Measurements of polarization transfer to a bound proton in light nuclei by quasi-elastic scattering at MAMI

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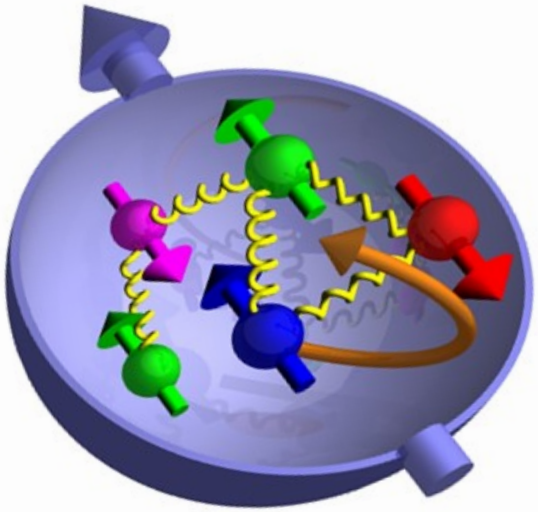
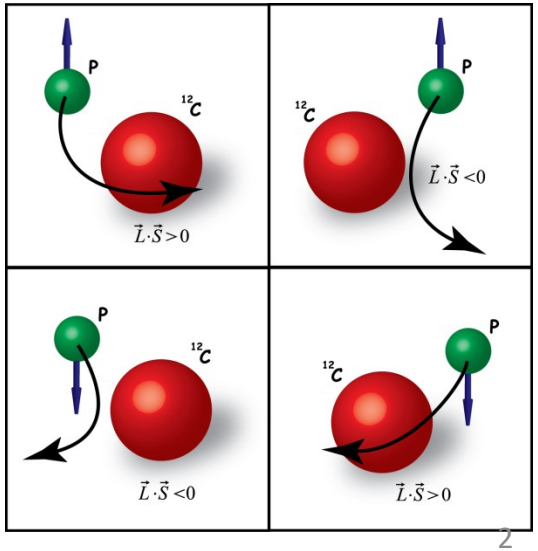
Outline

- Physics motivation
- Electromagnetic form factors
- Polarization transfer measurements
- Survey of polarization transfer data (ratios)
- Focus on the deuteron
- Measuring separate components
- Results
- Summary and Conclusions
- Outlook



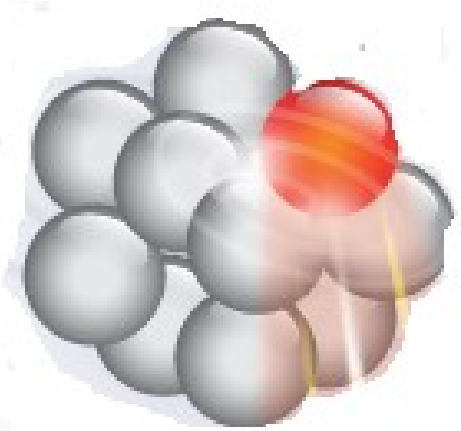


Physics Motivation

- Are nucleon global properties (mass, radius) modified inside nuclei?
  - Do their EM form factors $G_E(Q^2)$, $G_M(Q^2)$ change?
- If so, how do these changes depend on:
  - The nucleus size
  - Nuclear density
  - Q^2
- Can one disentangle inter-nucleon effects (FSI, nucleon-nucleon interactions) from intra-nucleon medium modifications?

