$^4He(e,e'p)$ reactions – study of bound nucleon

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SRC 2007 Workshop
Jefferson Lab, October 26-27, 2007

Motivation

Conventional Nuclear Physics

Nucleons are effectively and well described as:

- point-like protons and neutrons (+ form factor)
- interaction through effective forces (meson exchange)

QCD

- Nucleons and mesons are not the fundamental entities
- Nucleons and mesons are composite objects of quarks and gluons

Is the structure of the nucleons modified by the nuclear medium?

Exclusive A(e,e'p) data provide for sensitive tests:

- Cross sections
- Polarization observables

Experimental Goal

Measure, *as accurate as possible*, observables that give access to possible modifications of the form factors in the nuclear medium.
=> Polarization observables

Free nucleon:

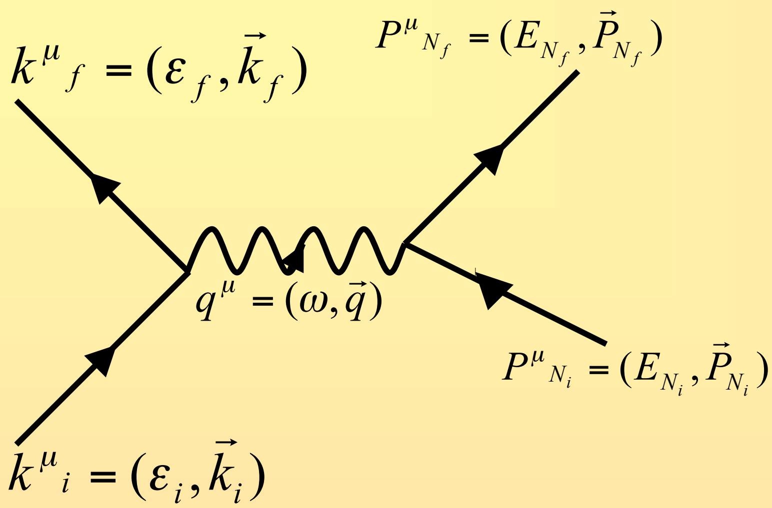
$$\frac{G_E}{G_M} = -\frac{P_x^{'}}{P_z^{'}} \cdot \frac{(E_i + E_f)}{2m} \tan\frac{\theta_e}{2}$$

Bound nucleon: **evaluation within model**

i.e. assumptions about the wave functions, current operators, final-state interactions (FSI)….

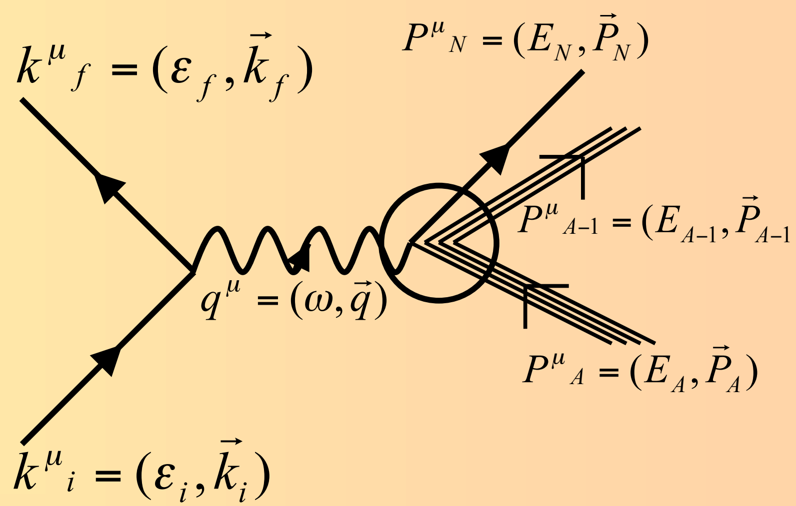
Theoretical Framework

Elastic scattering on free nucleon:



Born Approximation

Quasielastic scattering on bound nucleon:



Born + Impulse Approximation(IA)

$$W_{if} = \int dx \int dy \int \frac{dq}{(2\pi)^2} j_\mu{}^e(x) e^{-iq(x-y)} \frac{(-1)}{q_\mu{}^2} J_N{}^\mu(y)$$

electron current — $j_\mu{}^e(x)$

nuclear current — $J_N{}^\mu(y)$

Due to the presence of the nuclear medium, additional effects have to be taken into account when calculating the currents for e-N_{bound} scattering as opposed to e-N_{free} scattering.

