PR12-11-002

Proton Recoil Polarization in the $^{4}He(e,e'p)^{3}H$, $^{2}H(e,e'p)n$, and $^{1}H(e,e'p)$ Reactions

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Jefferson Lab PAC 37, January 12, 2011

Purpose of Proposal PR12-11-002

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

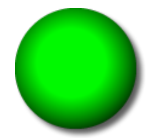
$$^4\mathrm{He},\ ^2\mathrm{H},\ ^1\mathrm{H}(\vec{e},e'\vec{p})$$

	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 • 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

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



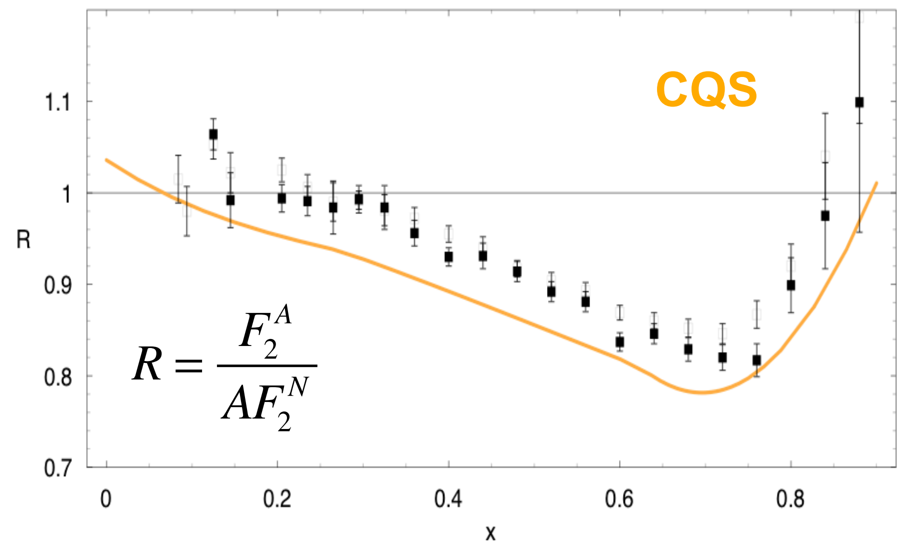
Free neutron:
τ_n = 15 min

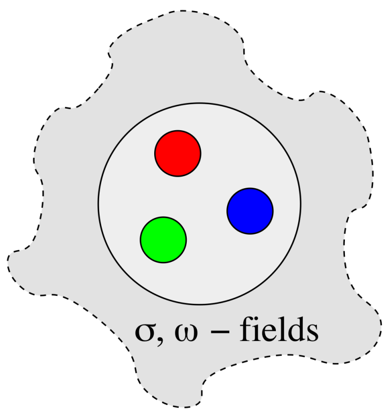
Neutron bound in ^{4}He
does not decay, $\tau_n = \infty$

In-Medium Structure Functions

- EMC Effect: observation of a depletion of the nuclear structure function F_2 in the valence-quark regime.
- 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.
- Where else do these changes emerge?

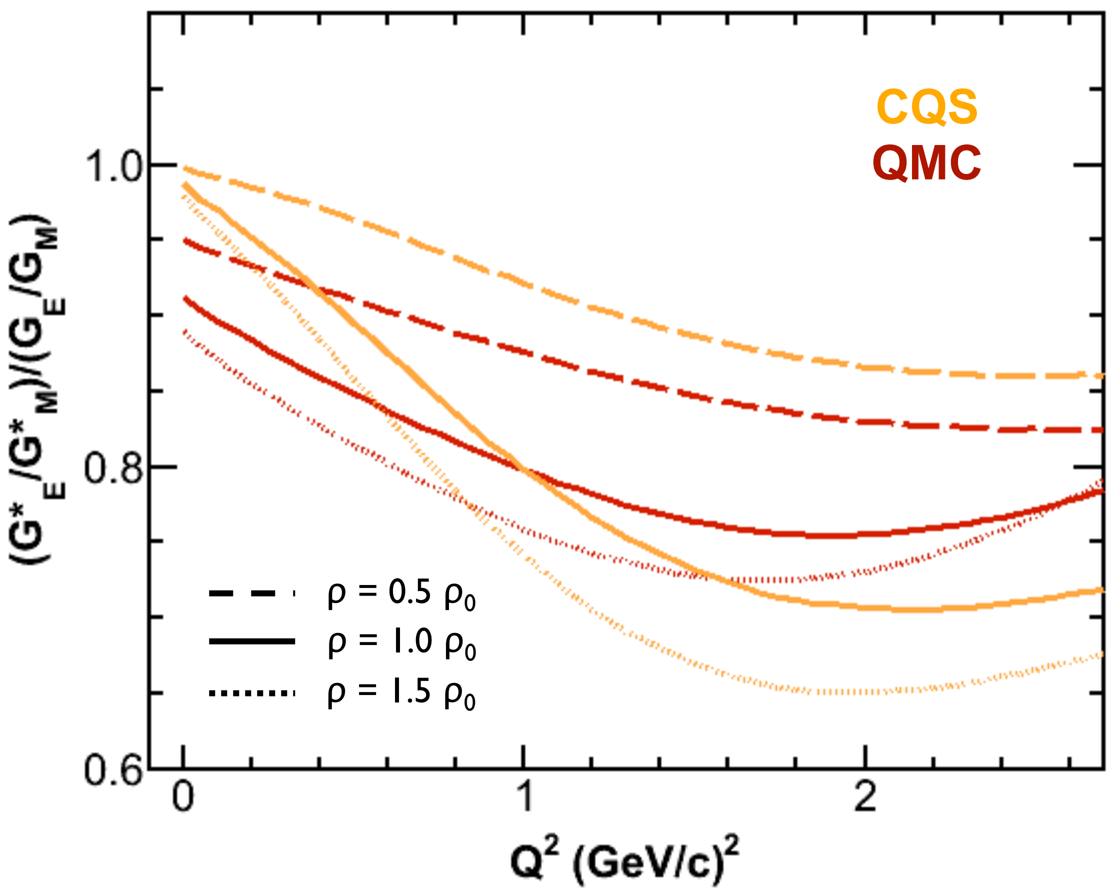
Chiral Quark-Soliton Model





J.R. Smith and G.A. Miller, Phys. Rev. Lett. **91**, 212301 (2003); SLAC E139 data for iron and gold
I. C. Cloët, W. Bentz, and A. W. Thomas, Phys. Rev. Lett. **102**, 252301 (2009)

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.

