0, 140, 220 MeV/c
- Significantly improved proton-virtuality coverage
- 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 (○).

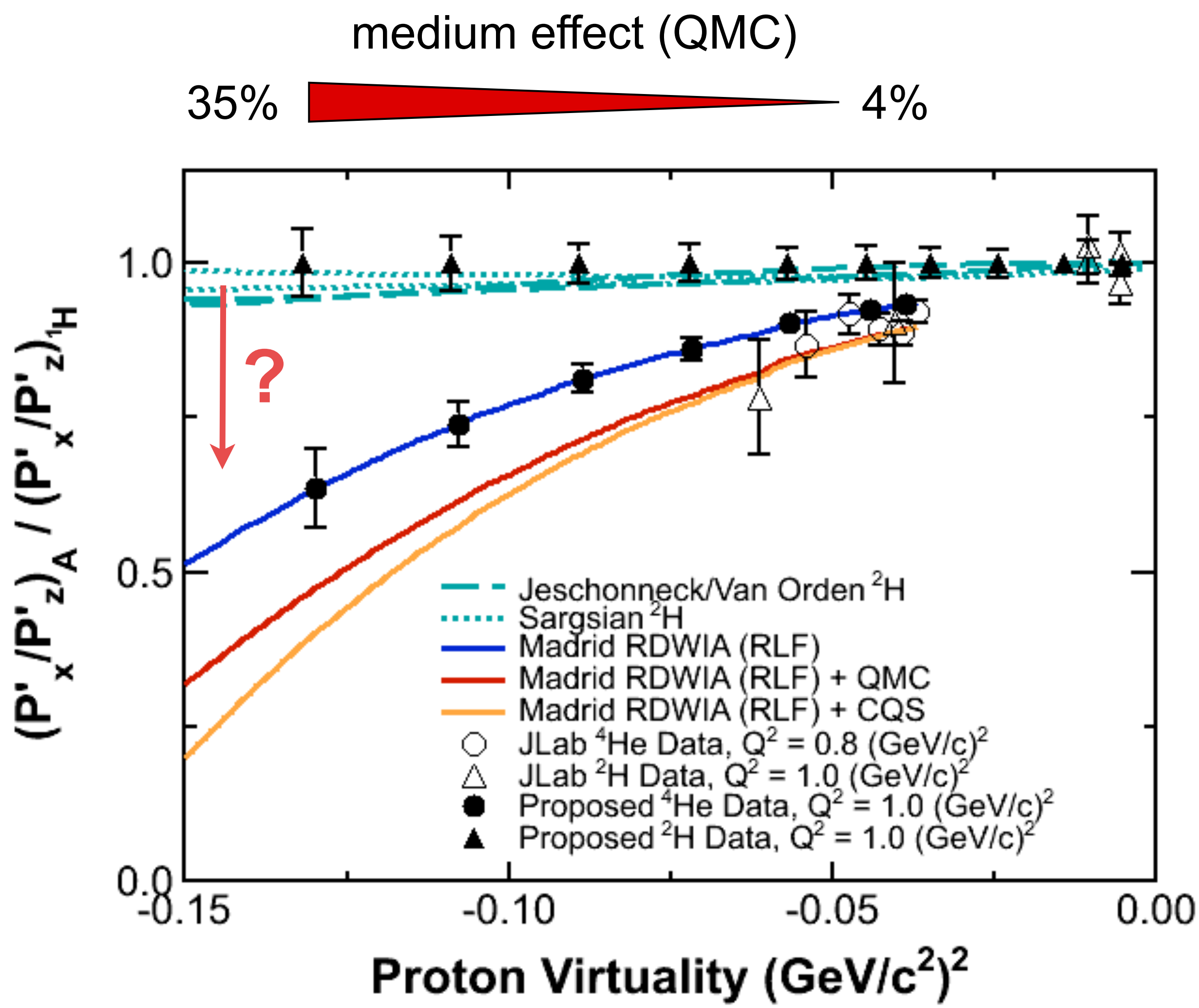
Modern, Rigorous $^2H(e,e'p)n$ Calculations Exist



- **Sargsian**: Generalized eikonal approximation; pn → pn and charge-exchange pn → np rescattering; Isobar configurations
- **Jeschonneck/Van Orden**: Fully relativistic calculation in the impulse approximation employing the Gross equation to describe the deuteron ground state, and final state interactions (FSIs).
- Both models use the SAID parametrization of the NN scattering amplitude
- Reaction-dynamics effects and FSI will change the ratio up to 5% (maximum 8%) in this kinematics