Free neutron

$$\tau_n = 15\,\text{min}$$



Bound neutron

$$\tau_{n^*} = \infty$$

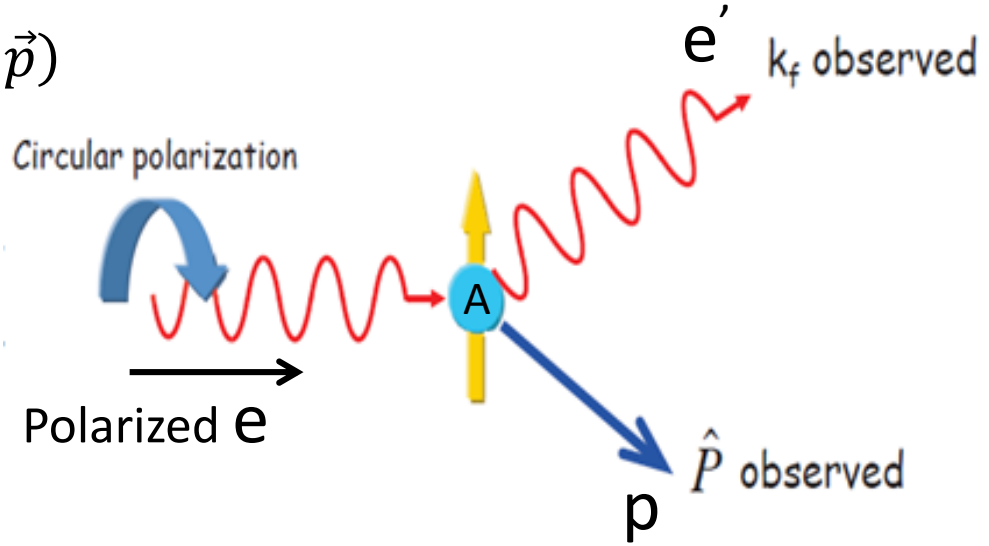
The observables of choice (1)

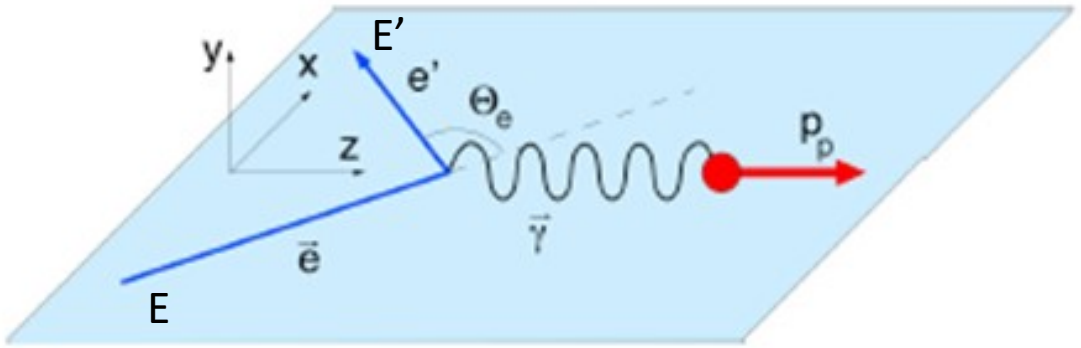
- Use **nucleon spin** as a **tool** to study the nuclear effect on nucleons
- **Polarization transfer** to a knocked-out proton in QE $A(\vec{e}, e'\vec{p})$
- Search for **deviations** w.r.t. ${}^1H(\vec{e}, e'\vec{p})$
- ${}^1H(\vec{e}, e'\vec{p})$, 1-$\gamma$ exchange approximation:

$$hP_e P'_x = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\left(\frac{\theta_e}{2}\right)/I_0\,,$$

$$hP_e P'_z = \frac{E_e + E'_e}{M}\sqrt{\tau(1+\tau)}G_M^2 \tan^2\left(\frac{\theta_e}{2}\right)/I_0$$

$$\frac{P'_x}{P'_z} = -\frac{2m_p}{(E_e + E'_e)\tan\left(\frac{\theta_e}{2}\right)}\frac{G_E}{G_M}$$