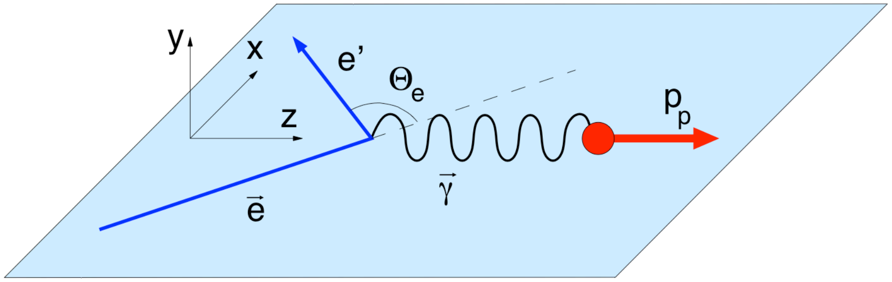
- Model Predictions:
  - are density and Q^2 dependent,
  - show similar behavior,
  - consistent with experimental data (within large uncertainties).

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

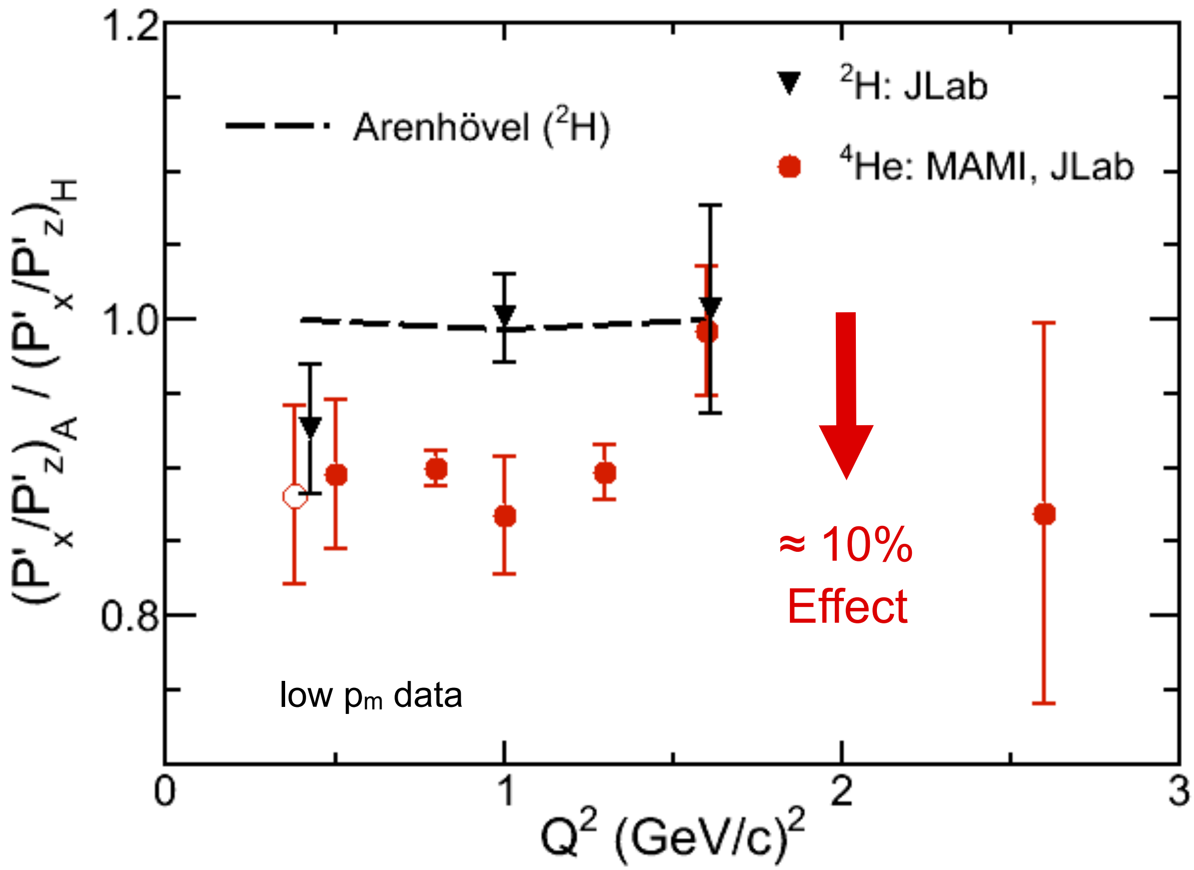
A.I. Akhiezer and M.P. Rekalo, Sov. J. Part. Nucl. **3**, 277 (1974)
R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C **23**, 363 (1981)