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)

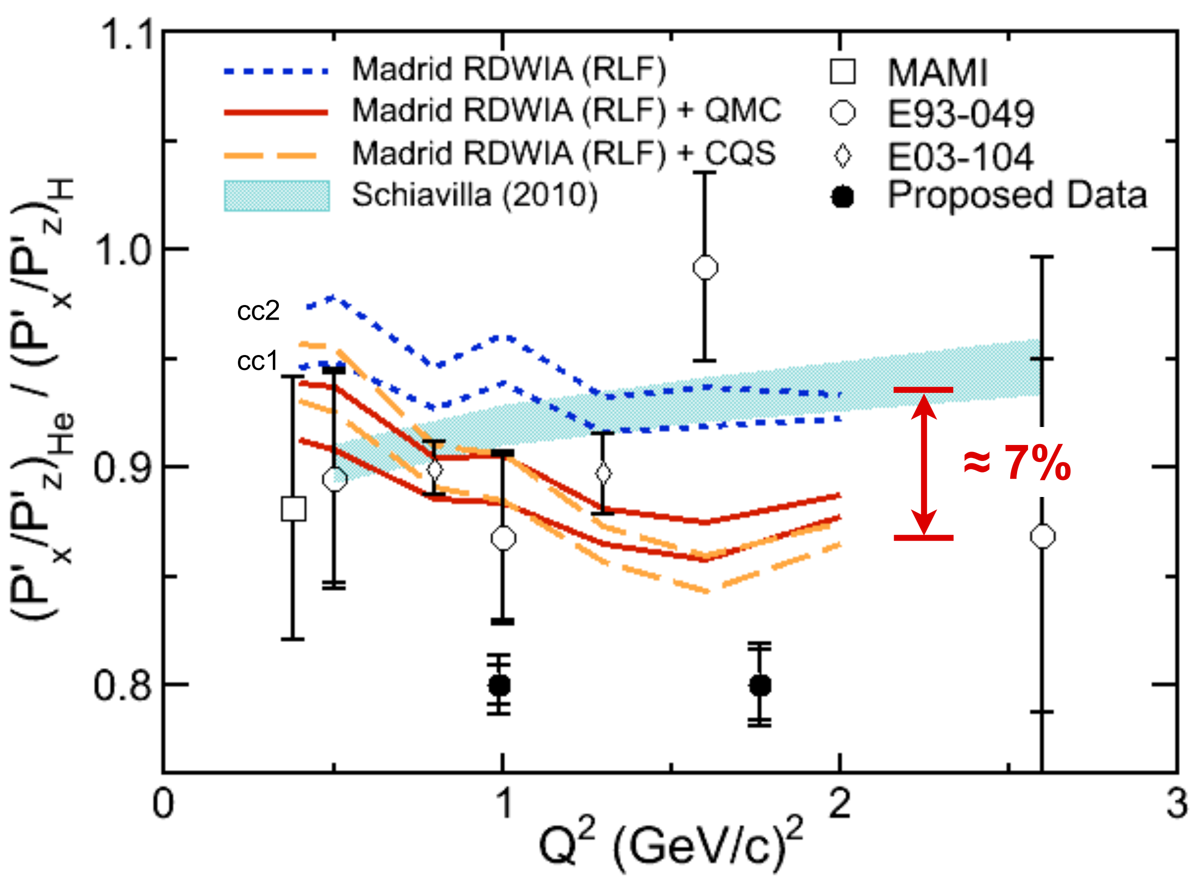
2nd Feature of E11-002



- **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 …