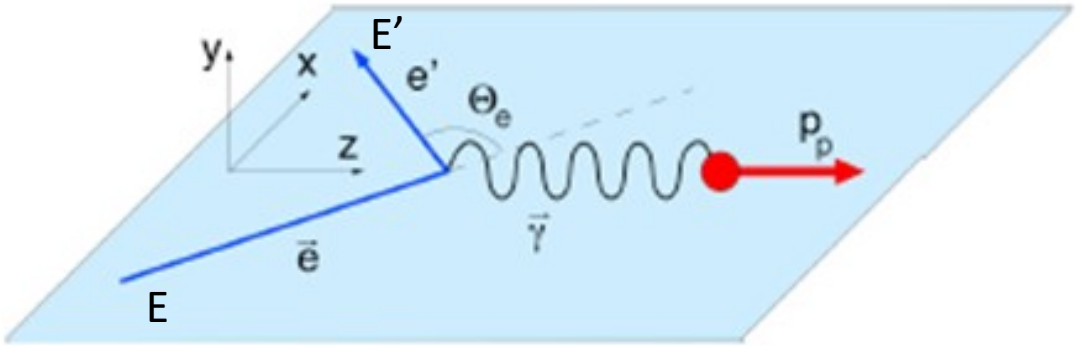




The observables of choice (2)

$$\frac{P_x}{P_z} = -\frac{G_E}{G_M}\frac{2M}{E+E'}\cot\frac{\theta_e}{2}$$

G_E, G_M: Proton Form Factors (FFs)