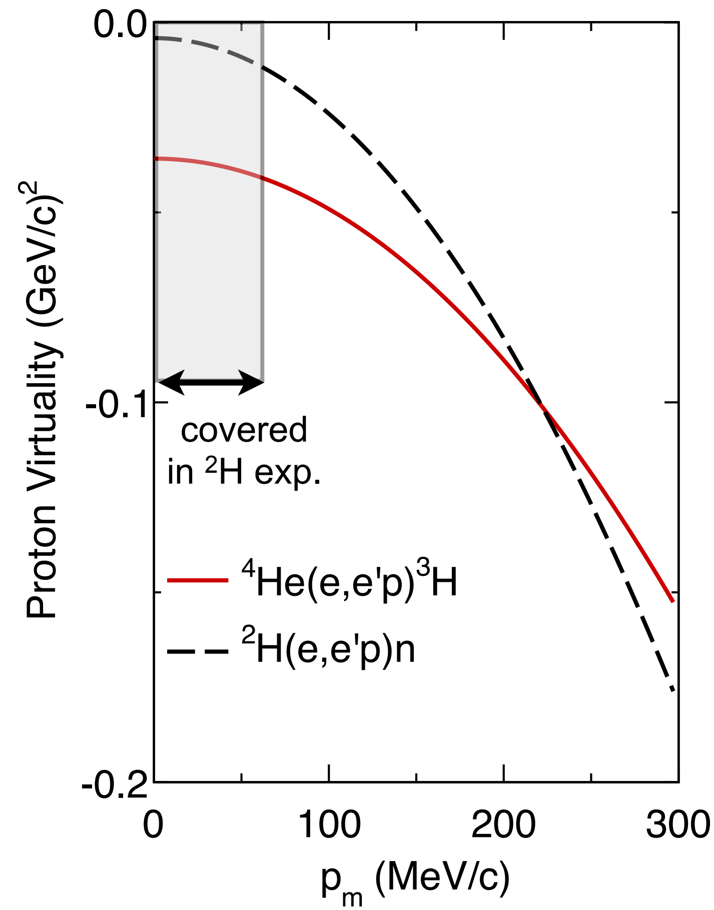
Bound proton

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

- 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

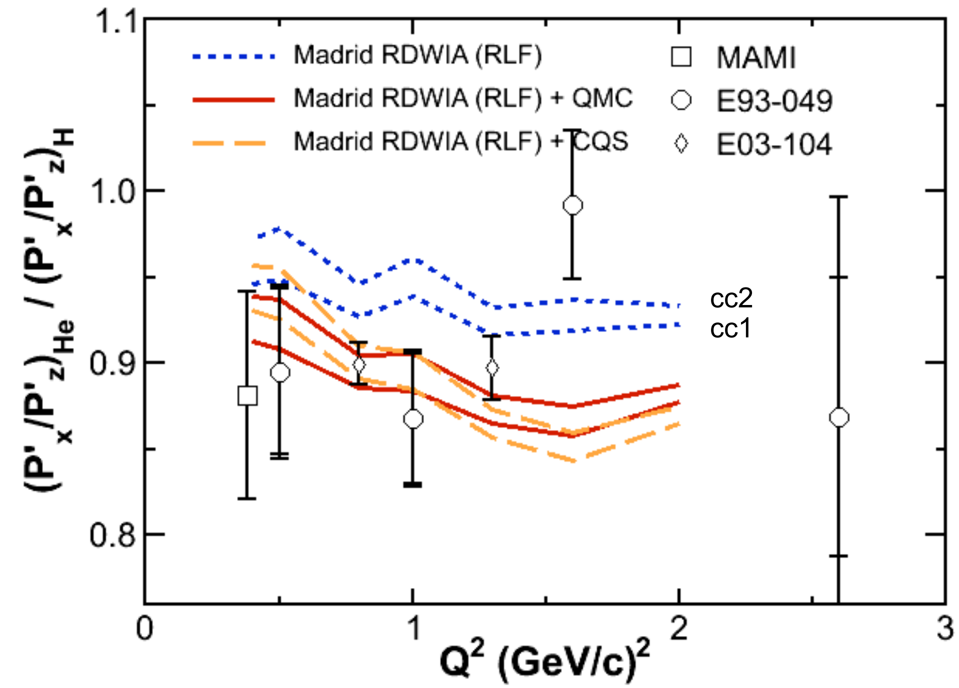


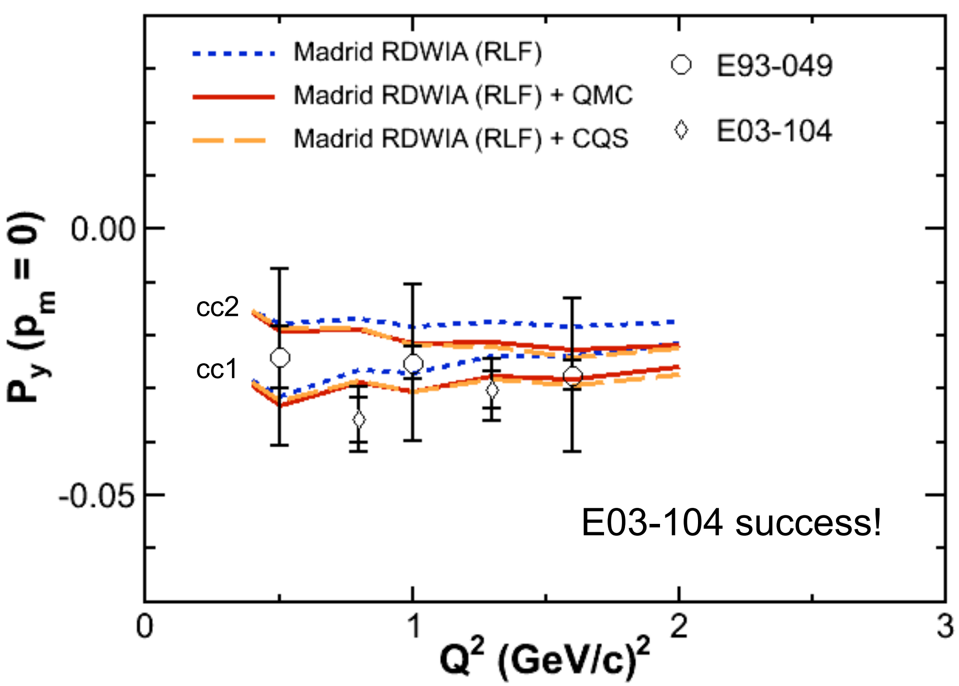


- ^{2}H and ^{1}H polarization-transfer data are similar
- ^{4}He data are significantly different than ^{2}H, ^{1}H data

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

^{2}H: B. Hu *et al.*, PRC 73, 064004 (2006). **^{4}He**: 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 (accepted for publication), arXiv:1011.4483v1 [nucl-ex]



