# Probing Bound Nucleons in $^4He$ and $^2H$

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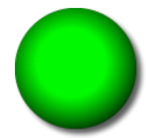
# Nucleons are Modified in the Nuclear Medium

- 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!

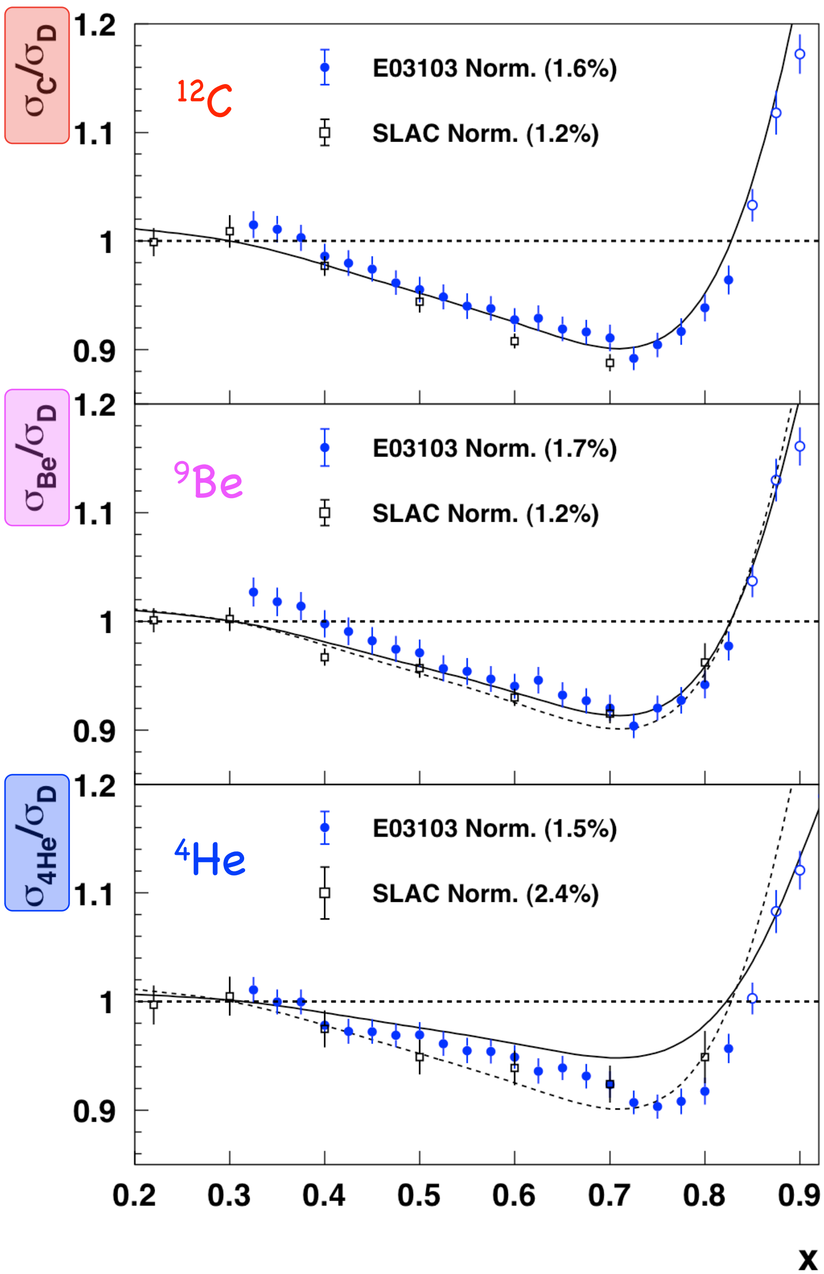
**In-Medium Life Time**



Free neutron:
$\tau_n$ = 15 min

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

# EMC Effect in Very Light Nuclei




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

● New JLab Hall-C measurements

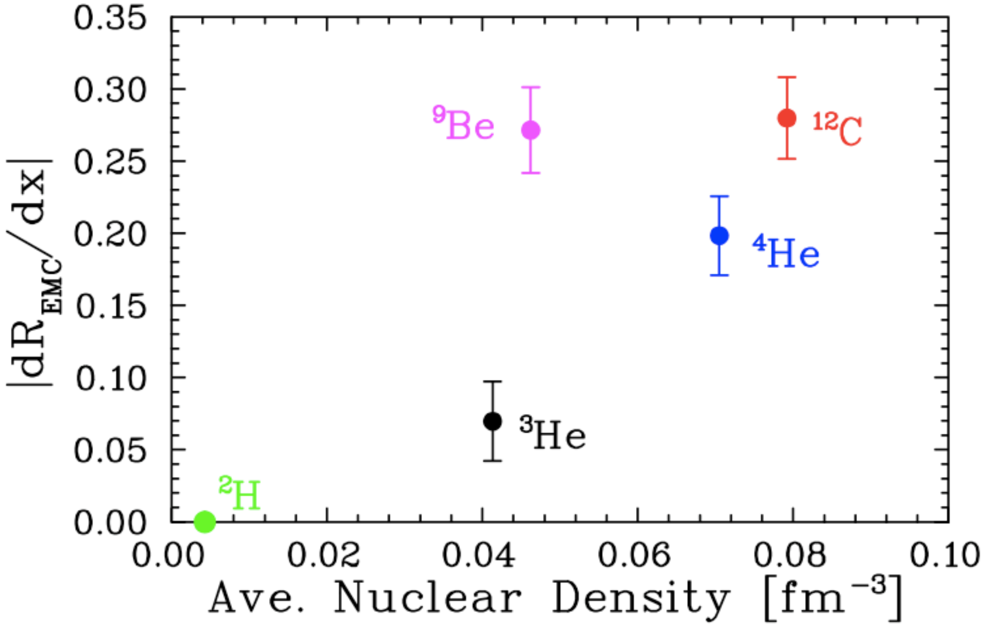
——— A-dependent fit to SLAC data

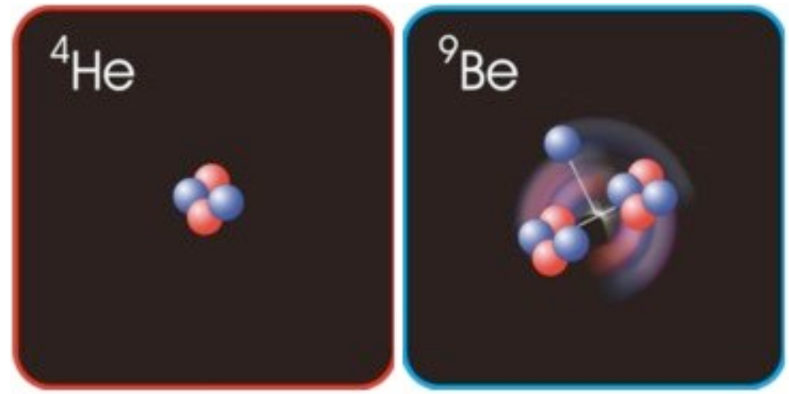
- - - - - Fit to $^{12}C$ data

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

# EMC Effect in Very Light Nuclei

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

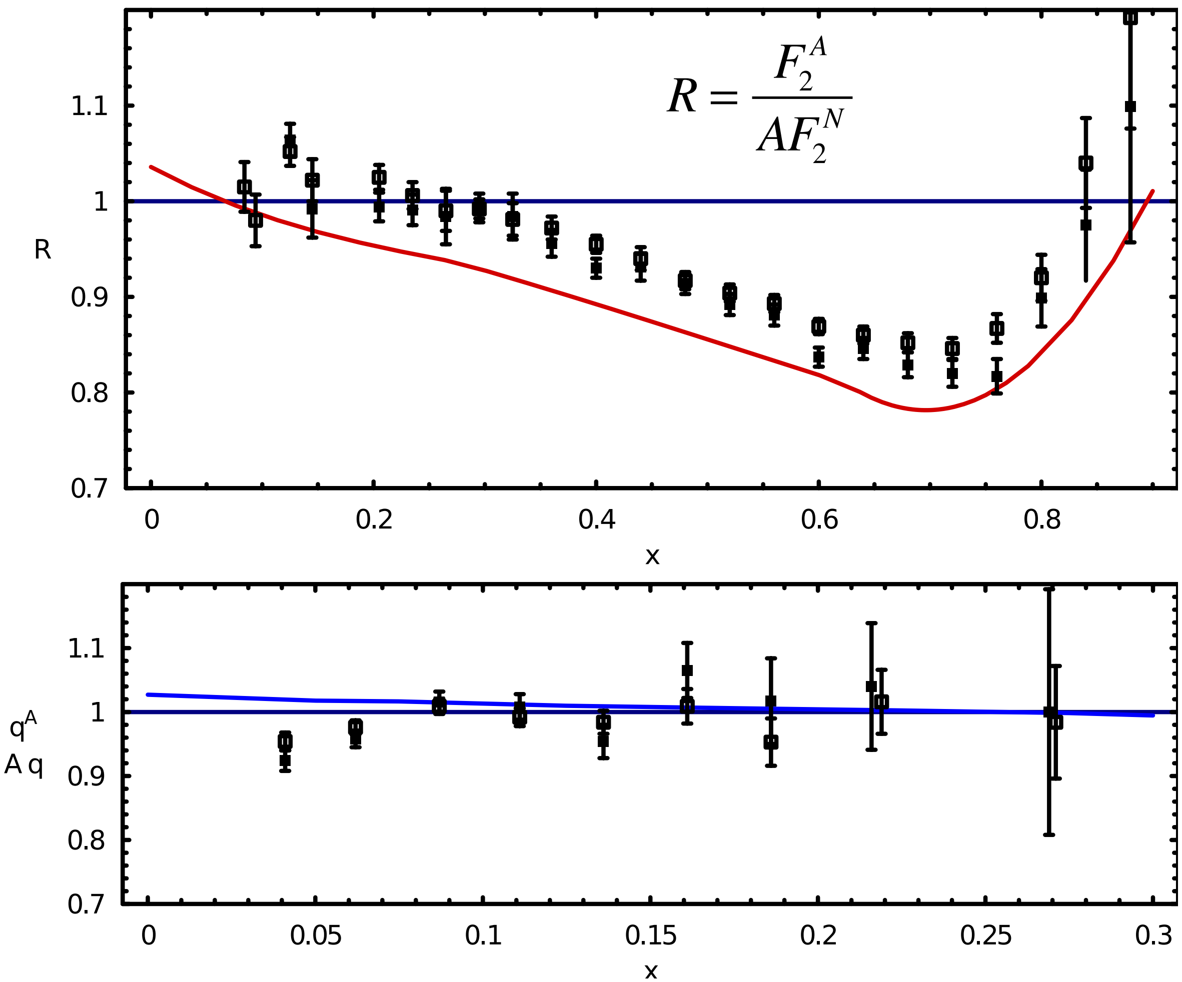



- Nuclear effects in $^4$He, $^9$Be (= 2α+n) comparable to effect in $^{12}$C
- Data suggest that **local** density drives the modification

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

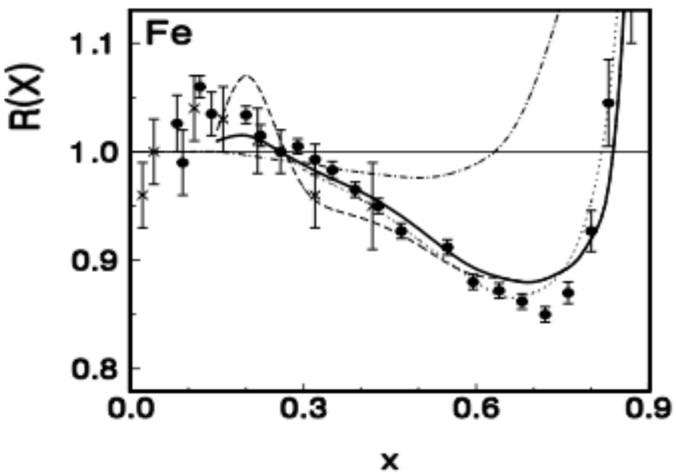
# Chiral Solitons in Nuclei

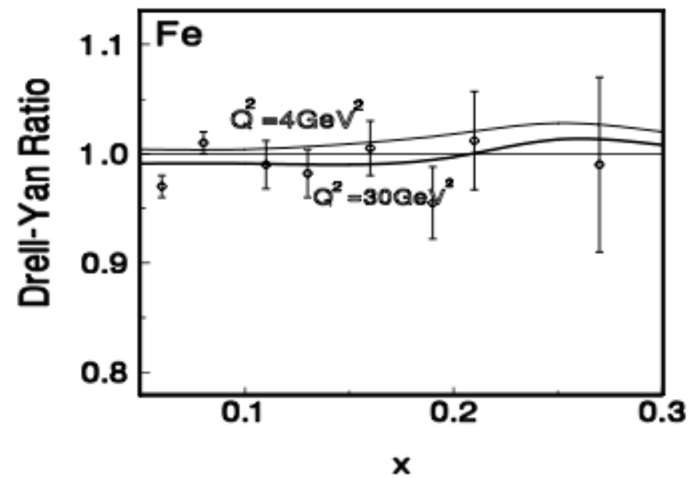



- The CQS model consistent with free nucleon properties, nuclear saturation properties, EMC effect, Drell-Yan experiments