In-Medium Effects

Electron-photon vertex current: $j_{\mu}{}^{e}(r) = \overline{\psi}_{f}{}^{e}(r)\gamma^{\mu}\psi_{i}{}^{e}(r)$

→ **Coulomb distortion of the electron wave function (especially important for heavy nuclei).** → J.M. Udias *et al.*, Phys.Rev.C 48, 2731

Photon-nucleon vertex current: $J_{N}{}^{\mu}(r) = \overline{\psi}_{F}{}^{N}(r)\hat{J}_{N}{}^{\mu}\psi_{B}{}^{N}(r)$

→ **Off-shell effects (no unambiguous treatment)**

$$\hat{J}_{cc1}{}^{\mu} = G_M(Q^2)\gamma^{\mu} - \frac{\kappa}{2M}F_2(Q^2)(P_i^{\mu} + P_f{}^{\mu}), \quad \hat{J}_{cc2}{}^{\mu} = \ldots, \quad \hat{J}_{cc3}{}^{\mu} = \ldots$$

→ T. De Forest, Jr. Nucl. Phys. A392, 232

$\hat{J}_{cc1}, \hat{J}_{cc2}, \hat{J}_{cc3}$ equivalent for free nucleon but not guaranteed to produce the same result for bound nucleons

- Current conservation (cc) rather exception than rule in most calculations.
- Prescriptions proposed to partially cure this deficiency: imposed cc => different gauges.
- Vary prescriptions seem to converge with increasing Q^2, especially at low missing momentum. → D. Debruyne, J. Ryckebusch…,Phys. Rev. C 62, 024611

In-Medium Effects

→ **Many-body currents: e.g. MEC- e.g. the photon couples to a meson which has been exchanged between two nucleons inside the nucleus.**

- IA ⇔ Direct Knockout Mechanism (DKO) ("zero-order approximation")
- To account for meson exchanges between nucleons we need "higher-order corrections" to the DKO.

two-body current

$$<\psi_f|\hat{J}^\mu|\psi_i> = <\chi(1)|J^\mu(1b)|\psi_\beta(1)> + \sum_{\alpha=1}^{A} <\chi(1)\psi_\alpha(2)|J^\mu(2b)|\psi_\beta(1)\psi_\alpha(2) - \psi_\alpha(1)\psi_\beta(2)>$$

→ A. Meucci et al., Phys. Rev. C 66, 034610

- The sensitivity of polarization observables on MEC was predicted to be moderate *only* at p_m > 200 MeV/c. → J. Ryckebusch, Phys. Rev. C 60, 034604

→ **Final-State Interactions: interactions which occur after the nucleon has been struck by the photon before it leaves the vicinity of the nucleus.**

- Most calculations account for FSI via **optical potentials (OPT).**
  - **(e,e'p)(p,p)** → J. Udias *et al.*, Phys. Rev. C 51
  - **(e,e'p)(p,p) + (e,e'n)(n,p)** → R. Schiavilla, Phys. Rev. Lett. 65, 835
- Some calculations use **Glauber framework** to incorporate FSI.

→ P. Lava, J. Ryckebush, B. Van Overmeire, Phys. Rev. C 71, 014605

Typical Glauber approaches rely on spin-independent NN scattering amplitudes => the effect of FSI smaller in Glauber framework than in a relativistic OPT one.

In-Medium Effects

→ <u>Medium modifications of the electromagnetic current through the form-factor:</u>

e.g. $\hat{J}_{cc1}^{\ \mu} = G_M(Q^2)\gamma^\mu - \frac{\kappa}{2M} F_2(Q^2)(P_i^\mu + P_f^{\ \mu})$ → free or medium-modified nucleon form-factor ?