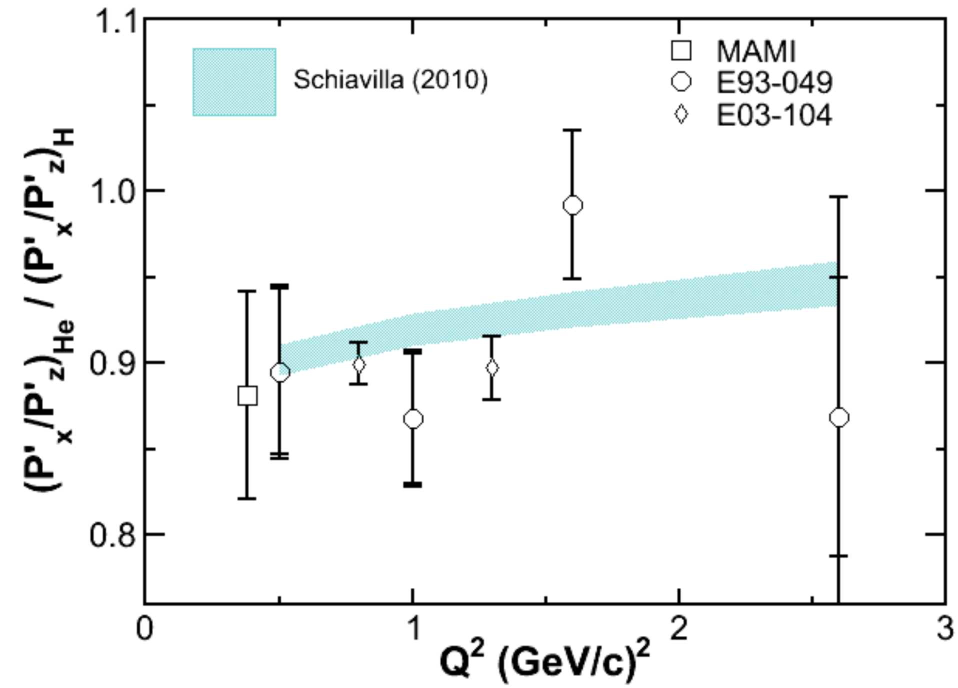


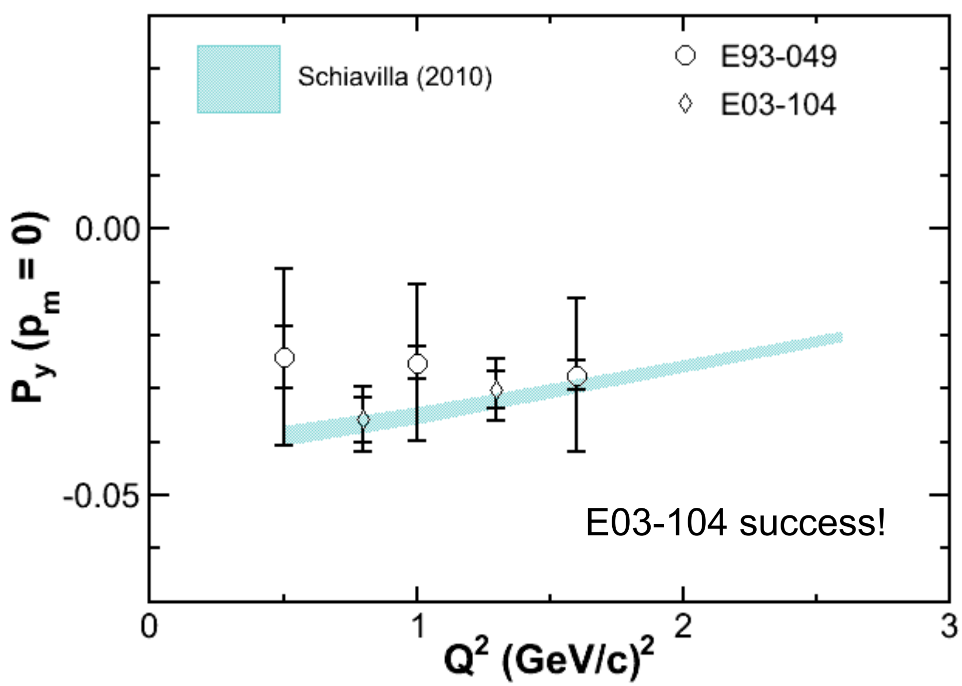
Madrid RDWIA

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





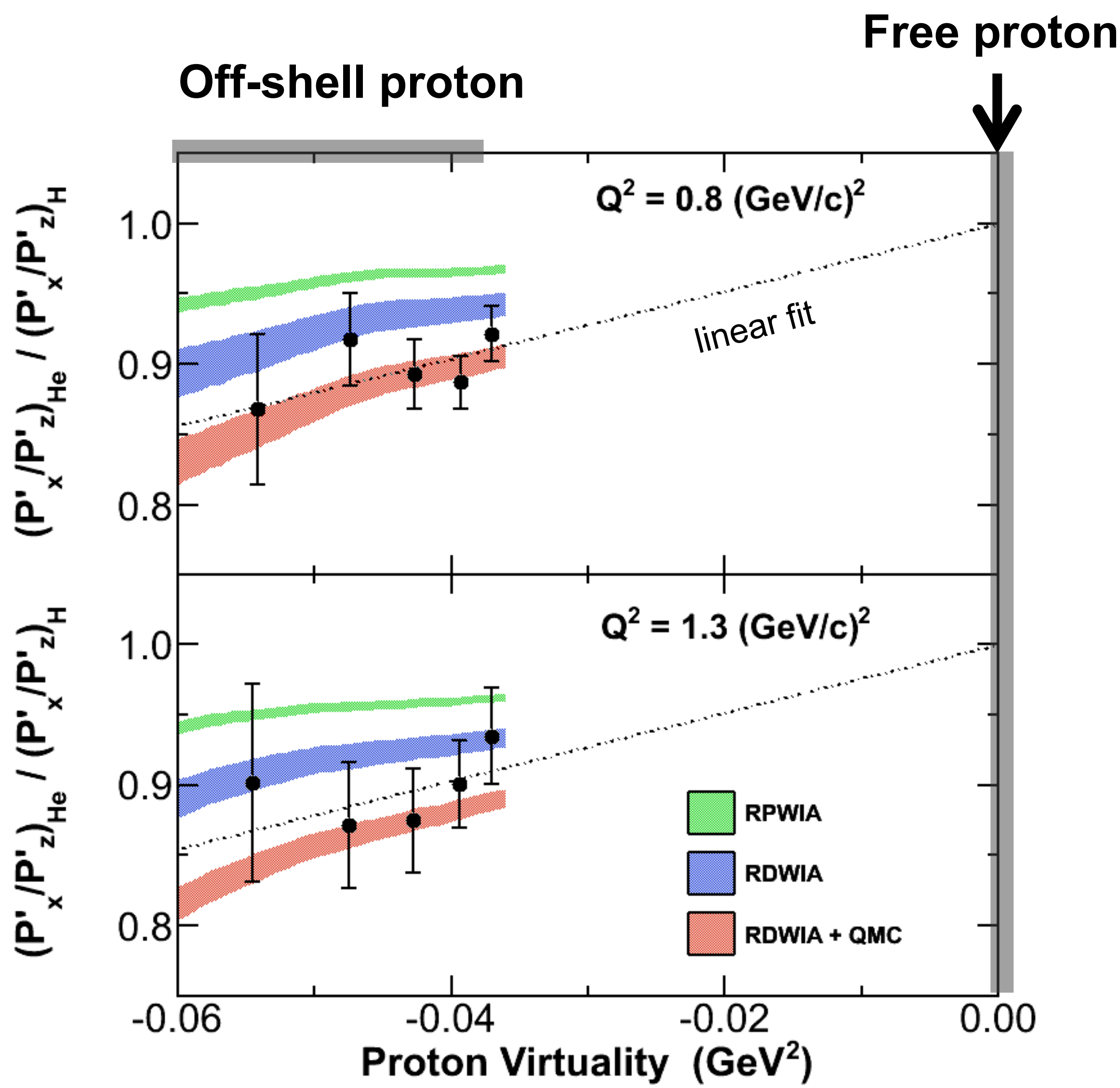
Schiavilla (2010)