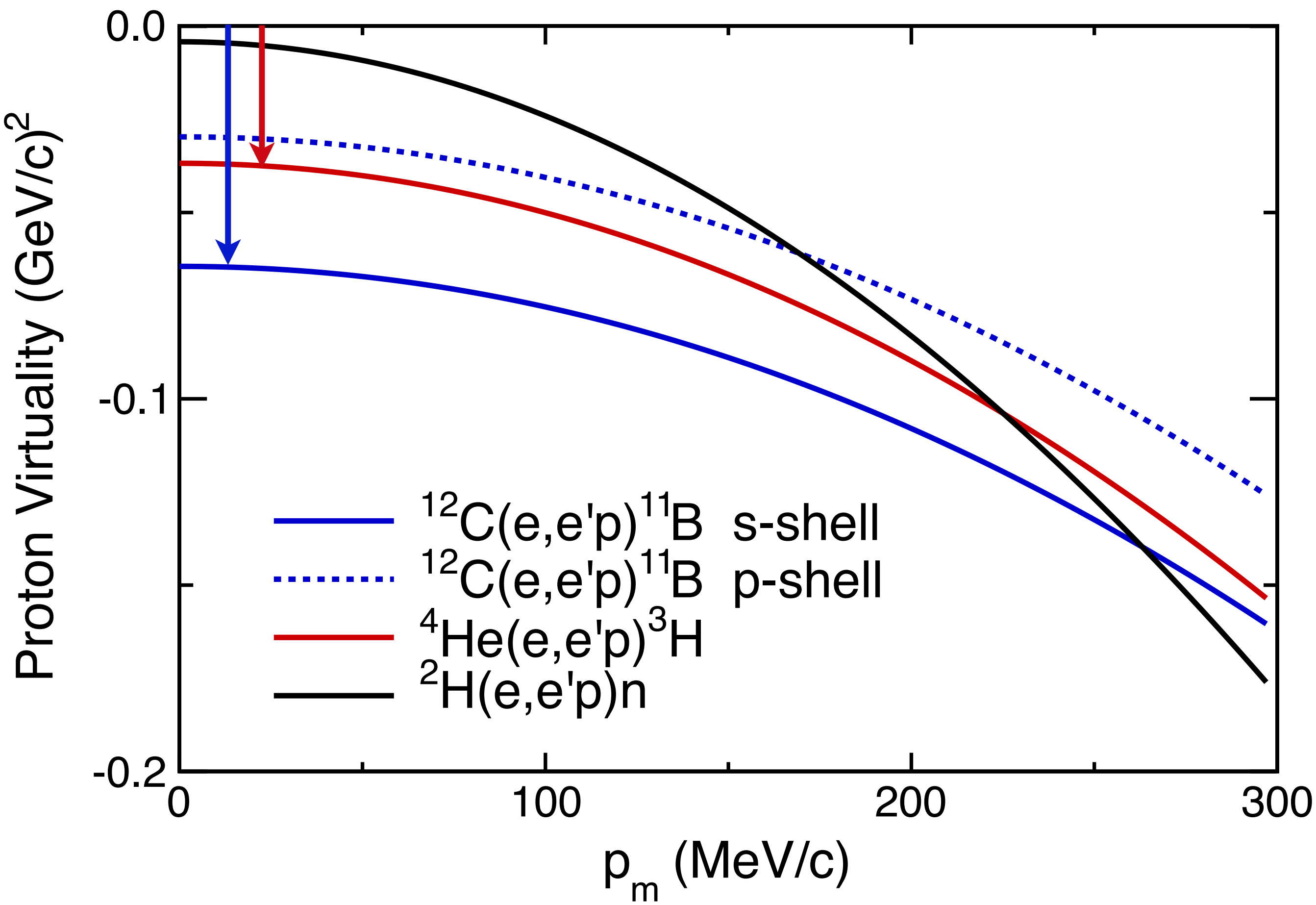
S. Jeschonnek and J.W. Van Orden, Phys. Rev. C **81**, 014008 (2010) and Phys. Rev. C **78**, 014007 (2008); M.M. Sargsian, Phys. Rev. C**82**, 014612 (2010)