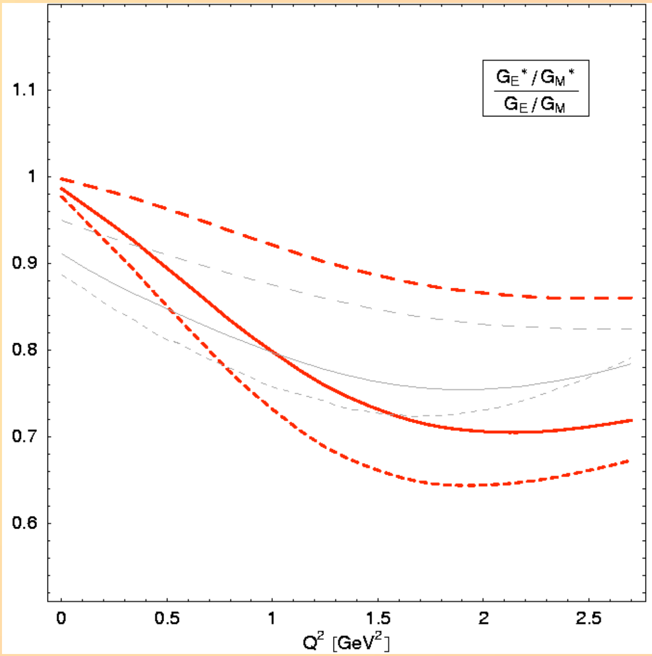
For example:

Quark Meson Coupling Model (QMC)

- Structure of the nucleon described by valence quarks in a bag (Cloudy-bag model).
- 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 *et al.*, Phys. Rev. C 60, 068201



Chiral Quark-Soliton Model of the Nucleon (CQSM)

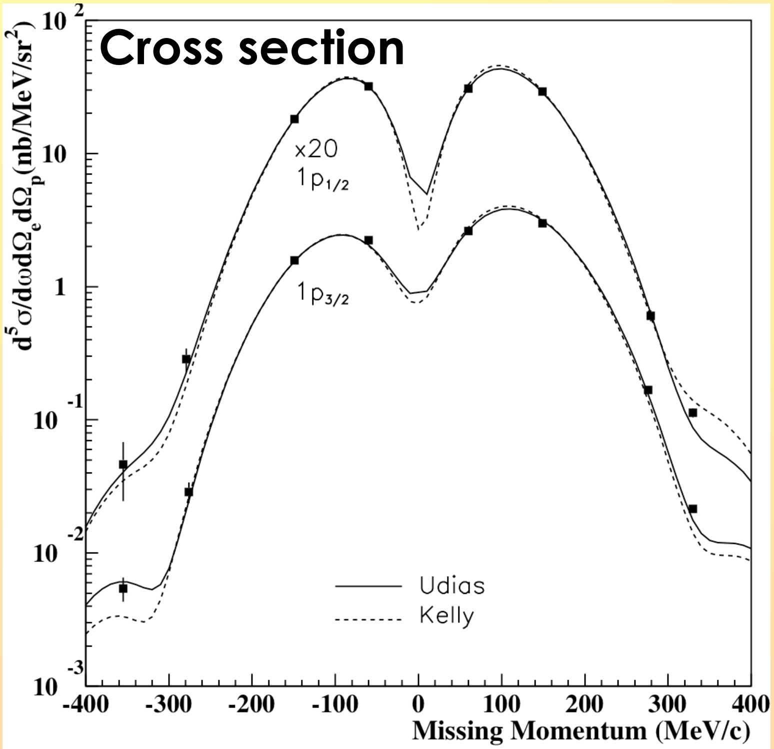
- The chiral quark-soliton model provides the quark and antiquark structure of the proton.
- The overall procedure for the form-factor extraction is similar to the QMC model.

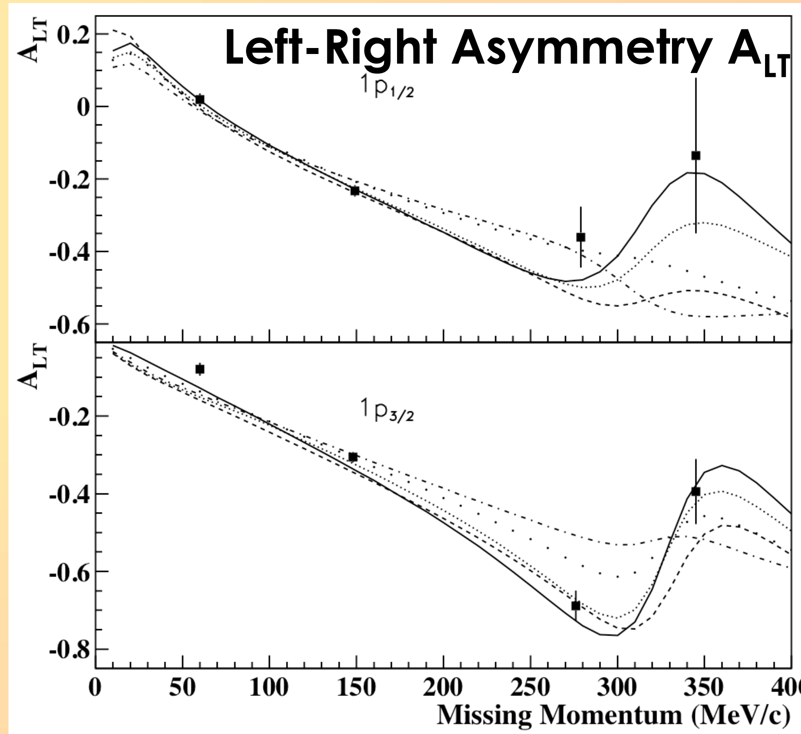
↳ J. R. Smith and G. A. Miller, Phys. Rev. Lett. 91, 212301