- 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

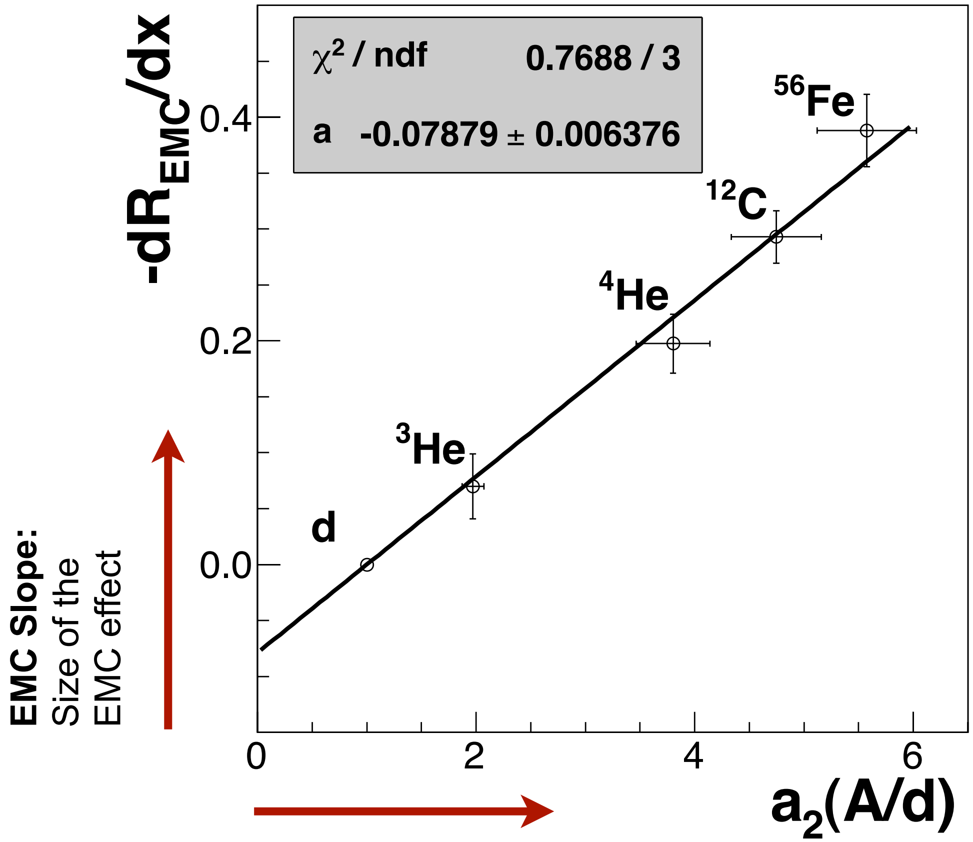
$$\nu = p^2 - m_p^2$$

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)

Momentum Dependence of the EMC Effect



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

Figure from: L.B, Weinstein et al.,arXiv:1009.5666 [hep-ph]
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.
- **PR12-11-002** 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.

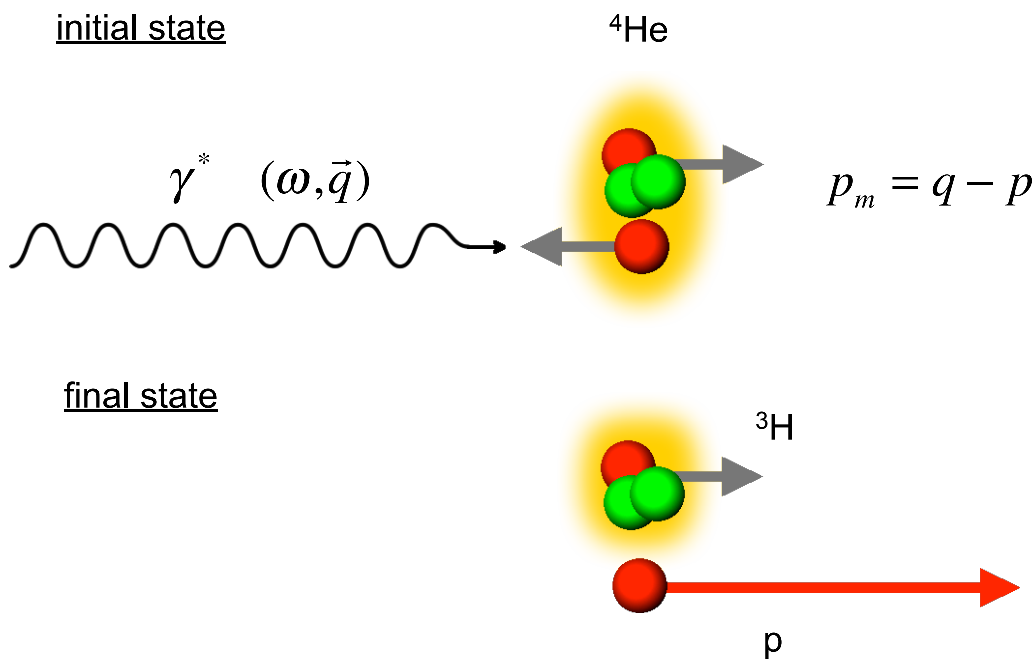
PR12-11-002: Kinematics

- 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**.