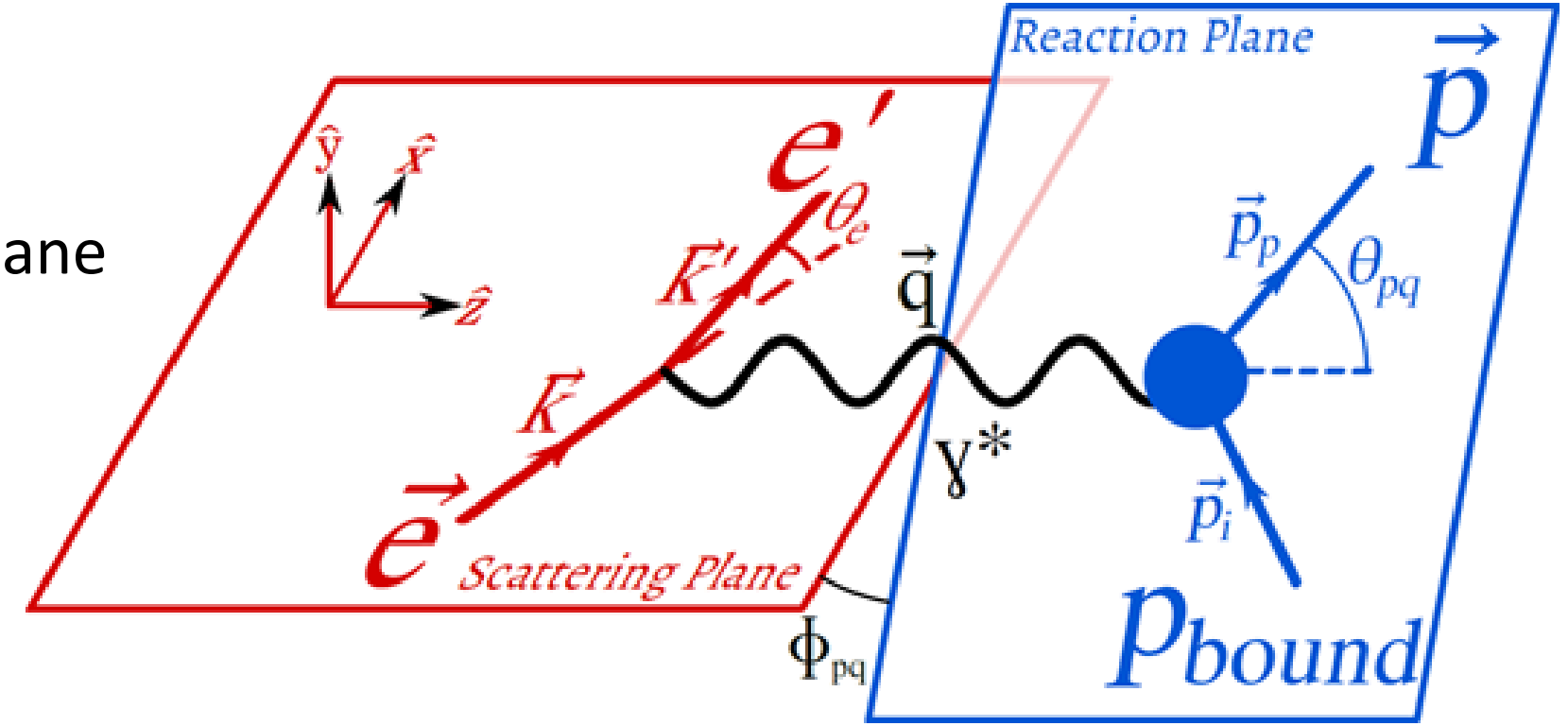


- Since $\left(\frac{P_x}{P_z}\right)_p \propto \frac{G_E}{G_M}$, then perhaps $\left(\frac{P_x}{P_z}\right)_A \propto \frac{G_E^*}{G_M^*}$
- G_E^*, G_M^*: nuclear-medium modified electromagnetic proton FFs
- The measurement of $\left(\frac{P_x}{P_z}\right)_A$ is:
  - obtained from a single measurement with a few % syst. and stat. uncertainties
  - minimally affected by radiative corrections

The observables of choice (3)

- $\left(\frac{P_x}{P_z}\right)_A$: Reaction Plane is rotated w.r.t. Scattering Plane