→ **Good description of the EMC effect.**

Excellent Description of Many Observables

$^{16}O(e,e'p)$ at $Q^2 = 0.8\ (GeV/c)^2$





- Importance of fully relativistic calculation.
- Also excellent description of $^{12}C(e,e'\mathbf{p})$ induced polarization.

J. Gao *et al.*, Phys. Rev. Lett. **84**, 3265 (2000);
J.M. Udias *et al.*, Phys. Rev. Lett. **83**, 5451 (1999)

E93-049 and E03-104 at Jlab Hall A

Target: ^{4}He, H

^{4}He:
- High density target => any possible medium effects are enhanced.
- Its relative simplicity allow realistic microscopic calculations.
- Variety of calculations show that polarization-transfer observables in ^{4}He(e,e'p)^{3}H are influenced little by FSI, MEC.

H:
- H is baseline when estimating the effect of the medium on the polarization-transfer ratio in ^{4}He(e,e'p)^{3}H .

Kinematics: **quasielastic scattering + low p_m + symmetry about p_m=0**

Q^2 = 0.5, 0.8, 1.0, 1.3, 1.6, 2.6 GeV^2

- We extract **P_x', P_z', P_y.**

Beam: **Longitudinally polarized electron beam (85%).**

- Incoming electron helicity flipped -> access to both the polarization transfer and the induced polarization.

Detection system: **Hall A High Resolution Spectrometers (HRS)**

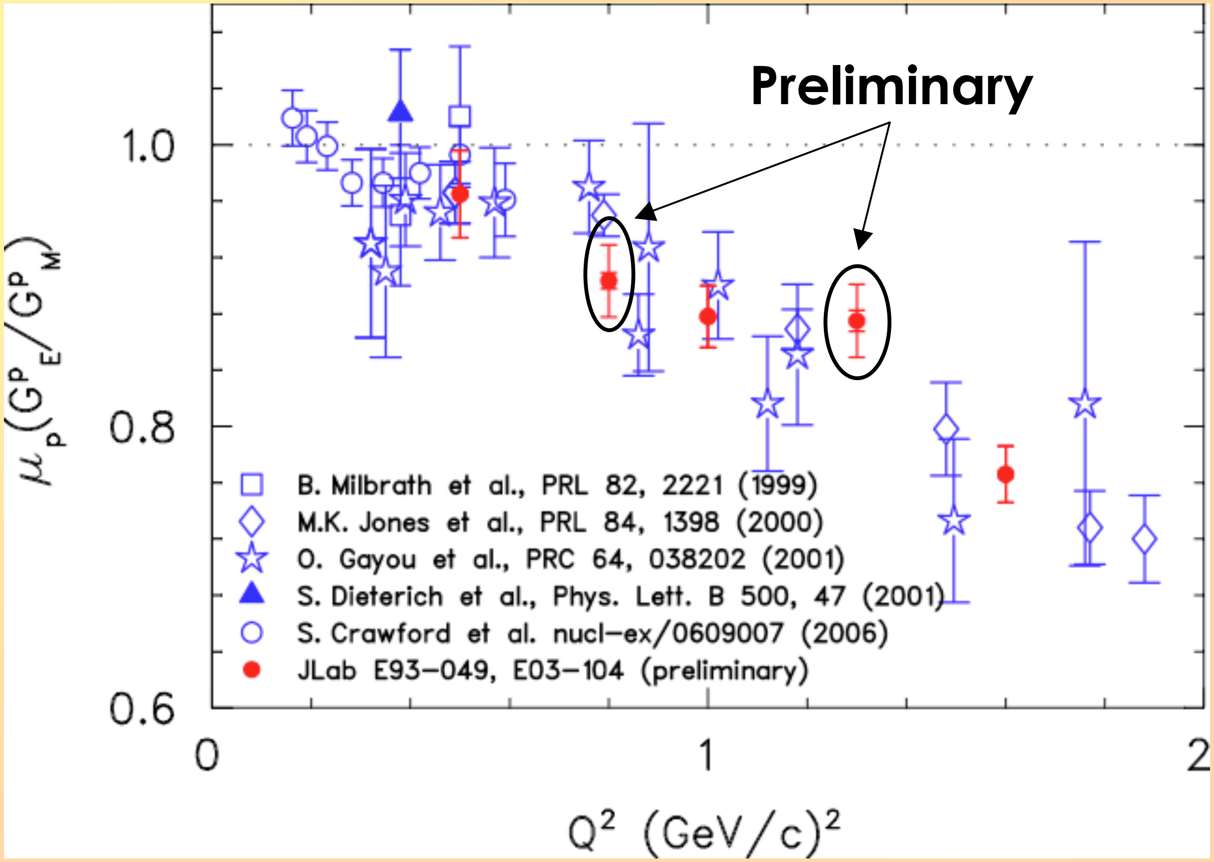
- Left/Right arm: polarized proton/scattered electron detection.
- We make sure we get triton in the final state.