- Medium induced increase of nucleon radius = 2.4%; consistent with A(e,e′p) limit of < 6%.
- EMC Effect is **not** due to conventional nuclear physics.
- Relativistic, quark-level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

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

# Modification of In-Medium Nucleon Rest Mass



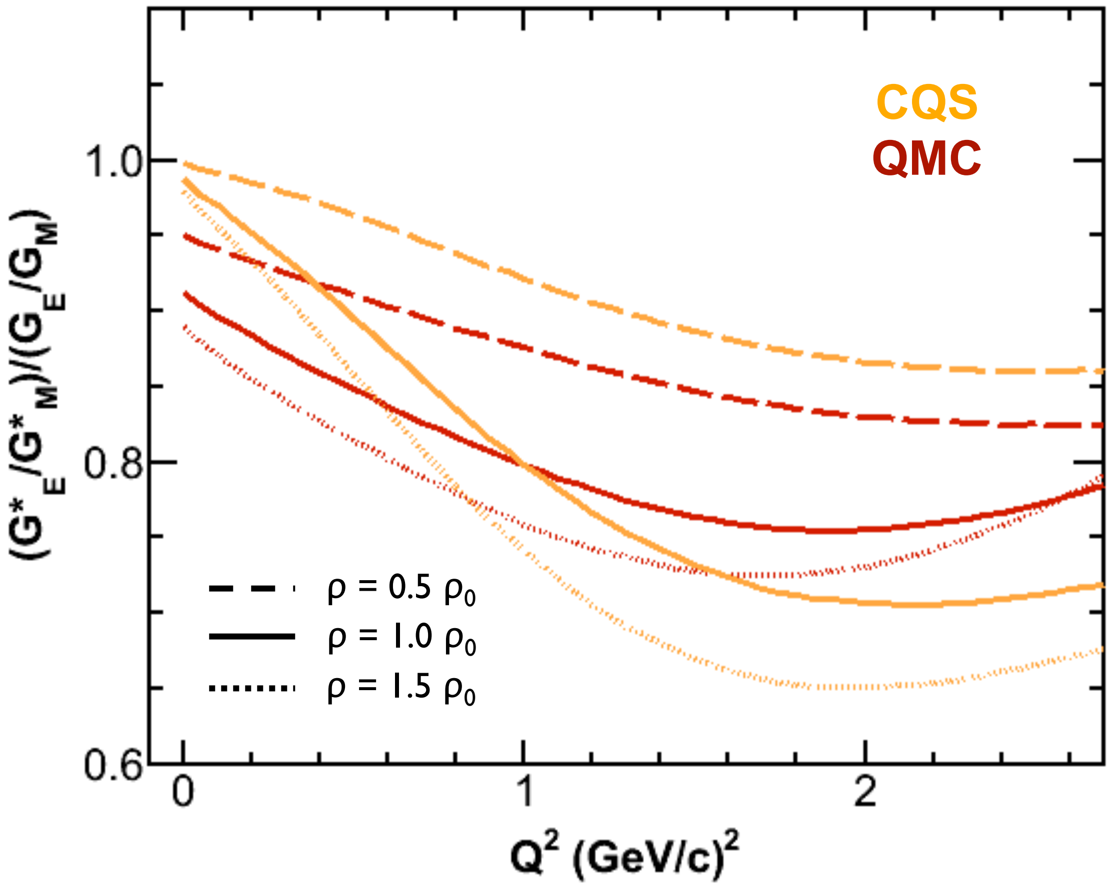

- Account for the EMC effect in DIS on nuclei by using the single particle approach with effective Fermi motion caused by nuclear interactions, which is also responsible for medium changes of the parton distributions inside nucleons.

- The nucleon rest energy is modeled by introducing x-dependent effective nucleon rest energy (nucleon mass) $M_x$
  - for $x > 0.6$: $M_x = M_N - (20 \div 30)$ MeV
  - for $x < 0.25$: $M_x = M_N$

J. Rozynek and G. Wilk, Phys. Rev. C **71**, 068202 (2005)

X

# In-Medium Form Factors




**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:

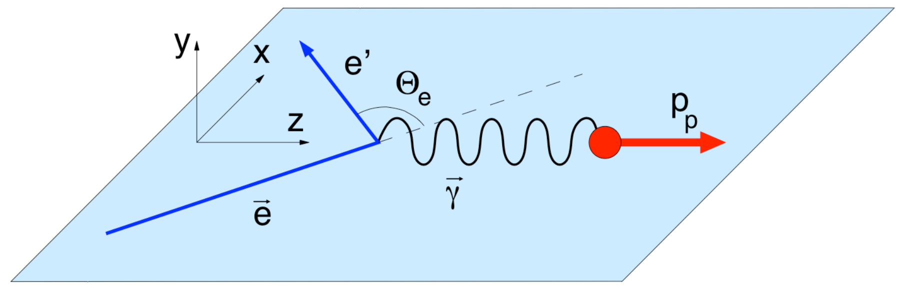
  Chiral Quark Soliton (CQS), Quark Meson Coupling (QMC), Skyrme, Nambu-Jona-Lasinio (NJL), GPD Models.
- Model predictions:
  - are density and $Q^2$ dependent,
  - show similar behavior,
  - consistent with experimental data (within large uncertainties).