3rd Feature of E11-002



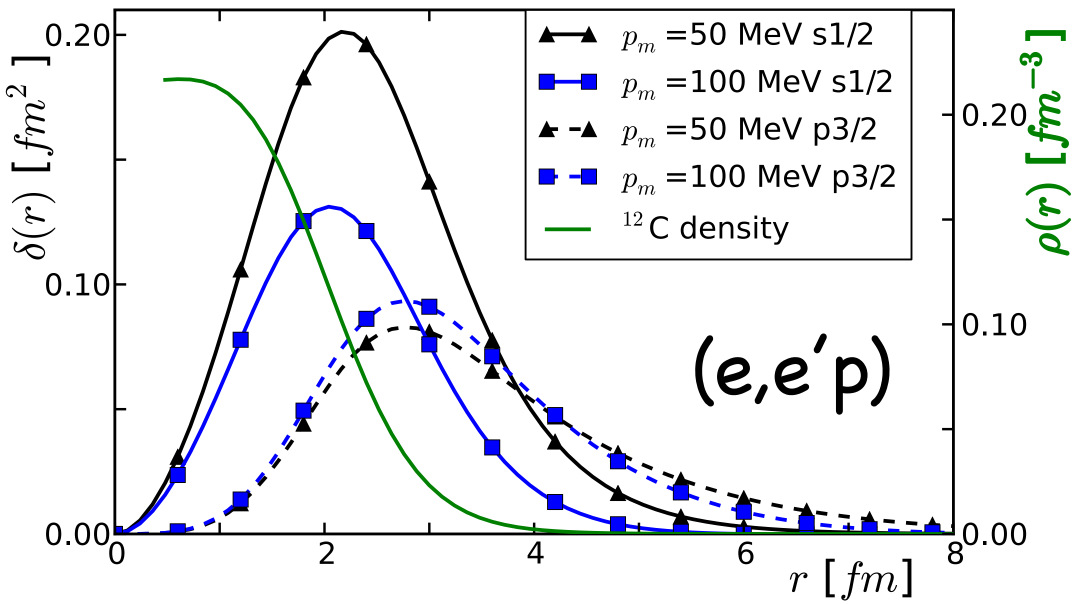
- Polarization-transfer data effectively described by in-medium electromagnetic form factors or charge-exchange FSI.
- For $Q^2 \geqslant 1.3$ (GeV/c)^2 Madrid RDWIA and Schiavilla (2010) results seem to agree.
- Additional data needed
- **E11-002** will measure one new high-precision data point of the ^{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?

Measurement of the $^{12}C(e,e'p)$ Reaction: A Powerful Extension of E11-002



- 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.

S-Shell Knockout Probes High Nuclear Densities in ^{12}C



G. Ron, W. Cosyn, E. Piasetzky, J. Ryckebusch, and J. Lichtenstadt, Phys. Rev. C **87**, 028202 (2013).

Reaction	Orbit	$\Delta\rho$ (fm)
(e,e'p)	$s_{1/2}$	0.086
(e,e'p)	$p_{3/2}$	0.038
(p,2p)	$s_{1/2}$	0.055
(p,2p)	$p_{3/2}$	0.025

$E_{kin}(p)$ = 1.5 GeV; Wim Cosyn and Jan Ryckebusch, Phys. Rev. C**80**, 011602(R) (2009)

To probe
highest densities …

$\Longrightarrow$

- s-shell knockout
- (e,e'p) or (γ,pp)
- high missing momentum

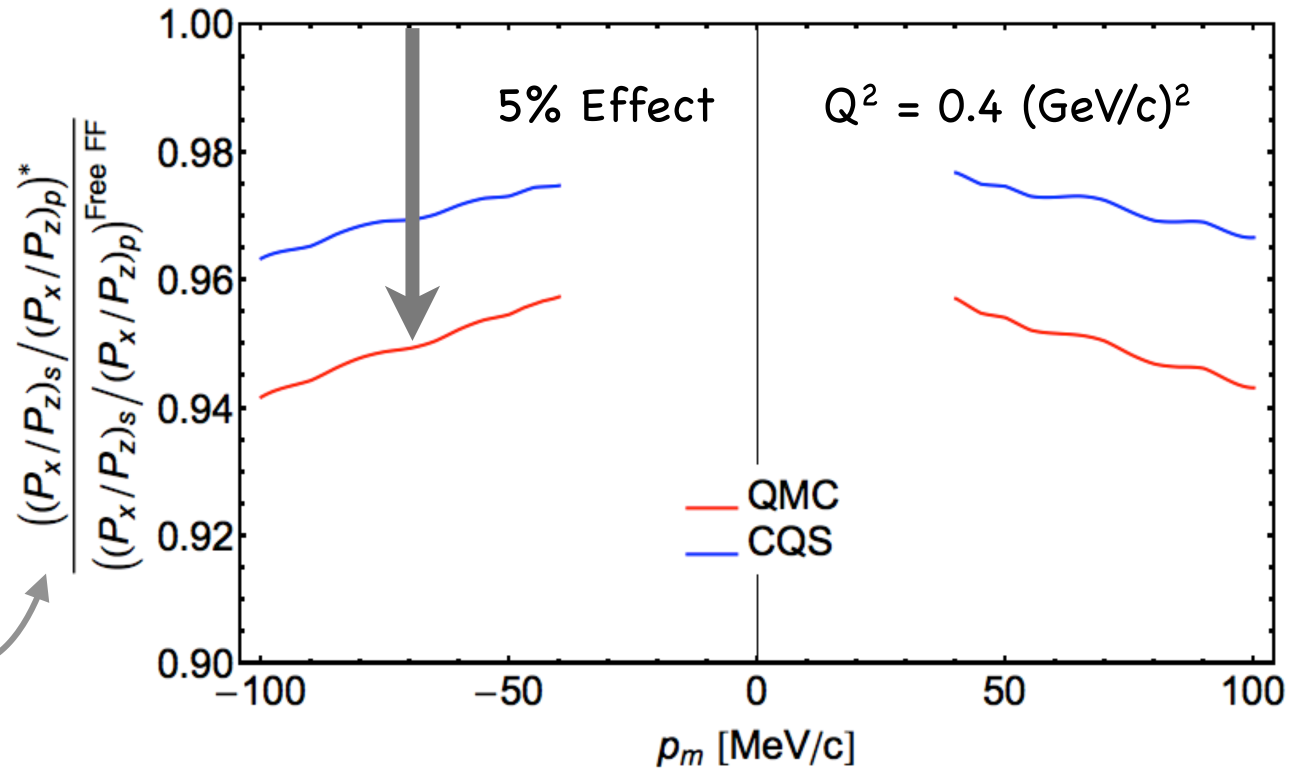
Proposed $^{12}C(e,e'p)$ Experiment at MAMI