E93-049 analysis: final (published). **E03-104** analysis: ongoing.

Free Proton Form-Factor Ratio G_E/G_M

- The systematic decrease of G_E/G_M indicates the difference between the spatial distribution of charge and magnetization in the proton.

- Preliminary results from E03-104 with small statistical uncertainty (~ 0.7%).



- Full analysis of E03-104 will yield smaller systematic uncertainties.

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

$$R = \left(\frac{P_x'}{P_z'}\right)_{e-N_{bound}} \Bigg/ \left(\frac{P_x'}{P_z'}\right)_{e-N_{free}}$$

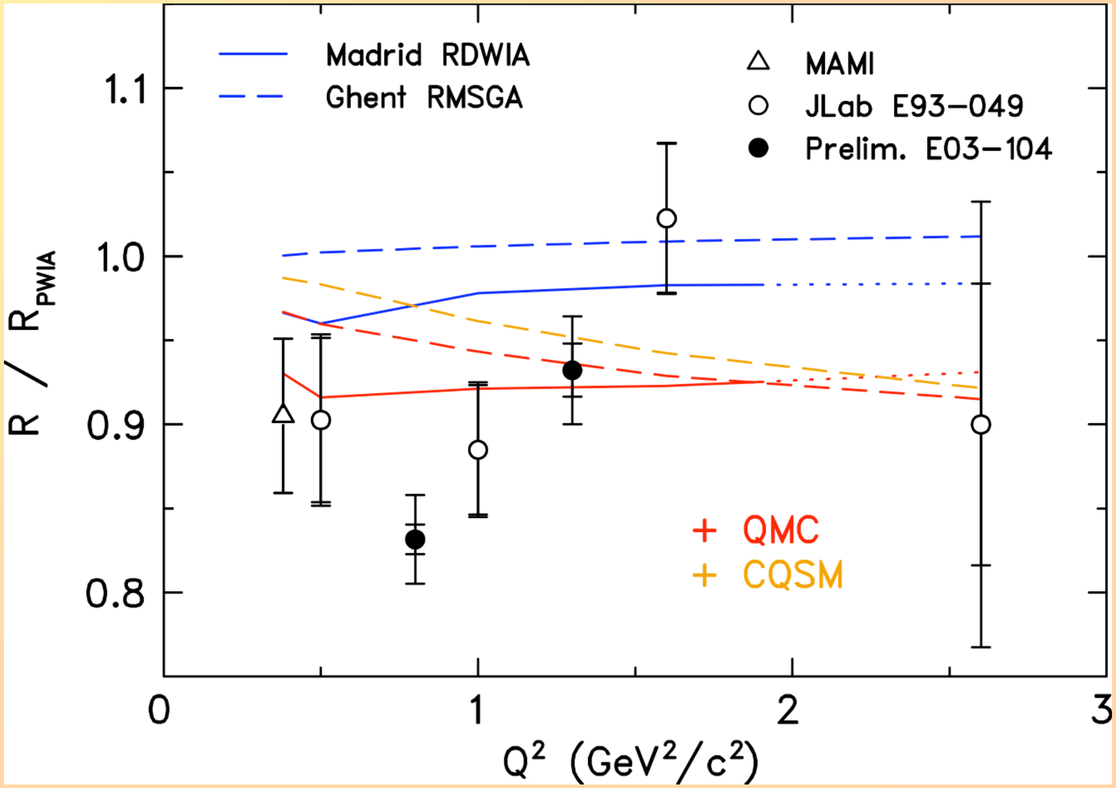
- RDWIA calculation: no MEC and no charge-exchange FSI terms.