# Polarization-Transfer Observable

One of the most intuitive methods to investigate the properties of nucleons inside nuclei is quasi-elastic scattering off nuclei.

## Free proton

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




- 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)

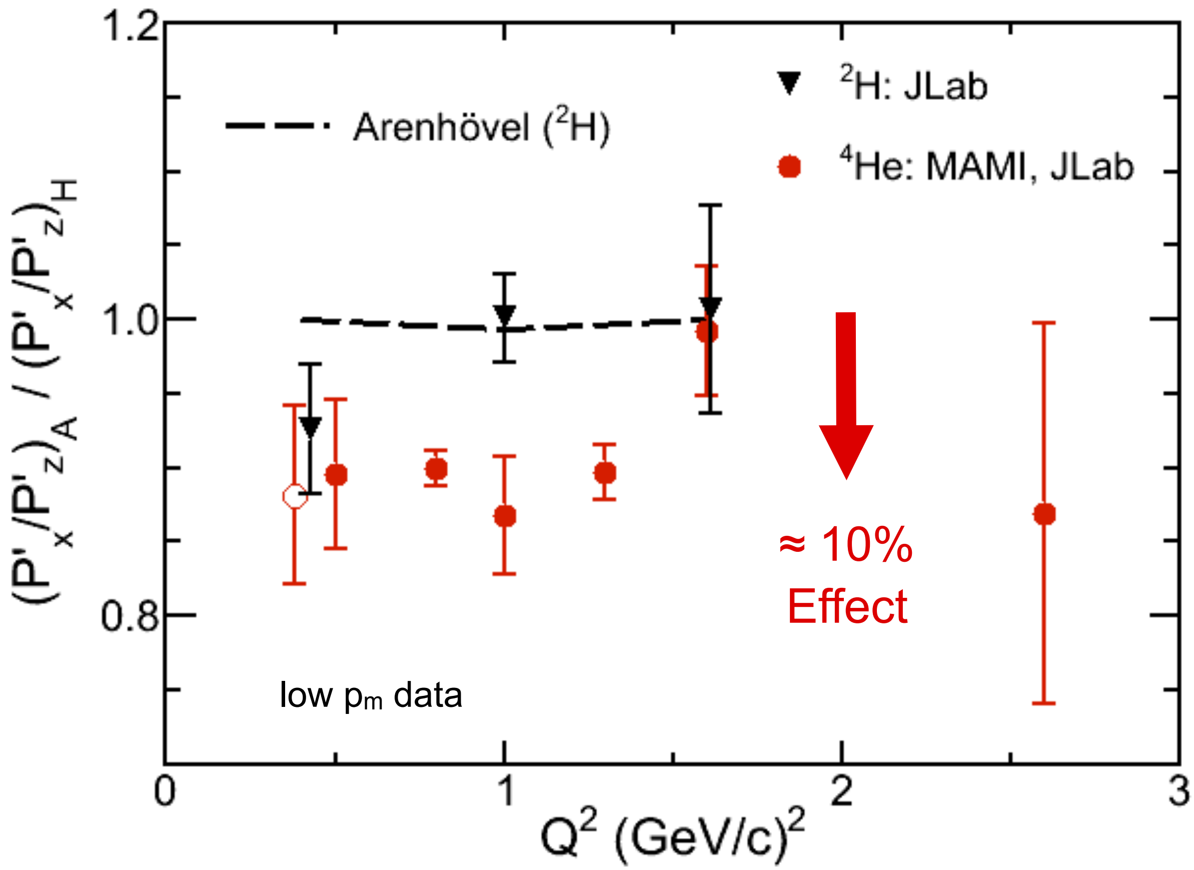
R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981)

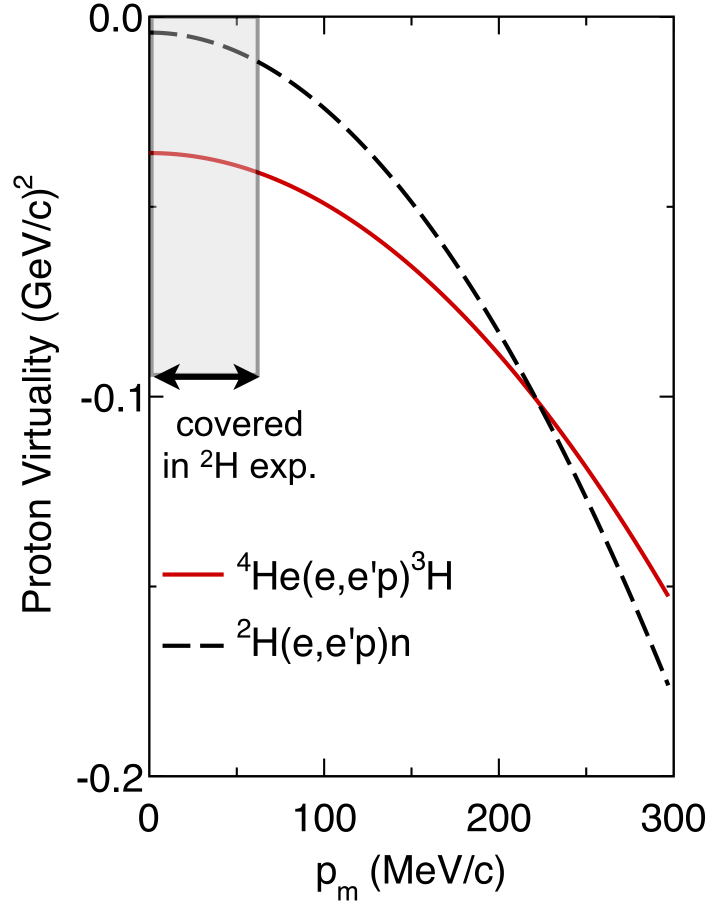
## Bound proton

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

- Compare quasi-elastic and free-proton scattering to study possible medium effects
- Bound nucleon data need evaluation within model
- Reaction-mechanism effects predicted to be small and minimal for quasi-elastic scattering at small missing momentum

# $^4$He, $^2$H, $^1$H Polarization-Transfer Double Ratios

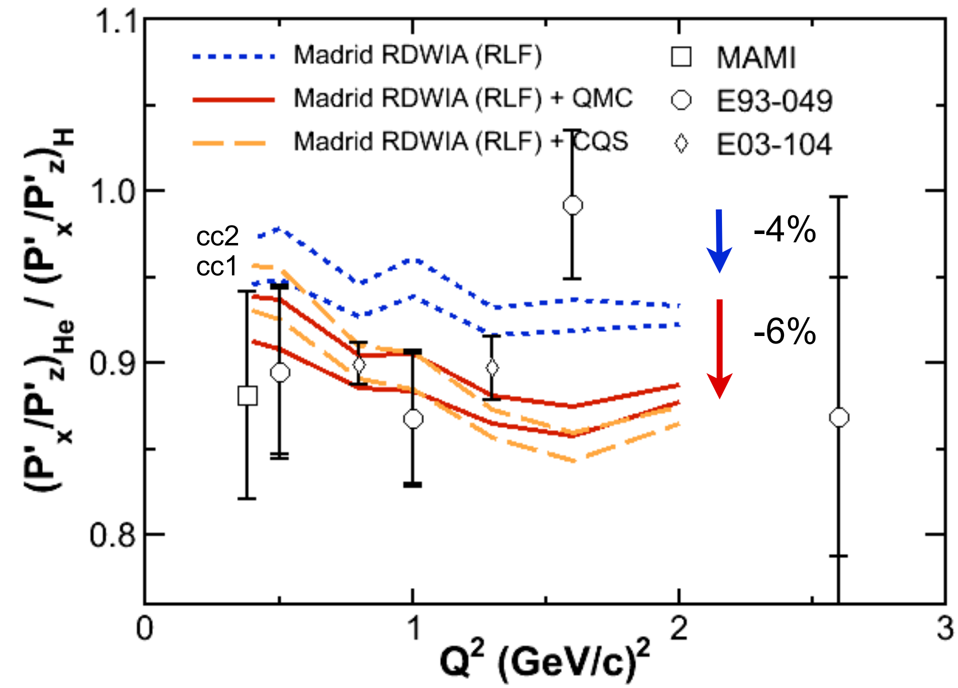


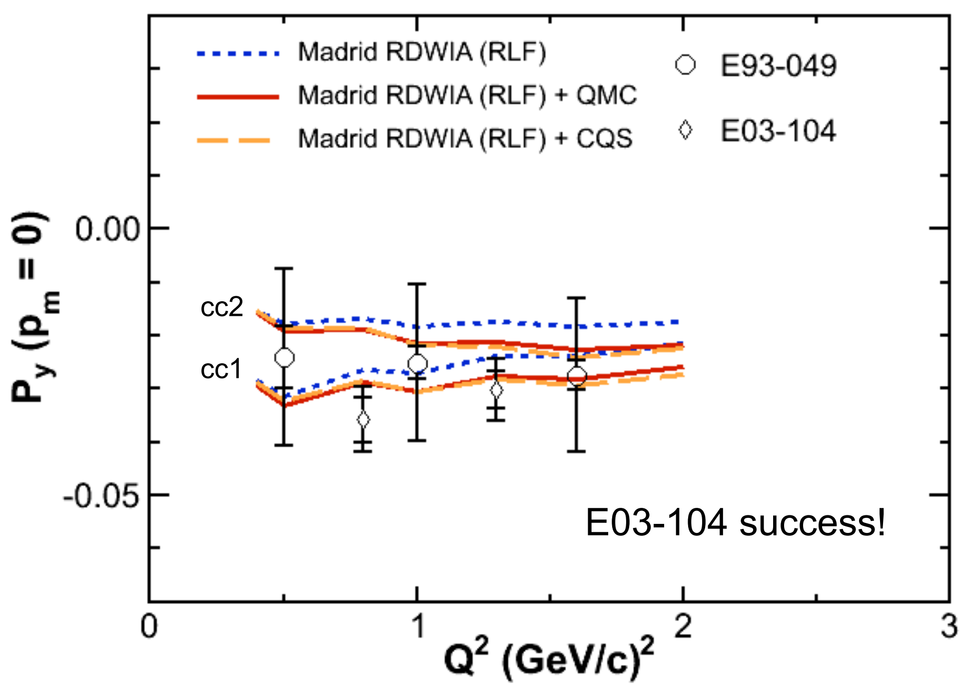




- $^2$H and $^1$H polarization-transfer data are similar
- $^4$He data are significantly different than $^2$H, $^1$H data

- **What generates the large medium effect?**
  - the nuclear density or
  - the larger proton virtuality probed in the $^4$He experiments?