Expected data:

Four pm bins
with 1-2%
uncertainty.

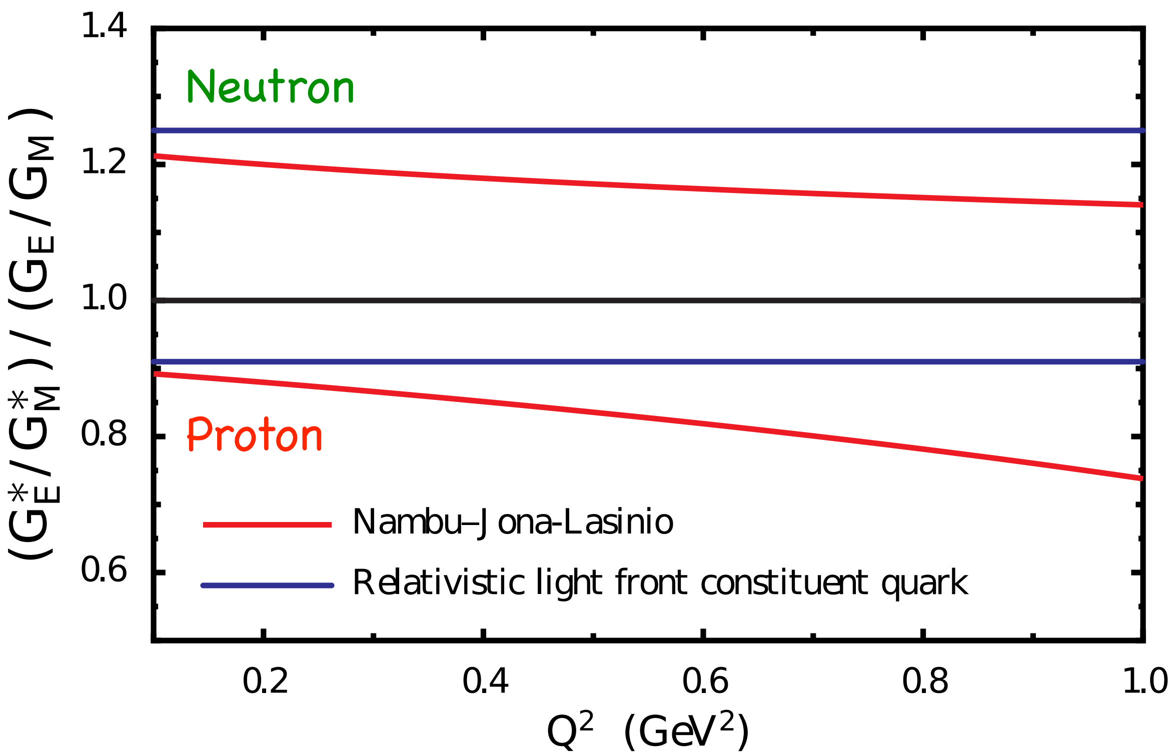
The super double ratio helps suppressing experimental and theoretical uncertainties