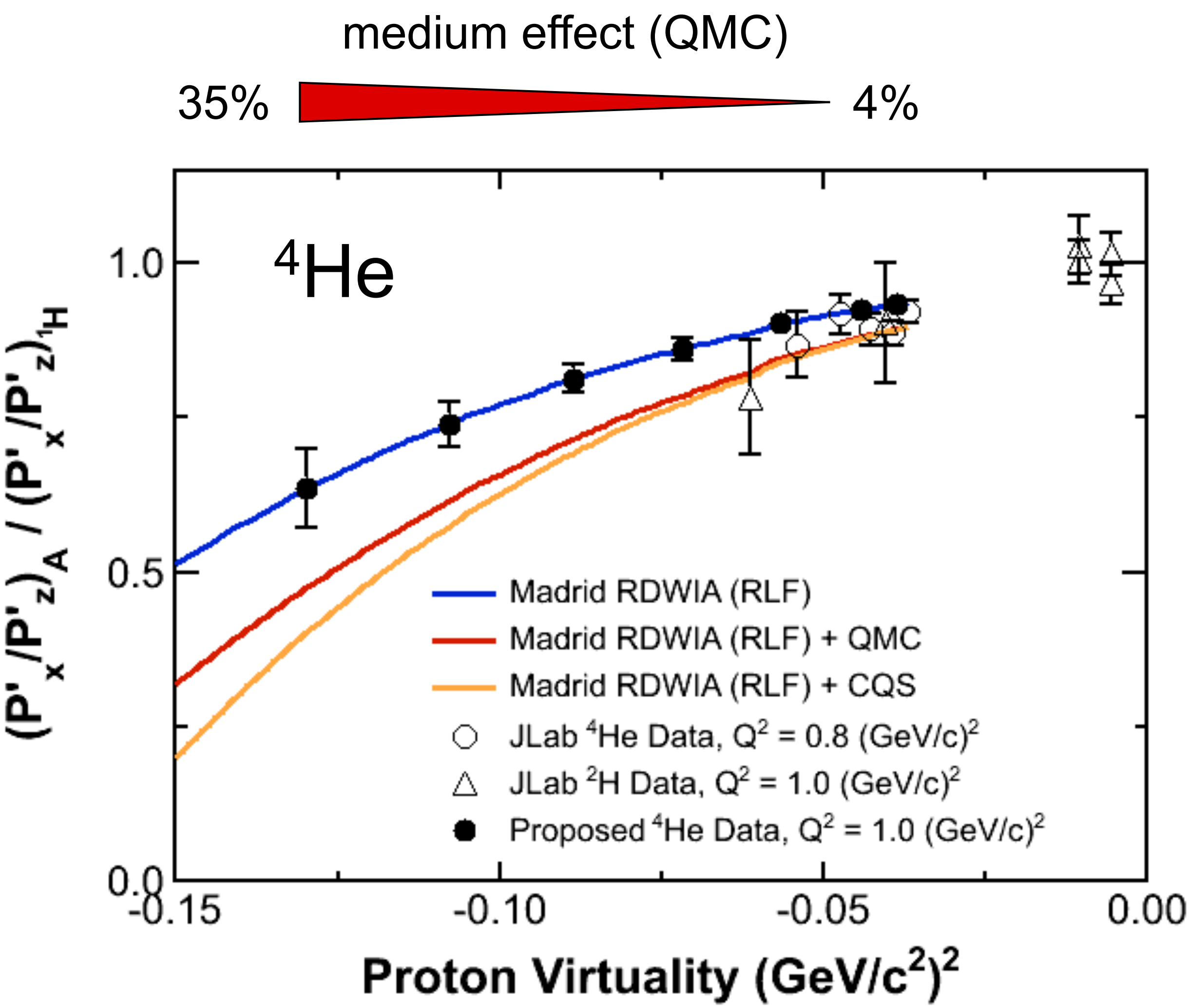


Q^2 $(GeV/c)^2$	p_m (MeV/c)	Targets
1.0	0, +140, +220	^{4}He, ^{2}H, ^{1}H
1.8	0	^{4}He, ^{1}H

*M. Sargsian, private communication

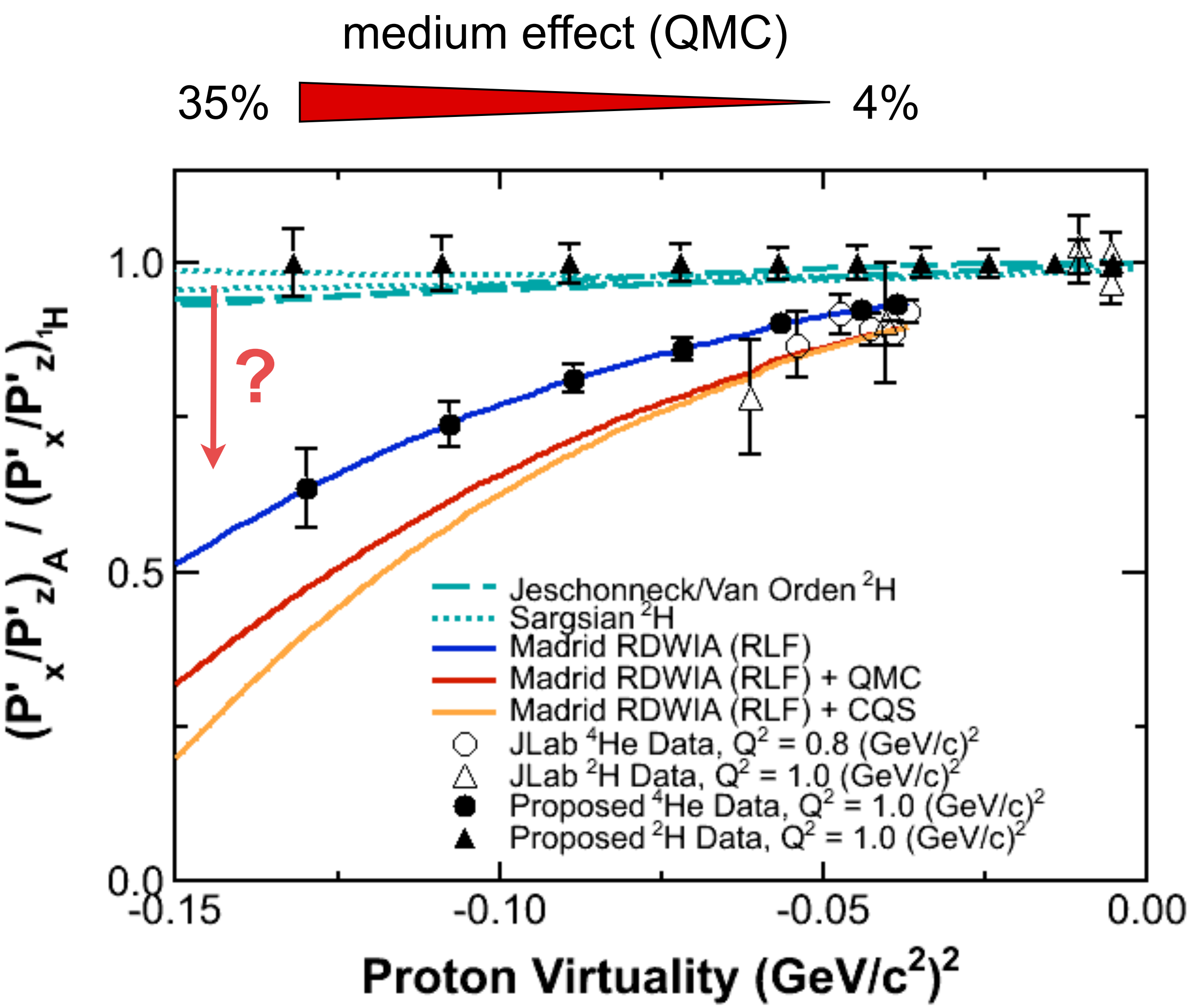
C. Ciofi degli Atti, L.L. Frankfurt, L.P. Kaptari, M.I. Strikman, Phys. Rev. C **76**, 055206 (2007)