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



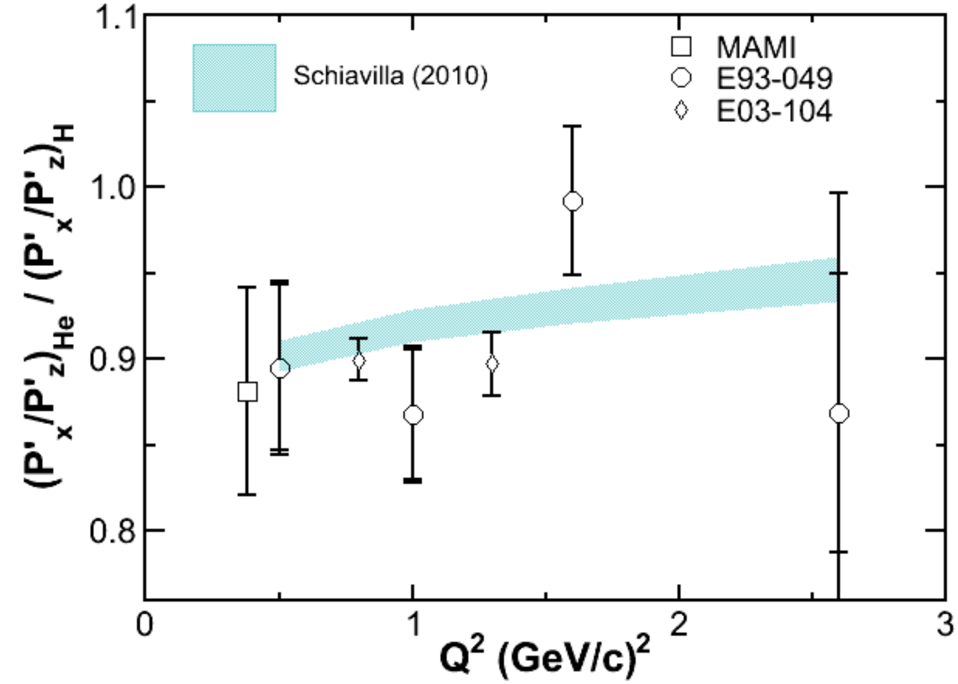



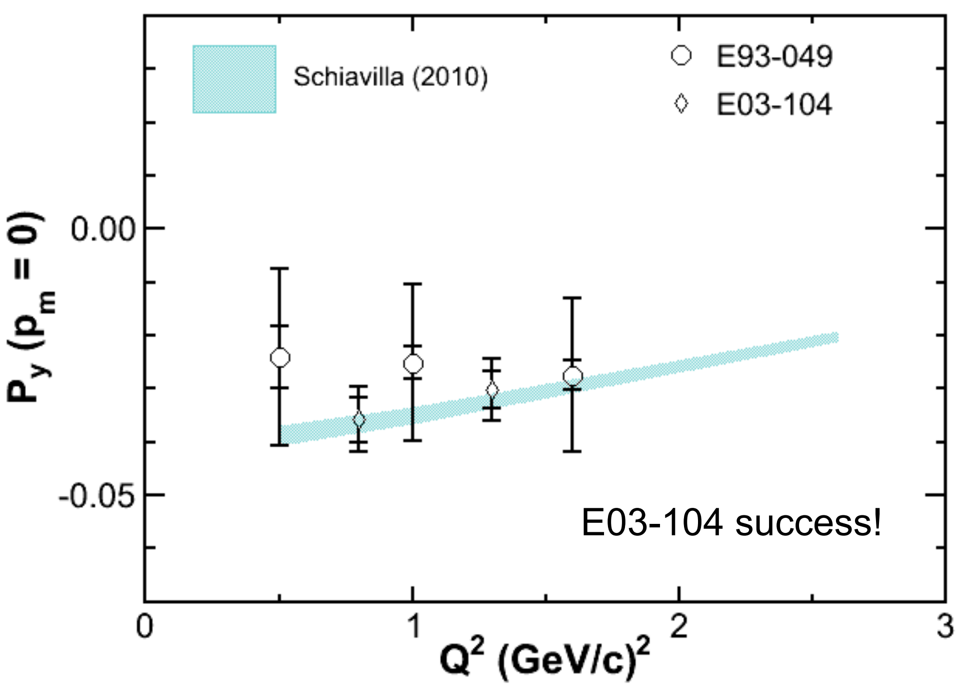

# Madrid RDWIA

- Relativistic calculation in distorted-wave impulse approximation **(RDWIA)** overestimates R
- Density-dependent in-medium form factors were evaluated at the local density $\rho(r)$

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

- 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



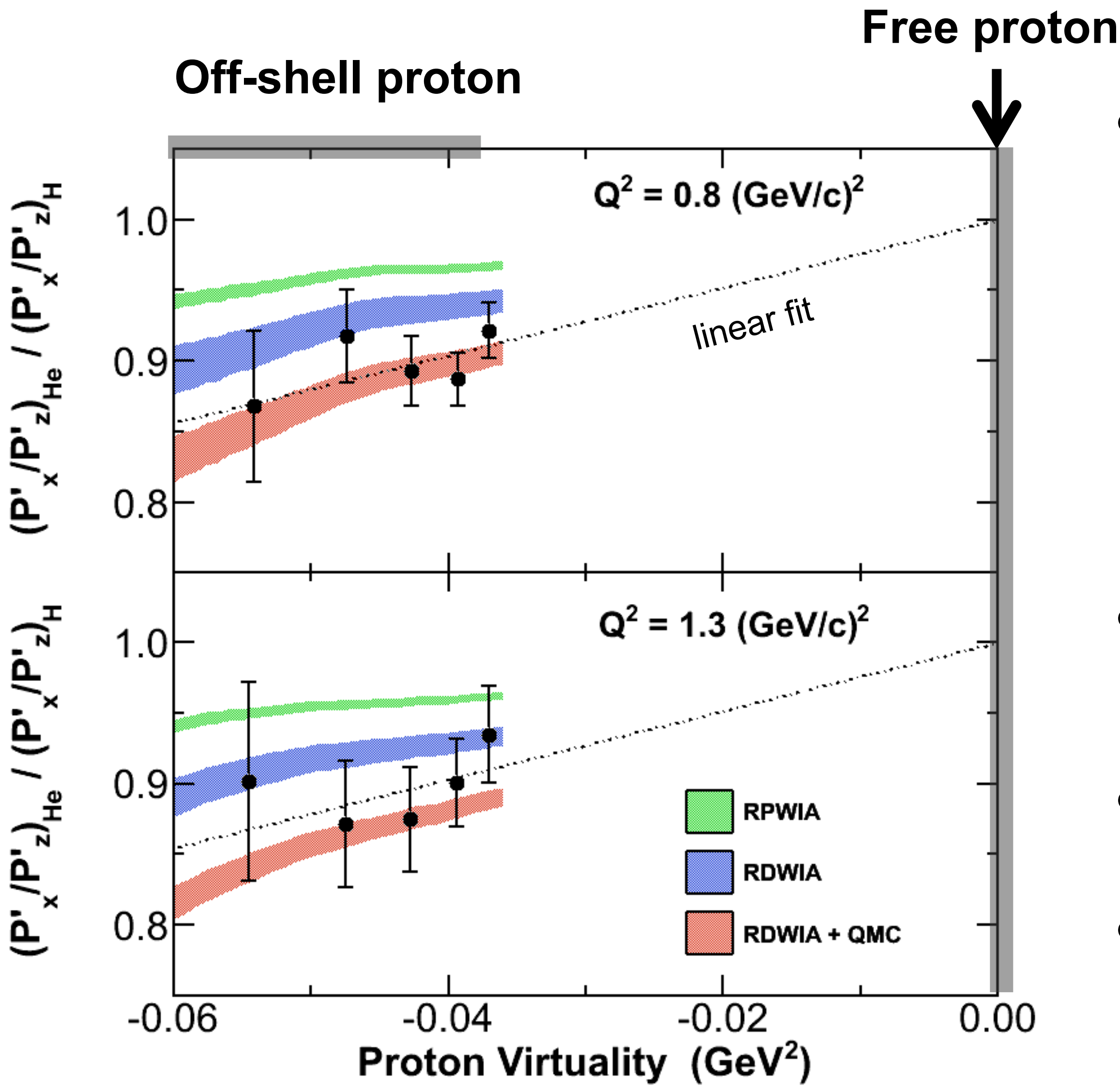

# Schiavilla (2010)

- 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 independent 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.