P'x/P'z s-shell over p-shell



G. Ron, W. Cosyn, E. Piasetzky, J. Ryckebusch, and J. Lichtenstadt, Phys. Rev. C **87**, 028202 (2013).

Neutron in the Nuclear Medium



Neutron: ≈ +20%

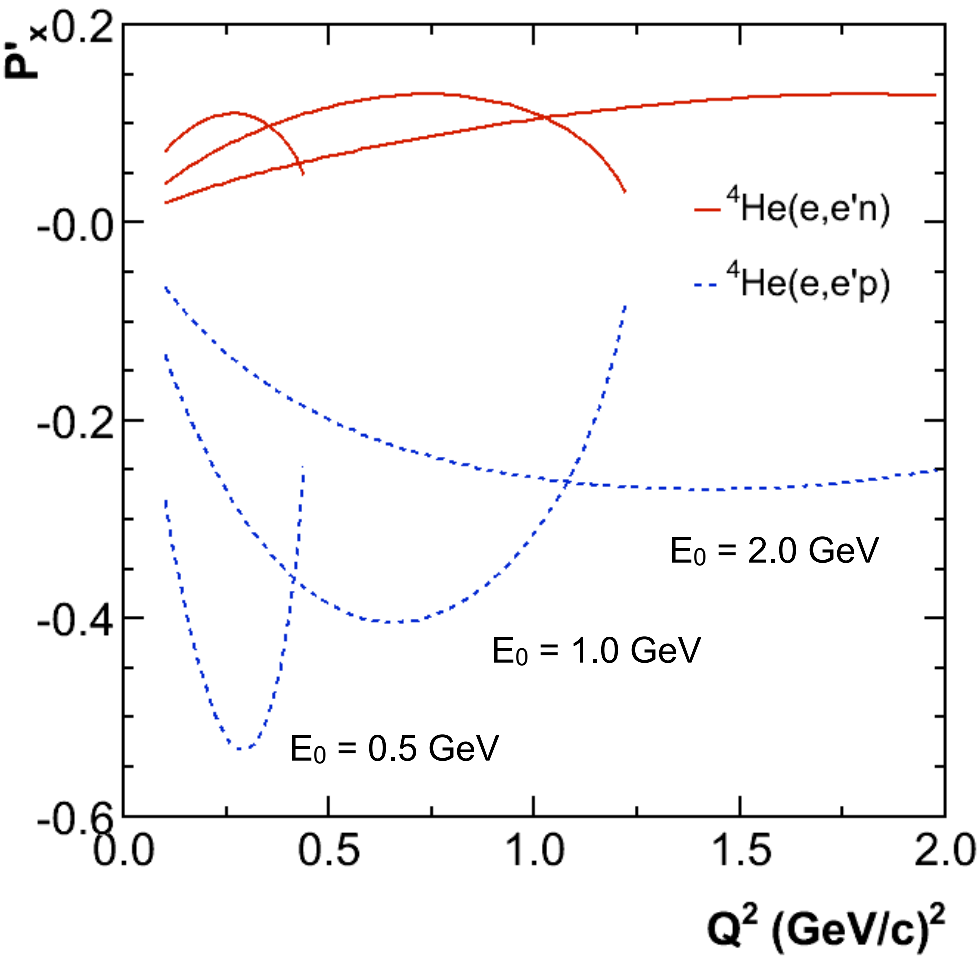
Proton: ≈ -10%

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

- 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

Summary

Reaction	Observable	Medium effect	Driving parameter
$(e,e')_{DIS}$	σ_A	depletion of the nuclear structure function F_2	local density; (indirect) proton momentum
$(e,e'p)_{QE}$	P'_x/P'_z	depletion of the polarization-transfer ratio, G_E/G_M(?)	proton virtuality (?)
$(p,pp)_{QE}$	P_1, P_2, C_{ij}	depletion of proton polarization; p-p scattering matrix(?)	proton (s-shell) binding energy

New experiments and plans:

- ^{4}He, ^{2}H, ^{1}H(e,e′p): large p_m and high Q^2; **virtuality**, [JLab, E11-002]
- ^{12}C(e,e′p): s-shell knockout, **high density**, high virtuality
- ^{4}He, ^{2}H(e,e′n): **neutron** medium modifications