1st Feature of the Proposal



- **PR12-11-002**:
  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 (○).

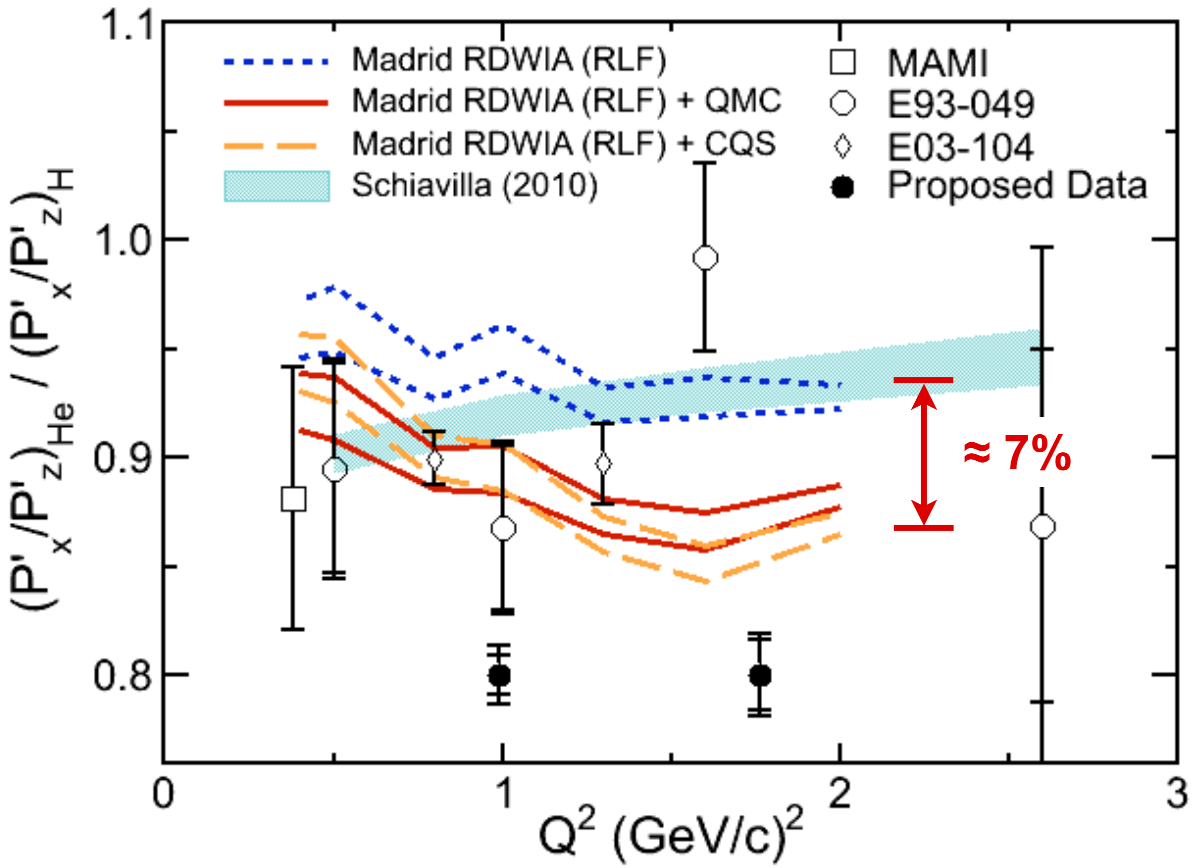
2^{nd} Feature of this Proposal



- **PR12-11-002**: 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 ...

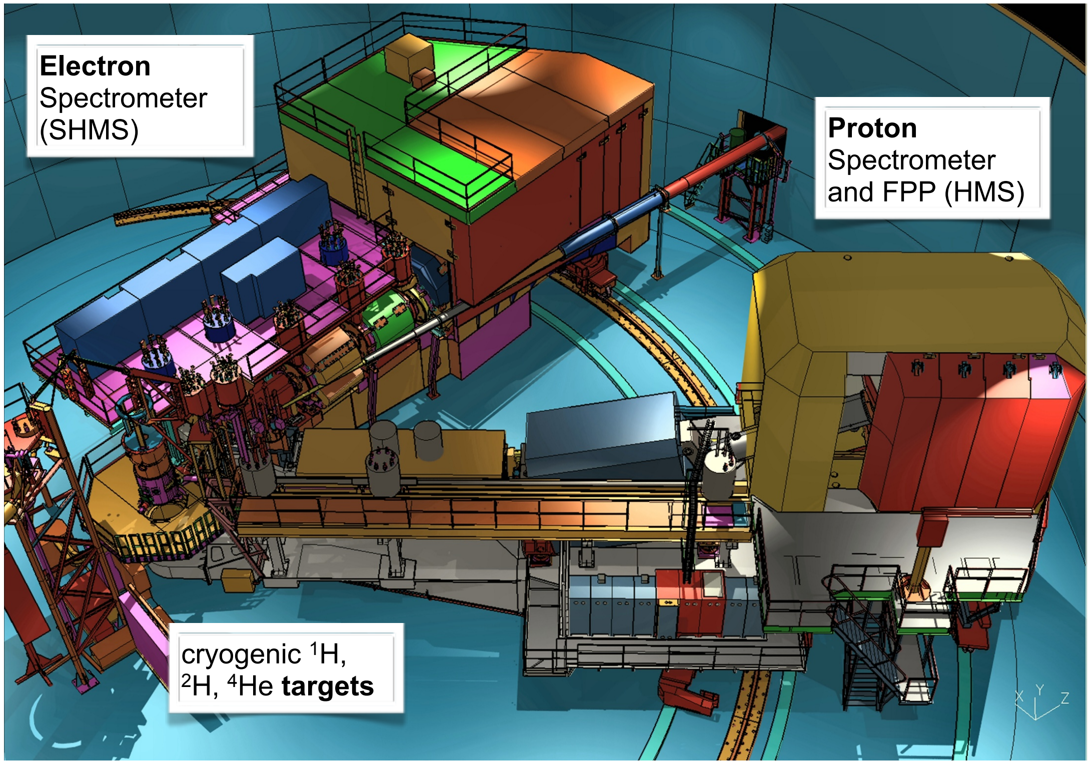
S. Jeschonnek and J.W. Van Orden, Phys. Rev. C**81**, 014008 (2010); C**78**, 014007 (2008);
M.M. Sargsian, Phys. Rev. C**82**, 014612 (2010)