- Measure $\left(\frac{P_x}{P_z}\right)_A (\vec{p}_i)$



- $\vec{p}_i$ is **unmeasurable,** but $\vec{p}_{miss} = \vec{q} - \vec{p}_p$ is **measurable**
- Within **PWIA**, and assuming **no FSI** → $\vec{p}_i = -\vec{p}_{miss}$

The observables of choice (4)

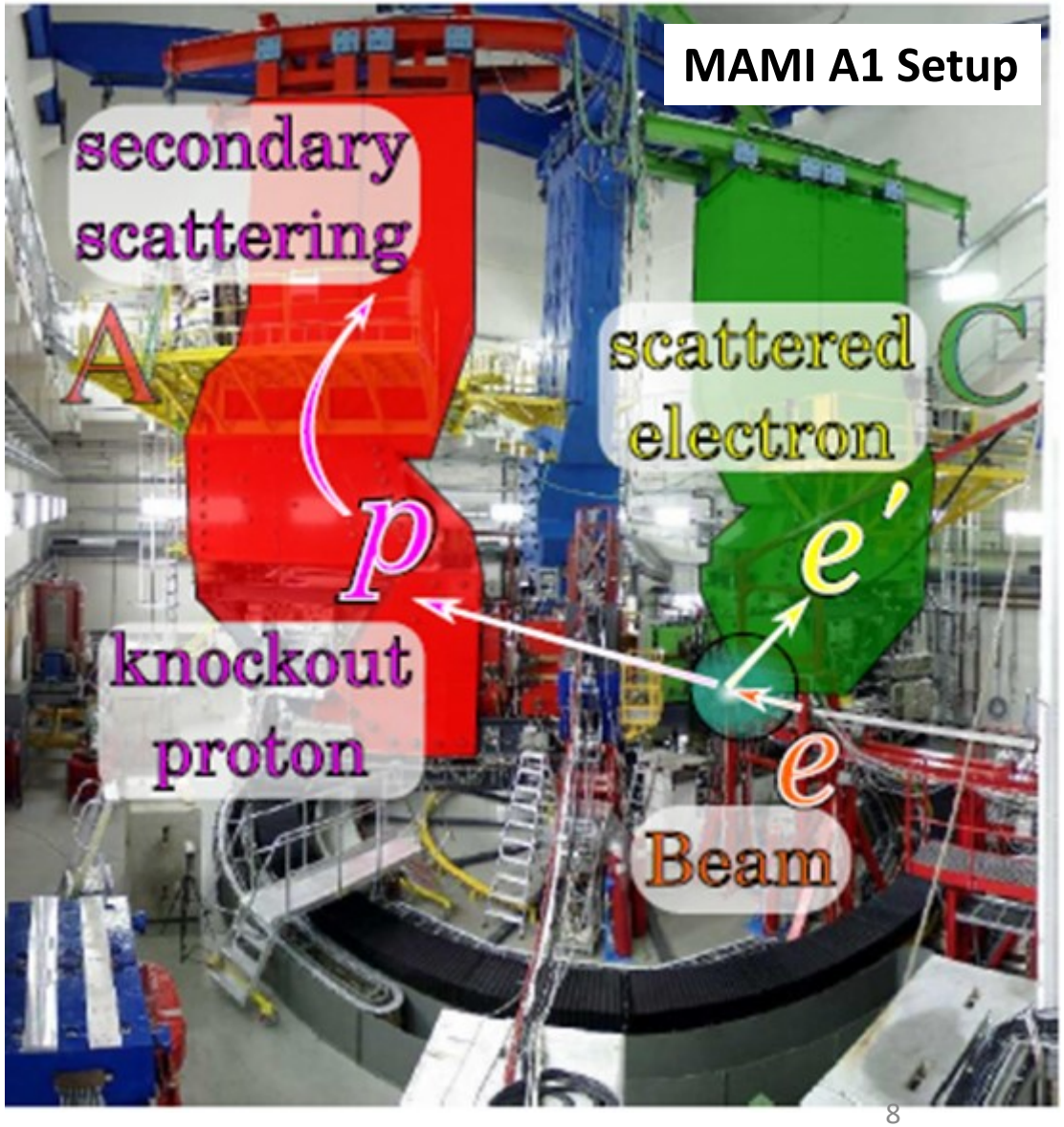
- Goal: measure gradual increase of nuclear effects on $\left(\frac{P_x}{P_z}\right)_A$
- Possible by reaching for higher $\vec{p}_{miss}$
- More straight-forward: measure $\left(\frac{P_x}{P_z}\right)_A$ versus nuclear effect on the proton:

  → how deeply it is bound → how 'off-shell' it is → how **virtual** it is:

- $\nu = P_{miss}^2 - M_p^2 = \left(M_A - \sqrt{M_{A-1}^2 + |\vec{p}|_{miss}^2}\right)^2 - |\vec{p}|_{miss}^2 - M_p^2$
- Note: assume that only struck proton is off-shell

Polarization transfer measurements

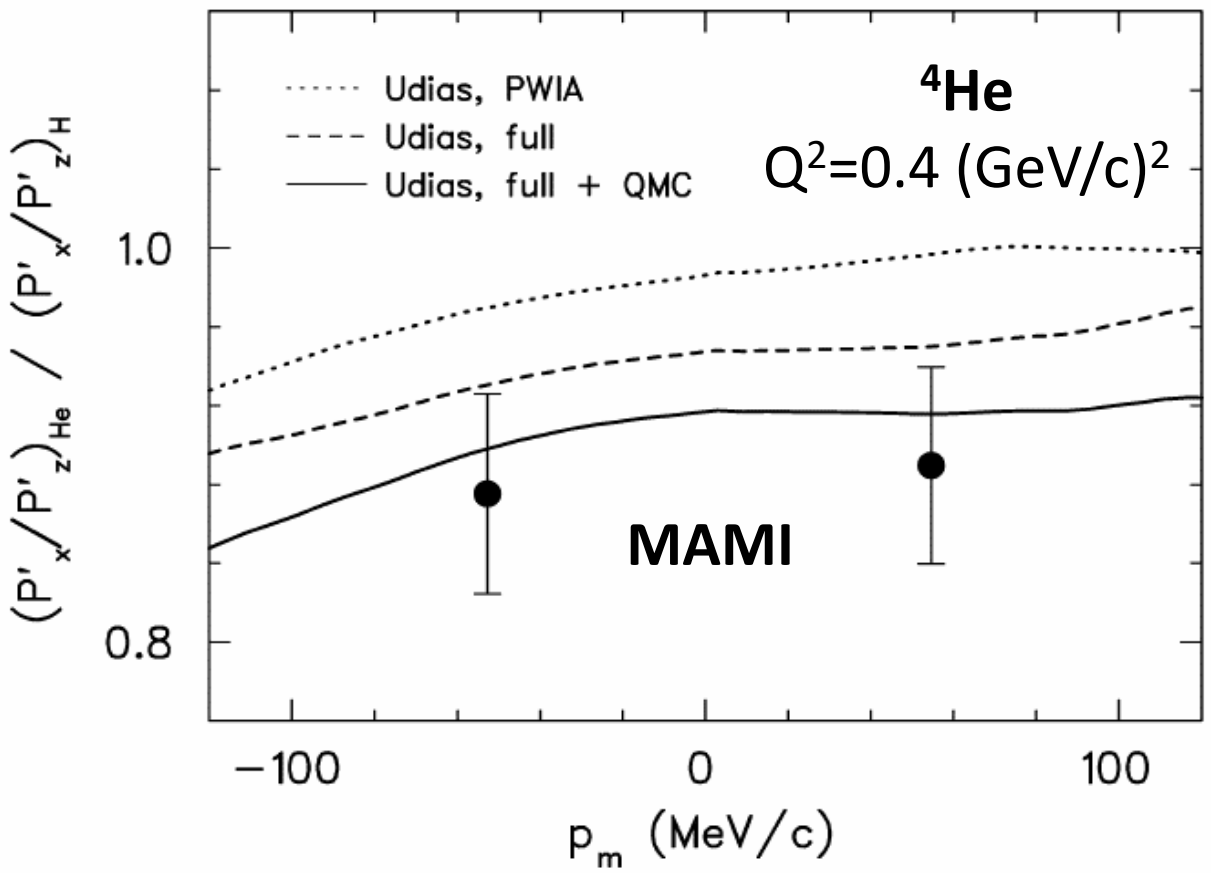
- $\left(\frac{P_x}{P_z}\right)_A$ were measured at
  - JLAB (Q^2 = **0.4 – 2.6** (GeV/c)^2)
  - MAMI (Q^2 = **0.18 – 0.4** (GeV/c)^2)
- Measurements performed on:
  ^{2}H, **^{4}He** and **^{12}C**
- At **MAMI** (**MA**inz **MI**crotron):