  Study shows: effect of MEC < 3%.

- RMSGA calculation: similar procedure as RDWIA but different treatment of FSI =>FSI underestimated.

- **RDWIA and RMSGA models cannot describe the data.**

- **Data effectively described by medium modified form factors.**

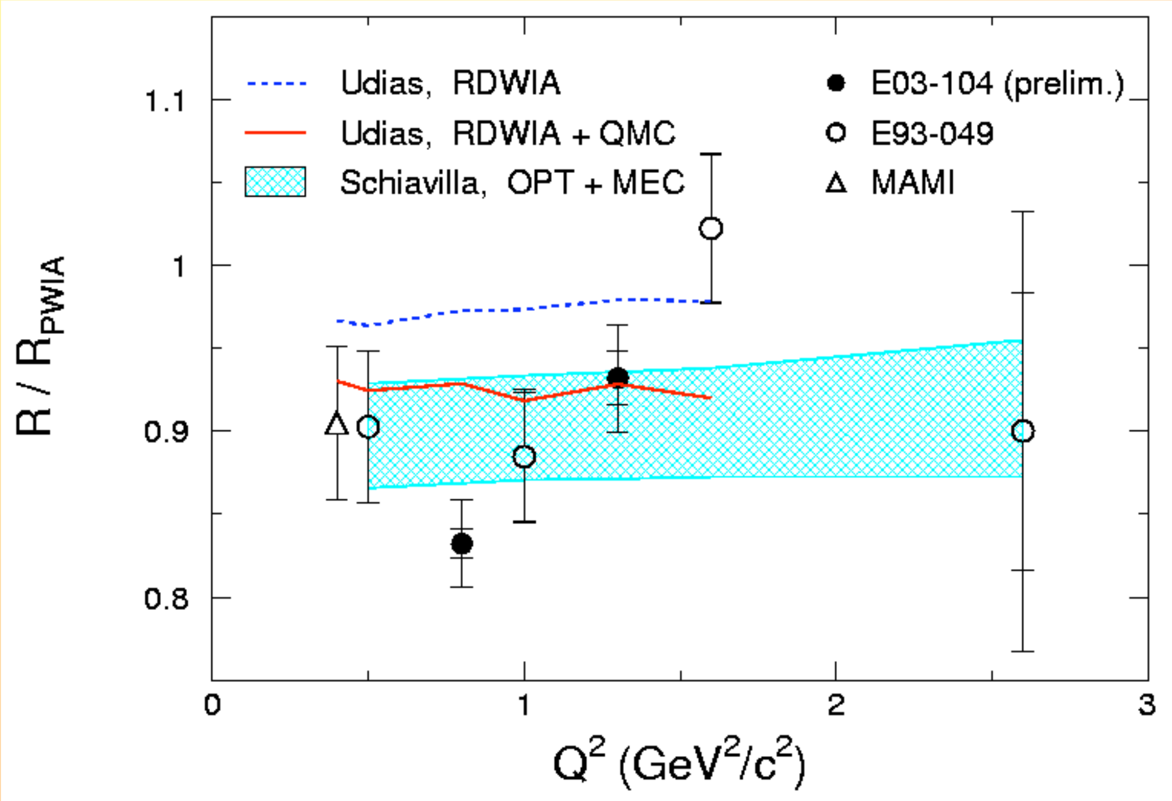


- **Preliminary data from E03-104 possibly hint an unexpected trend in Q^2.**

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

Schiavilla *et al.* calculation provides for alternative explanation:

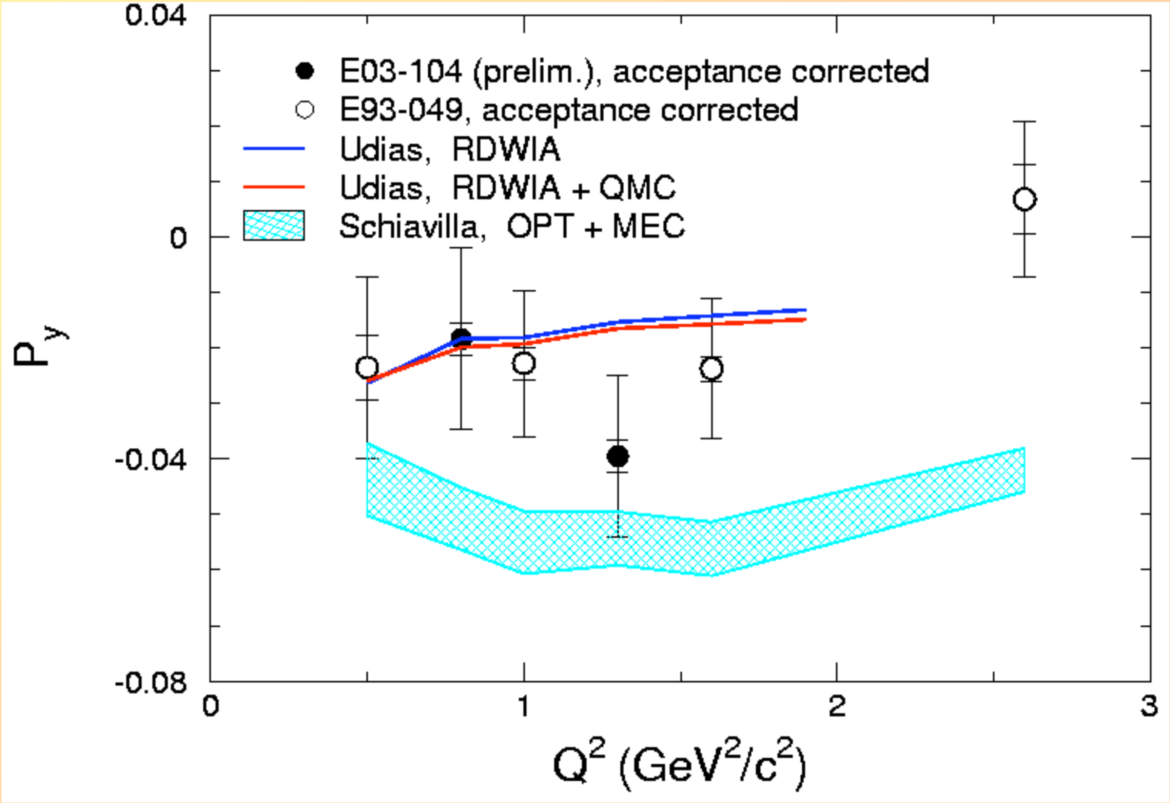
- **R is suppressed ~ 4% from MEC.**
- **Spin-dependent charge-exchange FSI suppresses R ~ 6%.**



- **Charge-exchange term not well constrained => need precise P_y data.**

Induced Polarization in $^4He(e,e'p)^3H$

- P_y is a measure of FSI.
- FSI small and with only very weak Q^2 dependence.
- Spin-dependent charge-exchange terms not constrained by N-N scattering and possibly overestimated.
- RDWIA results consistent with data.



- E03-104 took specific data that will set tight constraints on FSI.

Summary

Proton in the nuclear medium:

- Models predict change of the internal structure of a bound nucleon.
- Corrections due to in-medium form factors could be significant.

Polarization transfer in $^4He(e,e'p)$:

- Significant deviation from RDWIA results; data effectively described by proton medium modifications.
- Alternative interpretation in terms of strong charge-exchange FSI.
- Induced polarization crucial to clarify role of FSI.
- New results from E03-104 will provide needed constraints.
- Preliminary data from E03-104 possibly hint an unexpected trend in Q^2 for R.

Sensitivity to reaction mechanisms

$R^{RDWIA} \approx 0.97 \times R^{RPWIA}$

Small sensitivity to

- bound-state wave function
- current operator
- optical potential

Enhancement of lower components (spinor distortions) in RDWIA