# Proton Virtuality: E03-104 Data




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

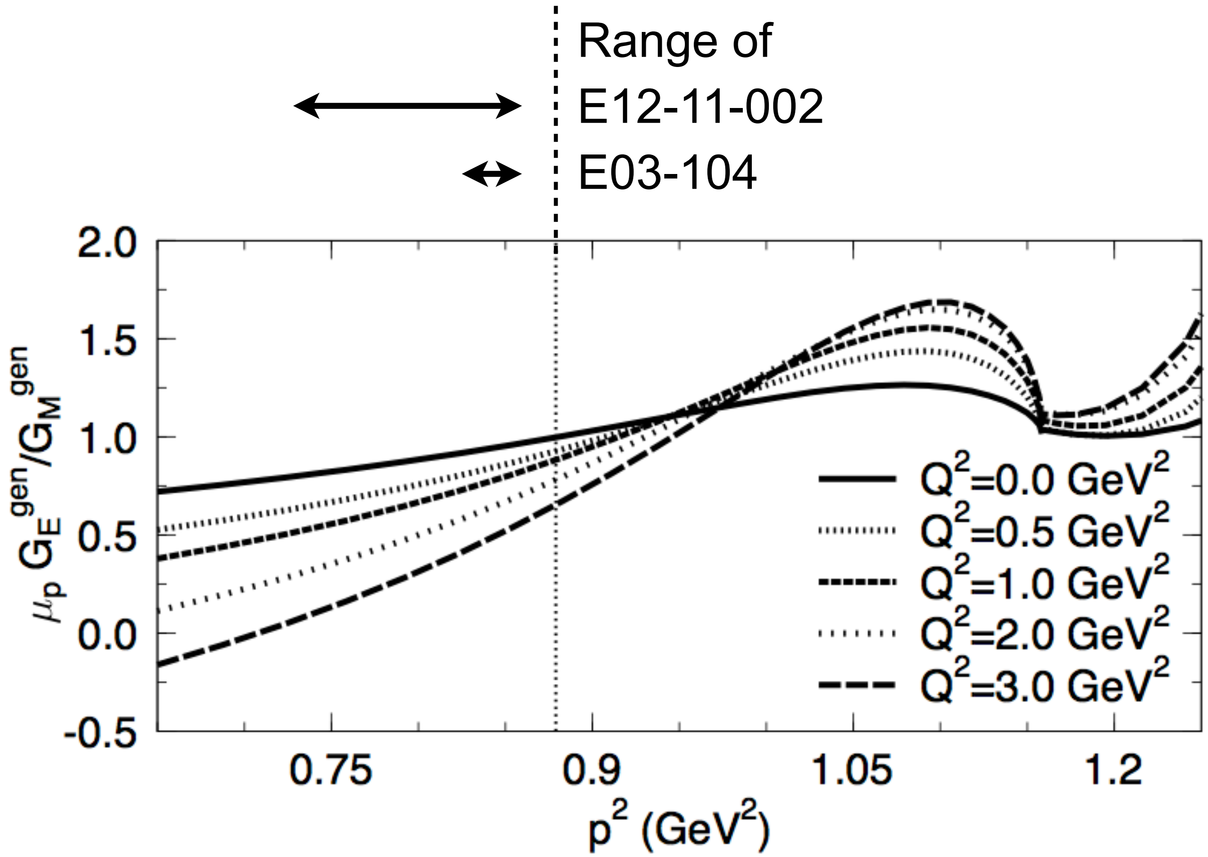
$$v = p^2 - m_p^2$$

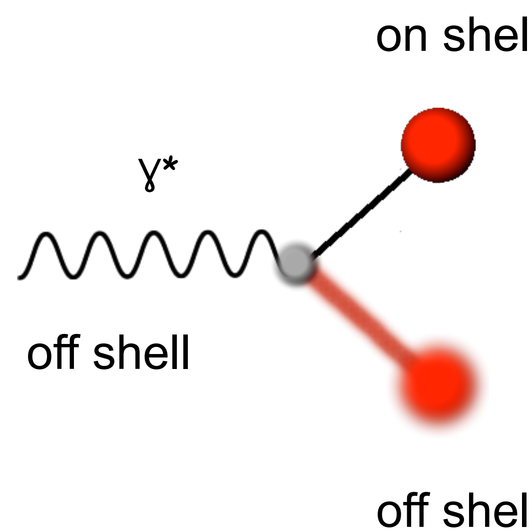
with the trend of $R \approx 1$ for $p^2 = m_p^2$; as it should be.

- Good description of E03-104 data with the RDWIA + QMC (in-medium form factors) model.
- Measuring at low $p_m$ minimizes medium effect.
- Increase of medium effects at large proton virtualities (momenta); 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)

# Form Factors in the Dressed γNN Vertex

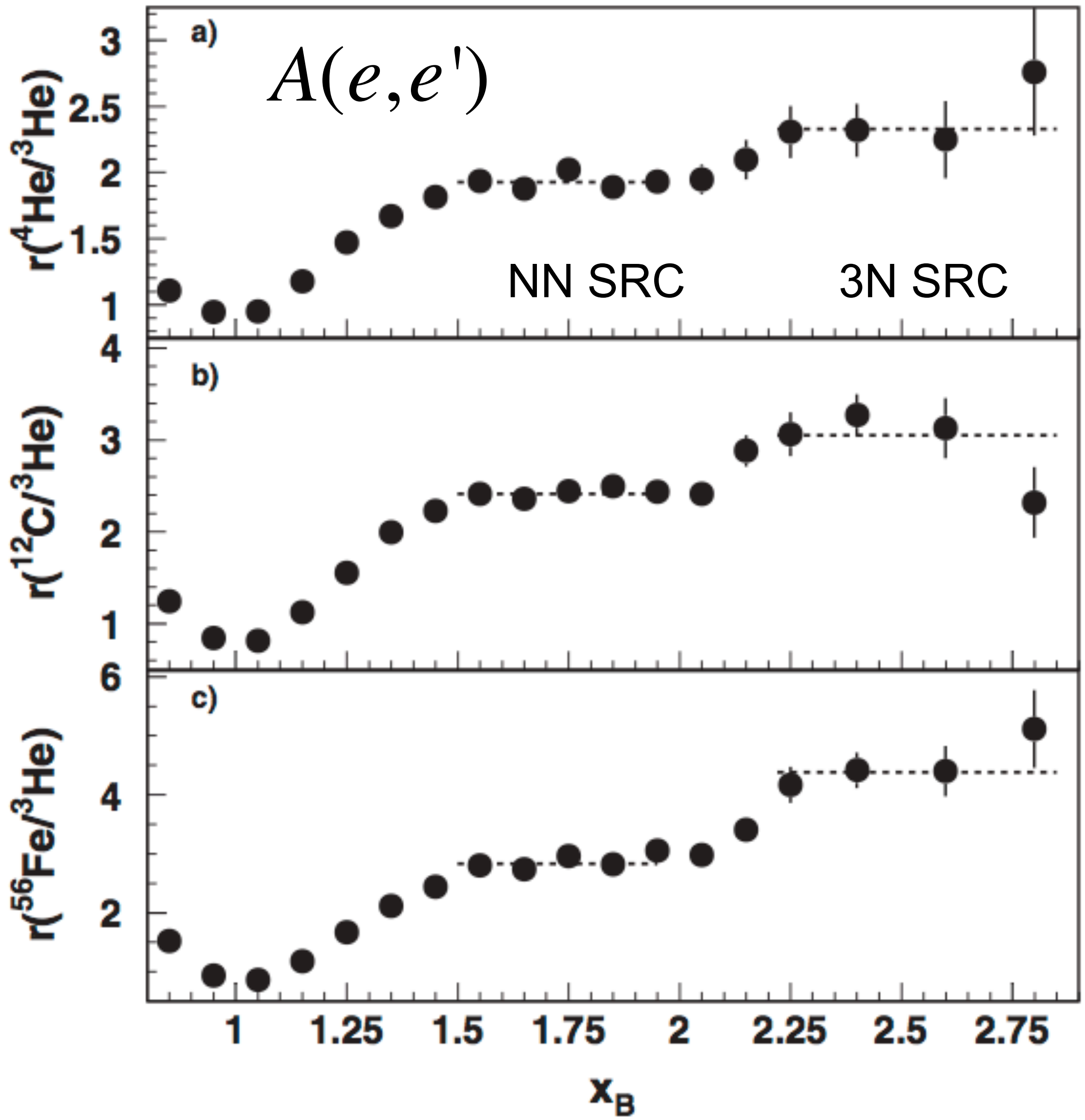



- Dressed K-Matrix model: dressing the bare vertex with an infinite number of meson loops (π, ρ, σ mesons)