  - Used 2 spectrometers in coincidence (A, C)
  - E_e = 600, 630 MeV (Q^2 = 0.18, 0.4 (GeV/c)^2)
  - I_e = 10 μA CW
  - Beam polarization ~ 80%
  - Used Focal Plane Polarimeter (FPP) in spectrometer A for polarization measurements



Polarization transfer data (1)

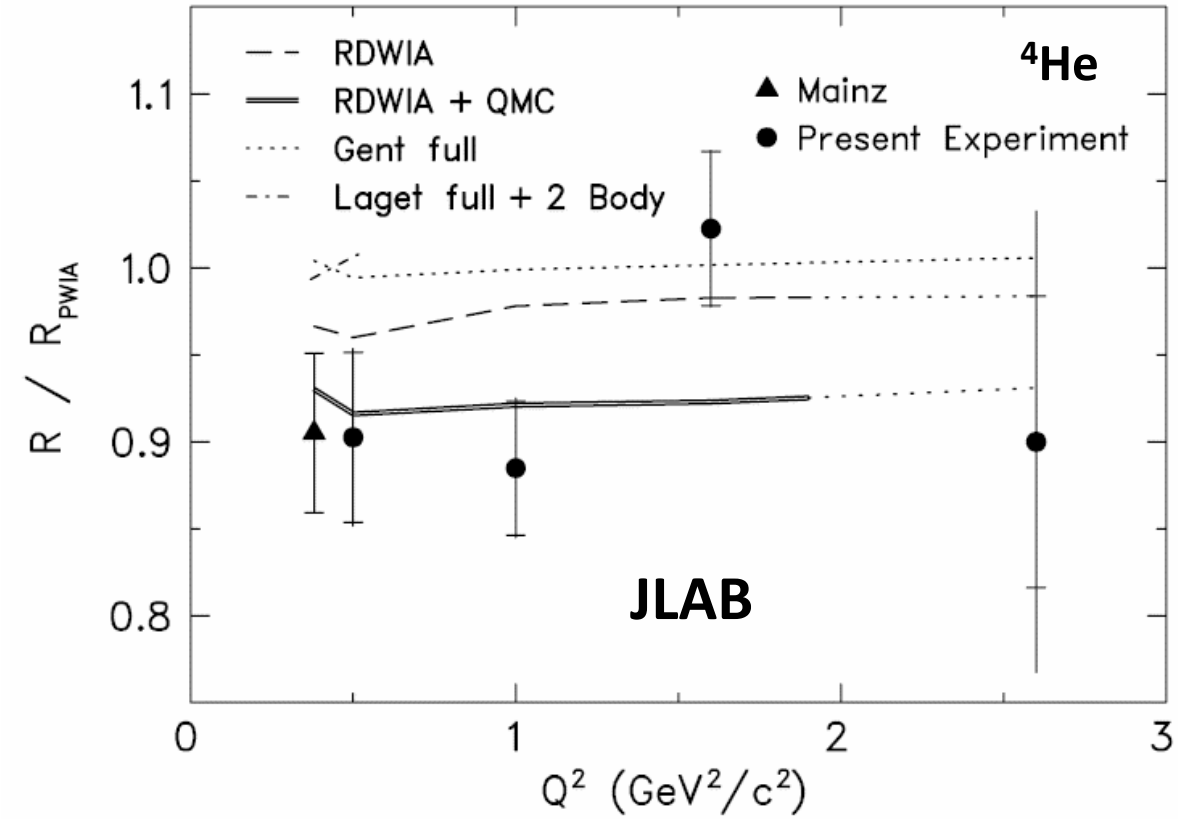
- **Consistent** with:
  full RC + medium modification of the proton FF (QMC model)
- In clear **disagreement** with:
  PWIA and **NR** calculations
- The statistical significance is
  not sufficient to exclude calculations without form factor modification