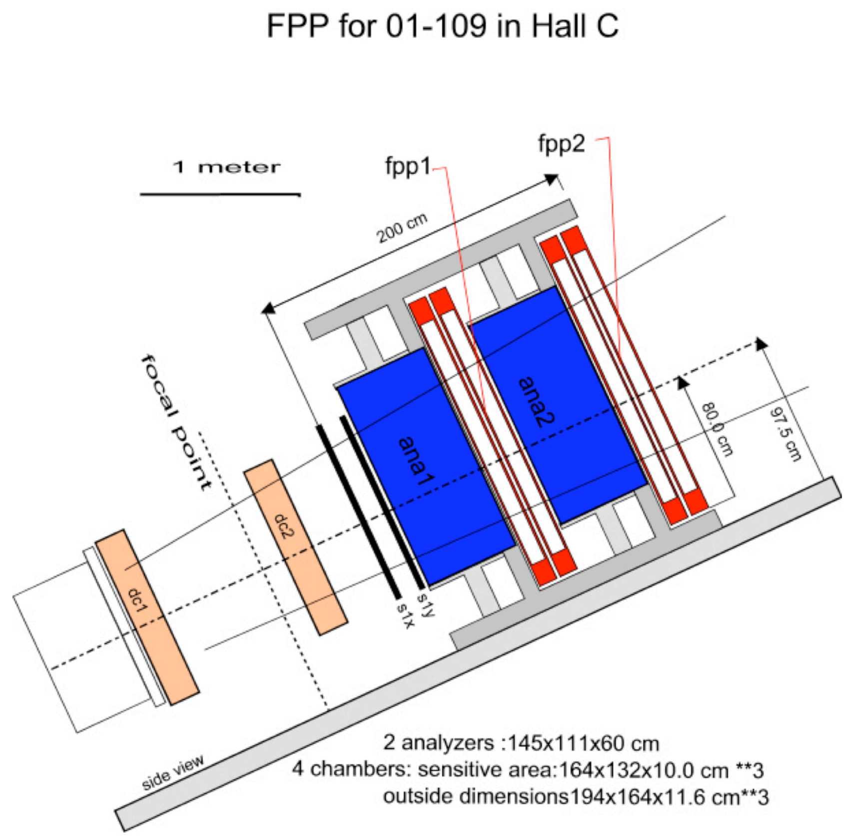
3rd Feature of the Proposal



- 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
- **PR12-11-002**: We propose to 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?

Experimental Setup in Hall C





- This is a standard-equipment experiment
- Polarized electron beam: E_0 = 2.25, 4.40 GeV
- Hall C Focal Plane Polarimeter
  - FPP wire-chamber upgrade to increase overall tracking efficiency
  - Segmented analyzer system to optimize analyzer for proton momenta
  - Active scintillator segment to provide second trigger layer

Relative Systematic Uncertainties

Source of Error	$\Delta P'$	$\Delta P'_x/P'_z$	ΔR	Mitigation
Luminosity	0	0	0	-
Beam Polarization	3%	0	0	-
Analyzing Power	3%	0	0	Determine A_c from our own *ep* data
Background	≈ 0	≈ 0	≈ 0	(e,e'p) coincidence requirement, vertex cuts, and missing-mass technique effectively removes background; can be studied with MC & dummy-target data; has been no issue in E03-104
Kinematics	≈ 0	≈ 0	≈ 0	Previous experiments and MC simulations show that we will attain sufficient resolution to reconstruct the missing mass of the final state; overdetermined *ep* kinematics allow for careful checks
Radiative corrections	?	< 0.5%	≪ 0.5%	Theory input needed
Spin transport	1% - 3%	1% - 2%	< 1%	Extraction of G_E/G_M from *ep* for various proton trajectories allows careful check of spin precession; COSY model well confirmed in previous experiments

Estimates are based on results which have been realized in earlier experiments in Hall A and Hall C.

Beam Request

Q^2 $(GeV/c)^2$	^4H (h)	^2H (h)	^1H (h)	Dummy (h)	Overhead (h)	Total (h)	Total (d)
1.0	346	172	21	35	20	594	**25**
1.8	225	-	42	23	8	298	**12**

- Total beam request of **37 days.**
- Overhead for beam-polarization measurements, possibly one additional day for helium/deuterium target change.
- The proposed experiment is standard and it is flexible as to different beam energies in order to optimize scheduling.

PR12-11-002: Proton Recoil Polarization

Investigation of the role of nuclear medium modifications

Strategy

- Choose an observable with high sensitivity to nucleon structure while being at the same time least sensitive to conventional medium effects.
  $\Rightarrow$ polarization-transfer, quasi-elastic scattering, parallel kinematics, $x > 1$

- Chose simple nuclear targets, which allow for microscopic calculations.
  $\Rightarrow$ ^{4}He, ^{2}H

- Study bound-proton momentum and density dependence of recoil-polarization observable.
  $\Rightarrow$ ^{4}He and ^{2}H data over a large range of proton virtuality

- Provide high-precision data to put Nuclear Physics models to rigorous test.