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

# Two- and Three-Nucleon Short-Range Correlation Probabilities in Nuclei




- SRC result in universal shape of the nuclear wave function for all nuclei at $k > k_F$.
- Ratios of inclusive cross sections as a function of $Q^2$ and $x_B$
- The experimental ratios show scaling, which, because of its small A dependence, must be a distinctly **local nuclear phenomenon**.
- The ratios of the per-nucleon SRC probabilities, $a_2(A/^3He)$, and $a_3(A/^3He)$, are just the values of the ratio r in the appropriate scaling region

K. S. Egiyan et al, Phys. Rev. Lett. **96**, 082501 (2006)

# Momentum Dependence of the EMC Effect

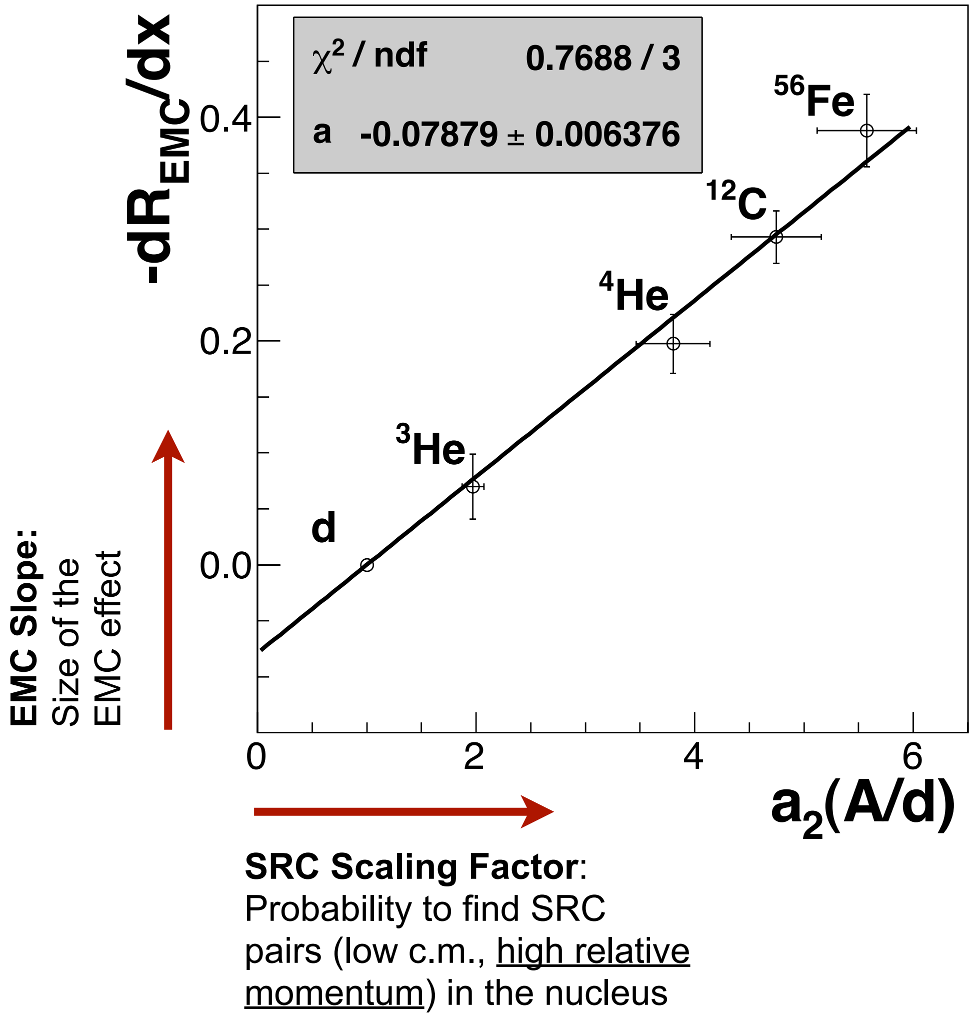



Figure from: L.B. Weinstein et al., Phys. Rev. Lett. **106**, 052301 (2011)

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

- Ciofi degli Atti et al. argue that the EMC effect is due to the virtuality of the nucleons and is approximately proportional to their kinetic energy.
- The observed EMC-SRC linear correlation supports the hypothesis that the EMC effect is mainly associated with the nucleons at high virtuality.
- **E11-002** will test with $^4He(e,e'p)$ and $^2H(e,e'p)$ data at high proton virtuality if medium effects in previous polarization-transfer measurements depend on:
  - nucleon momentum, off-shellness (virtuality), or
  - mean nuclear density.

# New Experiment E11-002

- Investigation of the role of nuclear medium modifications.
- Proton recoil polarization in quasielastic (e,e'p) is the observable of choice.

$$^{4}\mathrm{He},\ ^{2}\mathrm{H},\ ^{1}\mathrm{H}(\vec{e},e'\vec{p})$$

| | Key features | Impact |
|---|---|---|
| 1 | Wide coverage of proton virtualities at $Q^2 = 1.0\ (\mathrm{GeV/c})^2$ | • Study the momentum (virtuality) dependence of nucleon medium effects |
| 2 | $^4$He, $^2$H, and $^1$H targets | • Study the density dependence of nucleon medium effects<br>• State of the art RDWIA and microscopic calculations are available and will be constrained |
| 3 | High-precision data point of the proton recoil polarization in $^4\mathrm{He}(e,e'p)^3\mathrm{H}$ at $Q^2 = 1.8\ (\mathrm{GeV/c})^2$ | • Compare free and bound proton recoil polarization where model calculations predict largest sensitivity to effect of in-medium form factors |

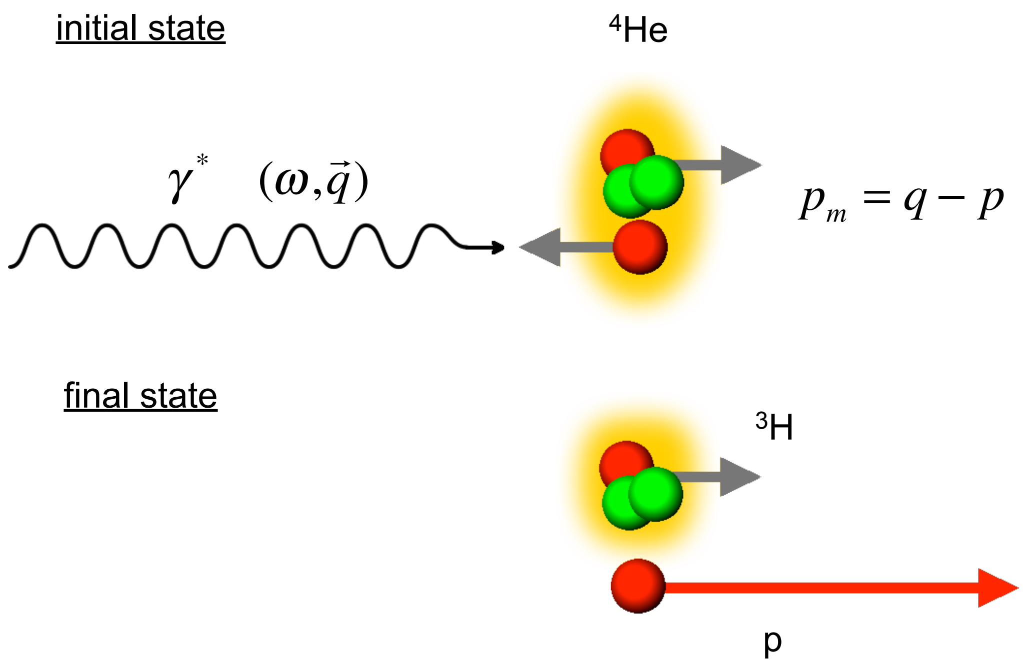
# E11-002: Kinematics

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

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

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

- Nucleon virtuality is a function of the nucleon momentum **only**.

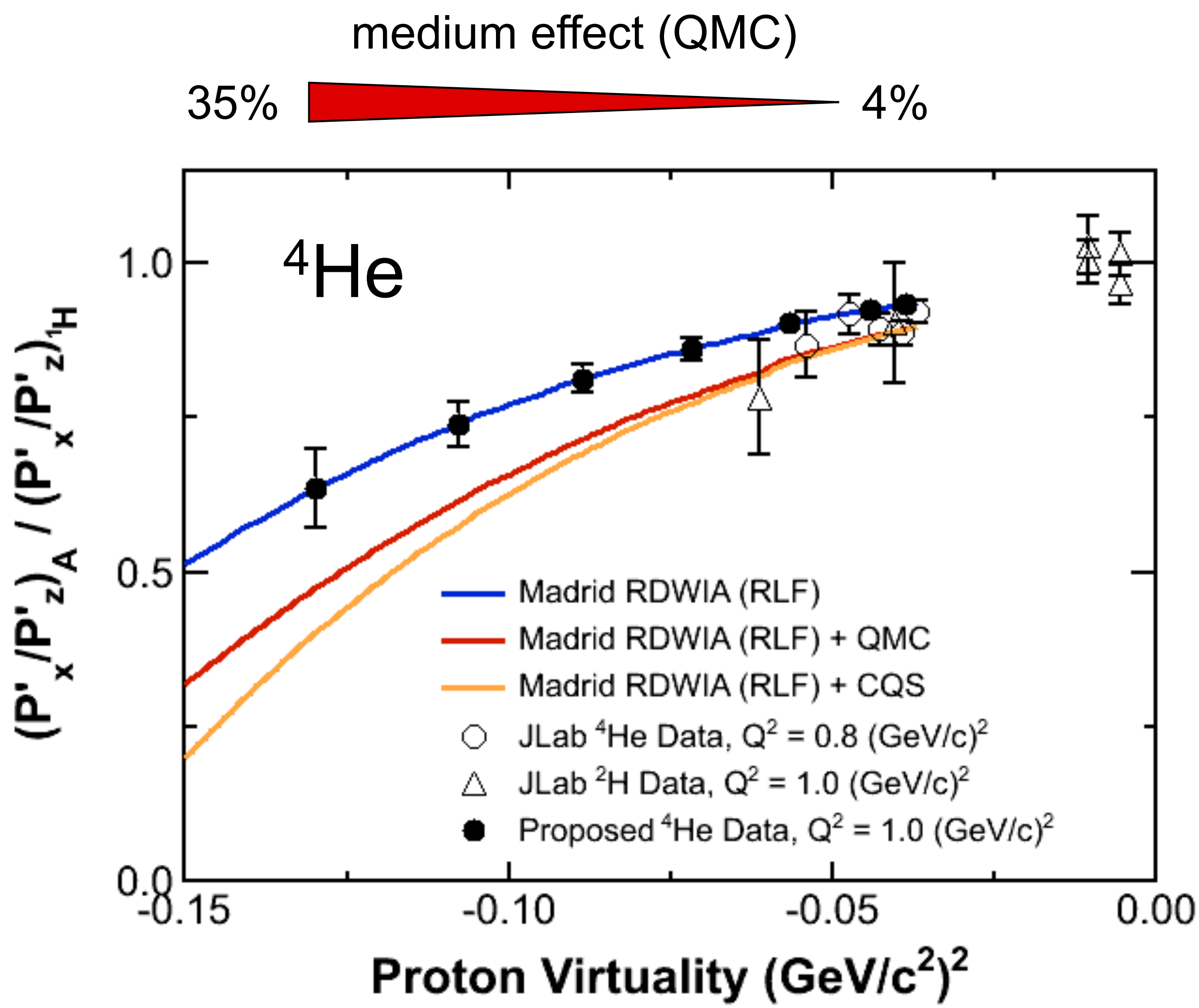



| $Q^2$ $(GeV/c)^2$ | $p_m$ (MeV/c) | Targets |
|---|---|---|
| 1.0 | 0, +140, +220 | $^4$He, $^2$H, $^1$H |
| 1.8 | 0 | $^4$He, $^1$H |

*M. Sargsian, private communication

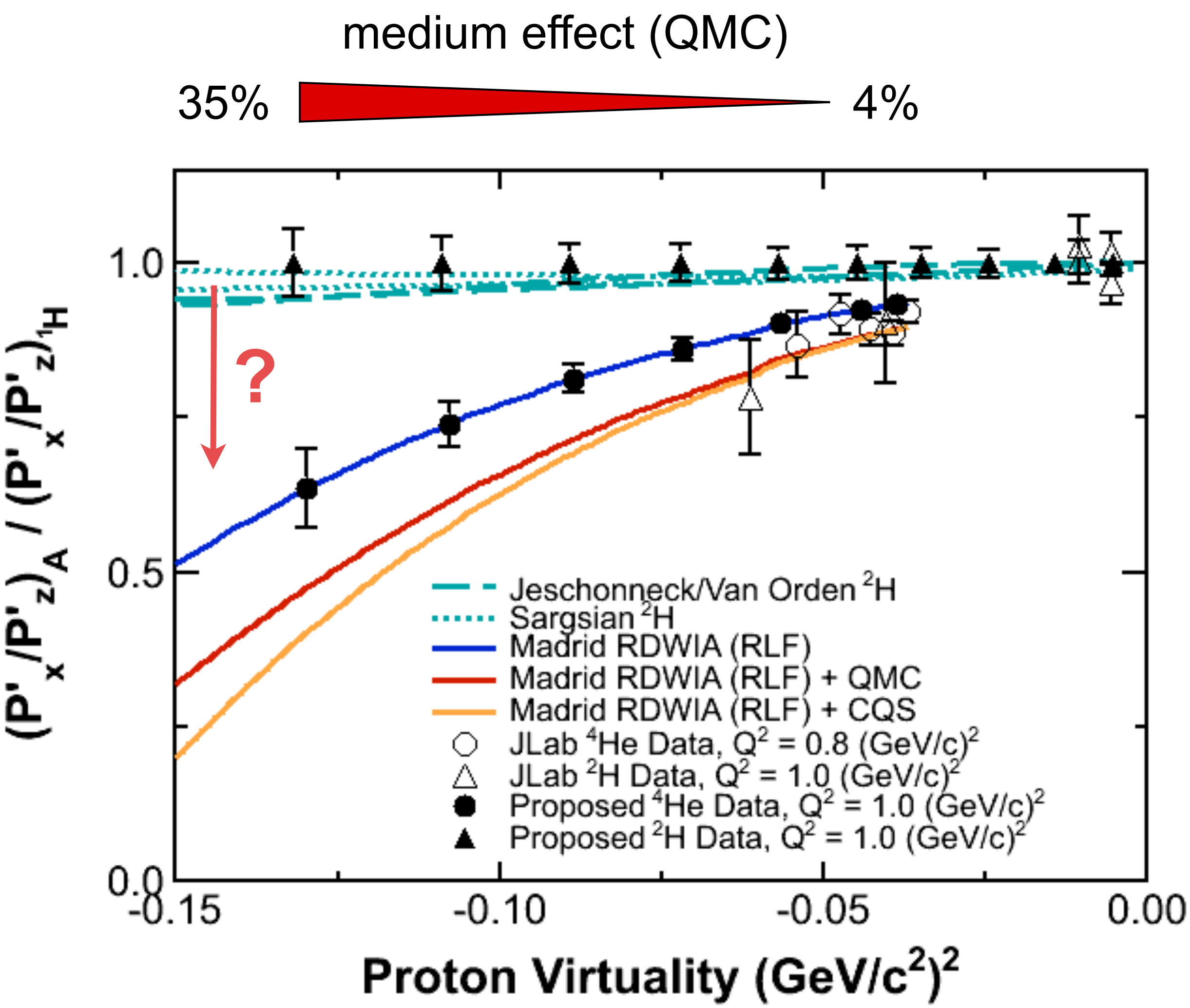
C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)

# $1^{st}$ 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 (○).

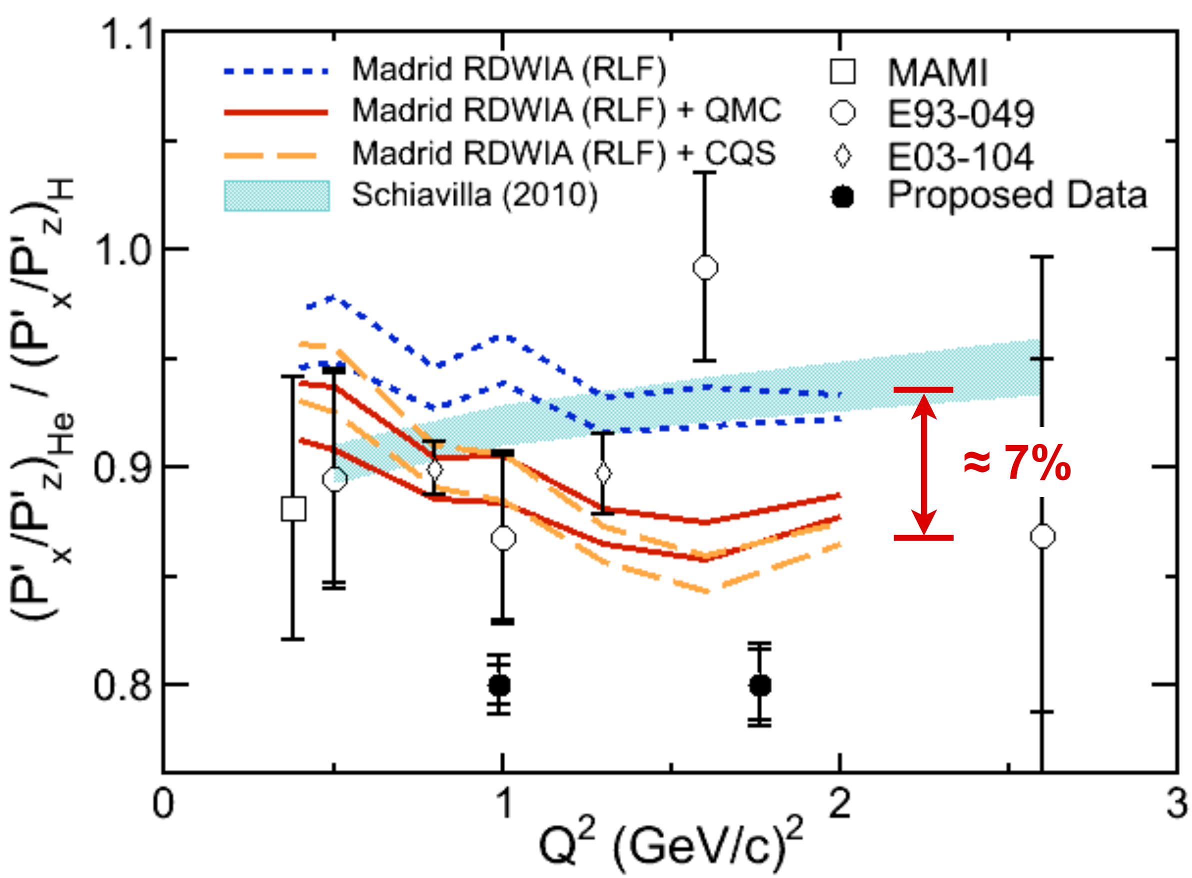
# $2^{nd}$ Feature of E11-002




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)

- **E11-002**:
  Compare proton knock-out from dense and thin nuclei: $^4He(e,e'p)^3H$ and $^2H(e,e'p)n$
- Modern, rigorous $^2H(e,e'p)n$ calculations including rescattering effects available.
  - SAID parameterization for of the full NN scattering amplitude
  - 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 …

# $3^{rd}$ Feature of E11-002




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

# Protons and Neutrons in the Nuclear Medium

- At small values of $Q^2$

$$G_{Ep}(Q^2) = 1 - \frac{1}{6} Q^2\, \hat{R}_{Ep}^2 + \ldots$$

$$\frac{1}{\mu_p} G_{Mp}(Q^2) = 1 - \frac{1}{6} Q^2\, \hat{R}_{Mp}^2 + \ldots$$

- Form factor ratios at small values of $Q^2$

$$\mathcal{R}_p \equiv \frac{G_{Ep}(Q^2)}{G_{Mp}(Q^2)} \simeq \frac{1}{\mu_p}\left[1 - \frac{1}{6} Q^2 (\hat{R}_{Ep}^2 - \hat{R}_{Mp}^2)\right]$$

$$\mathcal{R}_n \equiv \frac{G_{En}(Q^2)}{G_{Mn}(Q^2)} \simeq -\frac{1}{\mu_n} \frac{1}{6} Q^2\, \hat{R}_{En}^2$$

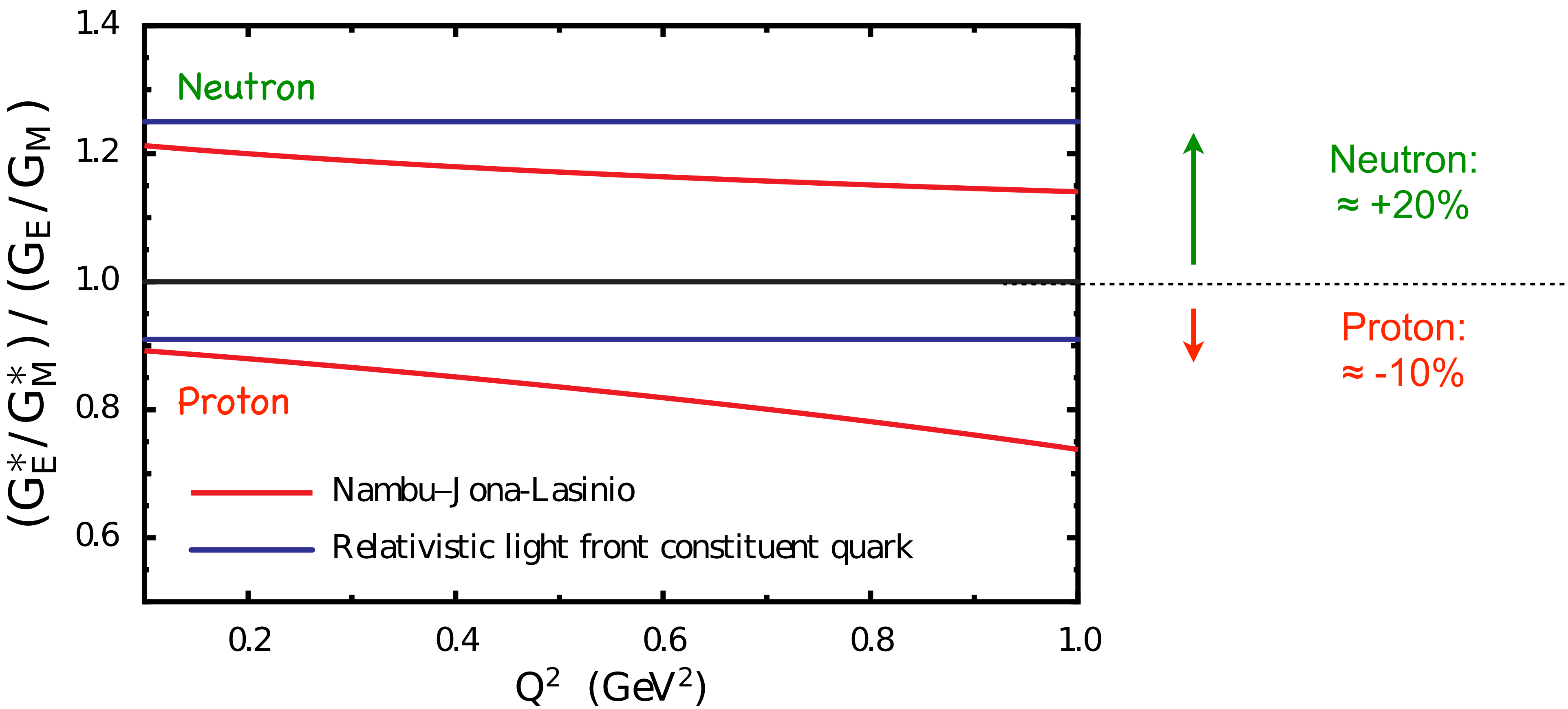
- Predictions for medium modifications

$$\mathcal{R}_p^* / \mathcal{R}_p < 1$$

$$\mathcal{R}_n^* / \mathcal{R}_n > 1$$

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

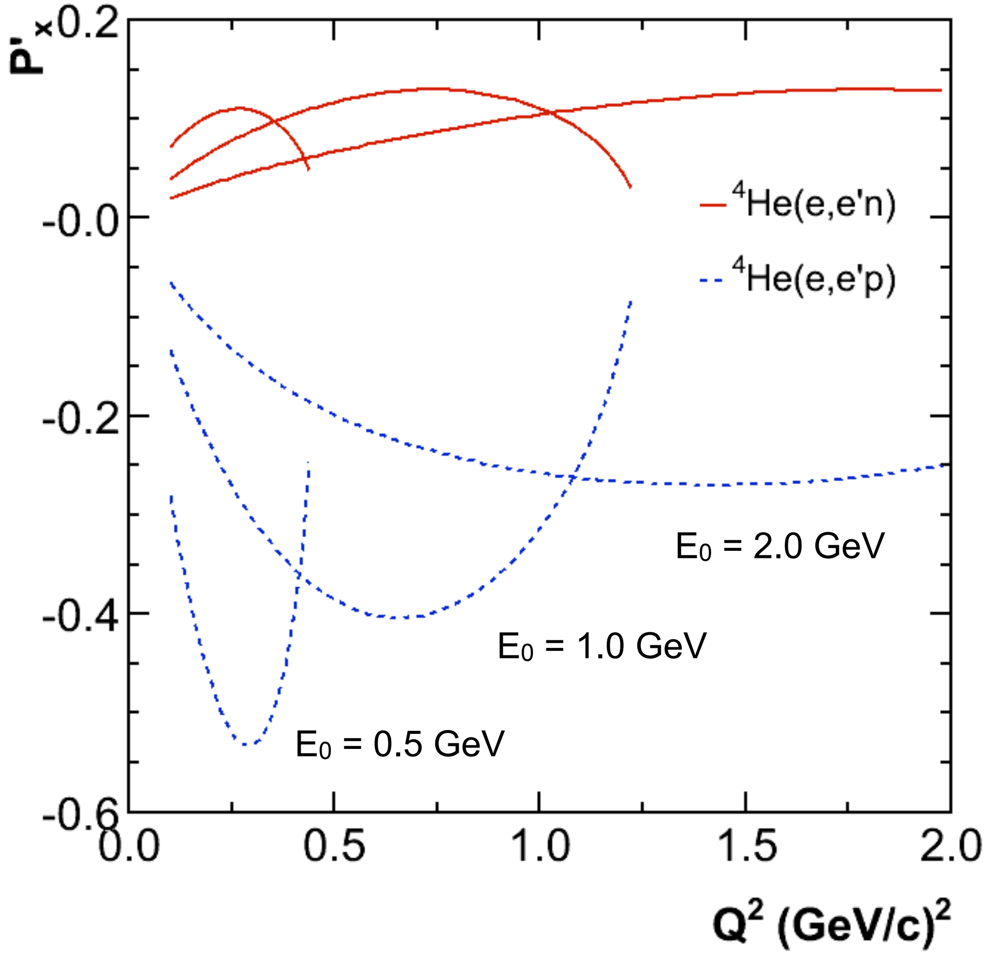
# Neutron in the Nuclear Medium




- Different models for medium modification all give same result.
- Effect on neutron form factor ratio **very different** from the proton!

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

- **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
  - Induced polarization strongly constrains FSI, but is insufficient as only constraint
  - Polarization-transfer data effectively described by in-medium electromagnetic form factors or charge-exchange FSI

- **Plans for future Experiments**
  - $^4He$, $^2H$, $^1H(e,e'p)$; large $p_m$ and high $Q^2$
  - $^4He$, $^2H(e,e'n)$