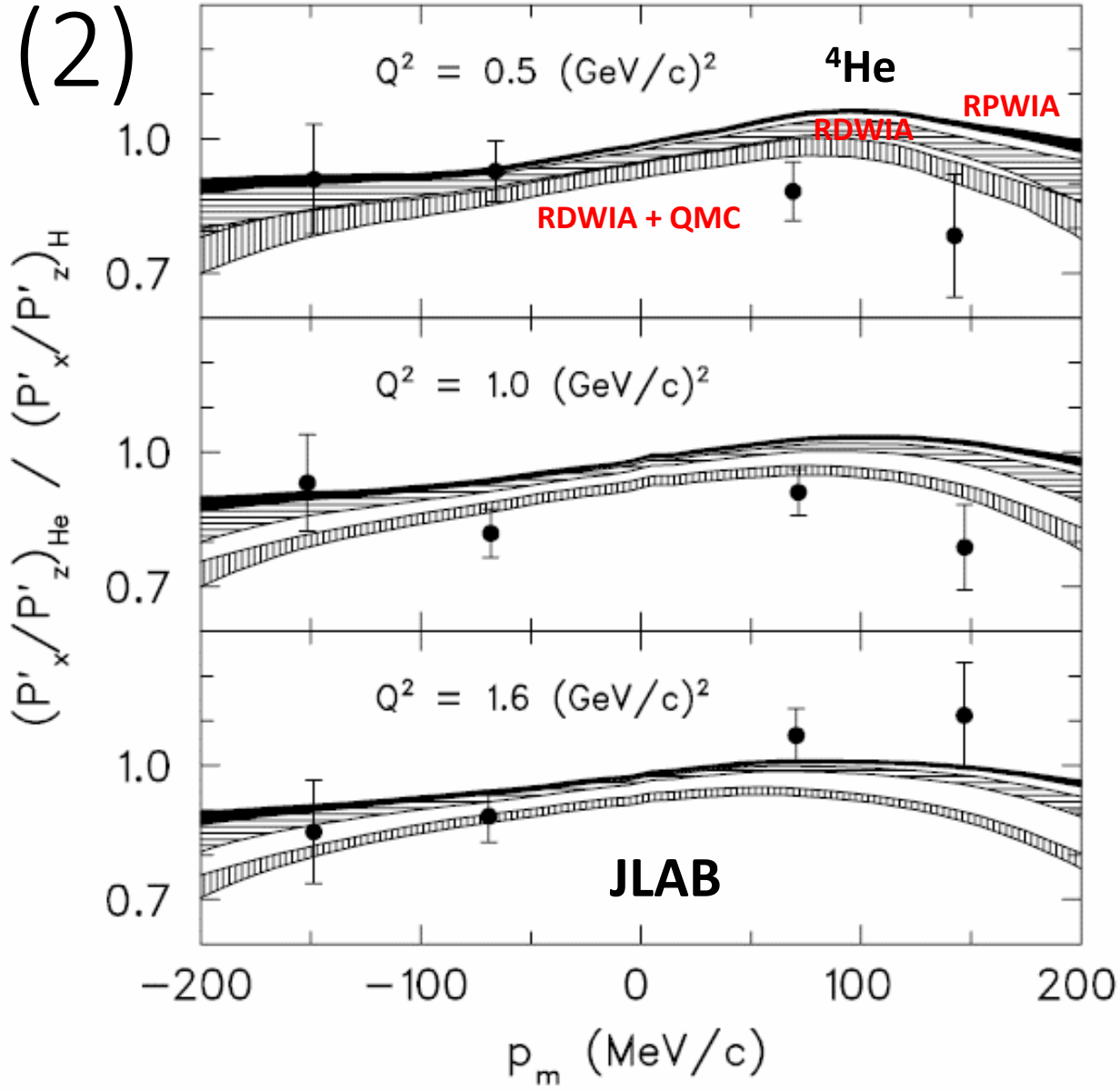
S. Dieterich et al., PLB 500 (2001) 47



Polarization transfer data (2)

- Practically **Q^2 independent**
- **Differs** from a **full RC**
- **Favors** a **medium modification of the proton form factors** predicted by a **QMC model**



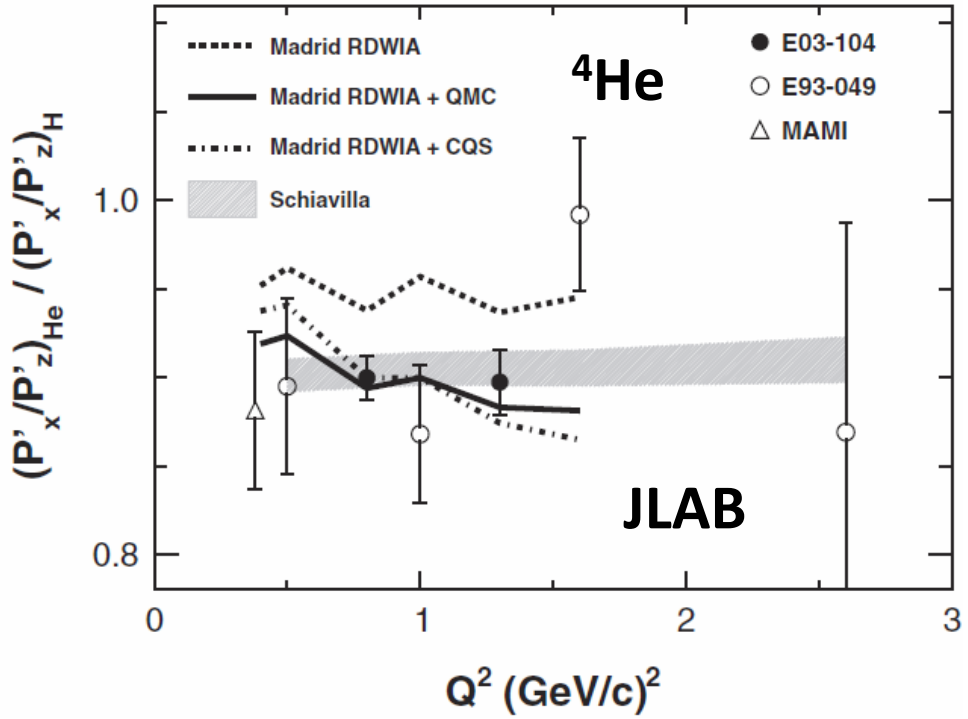


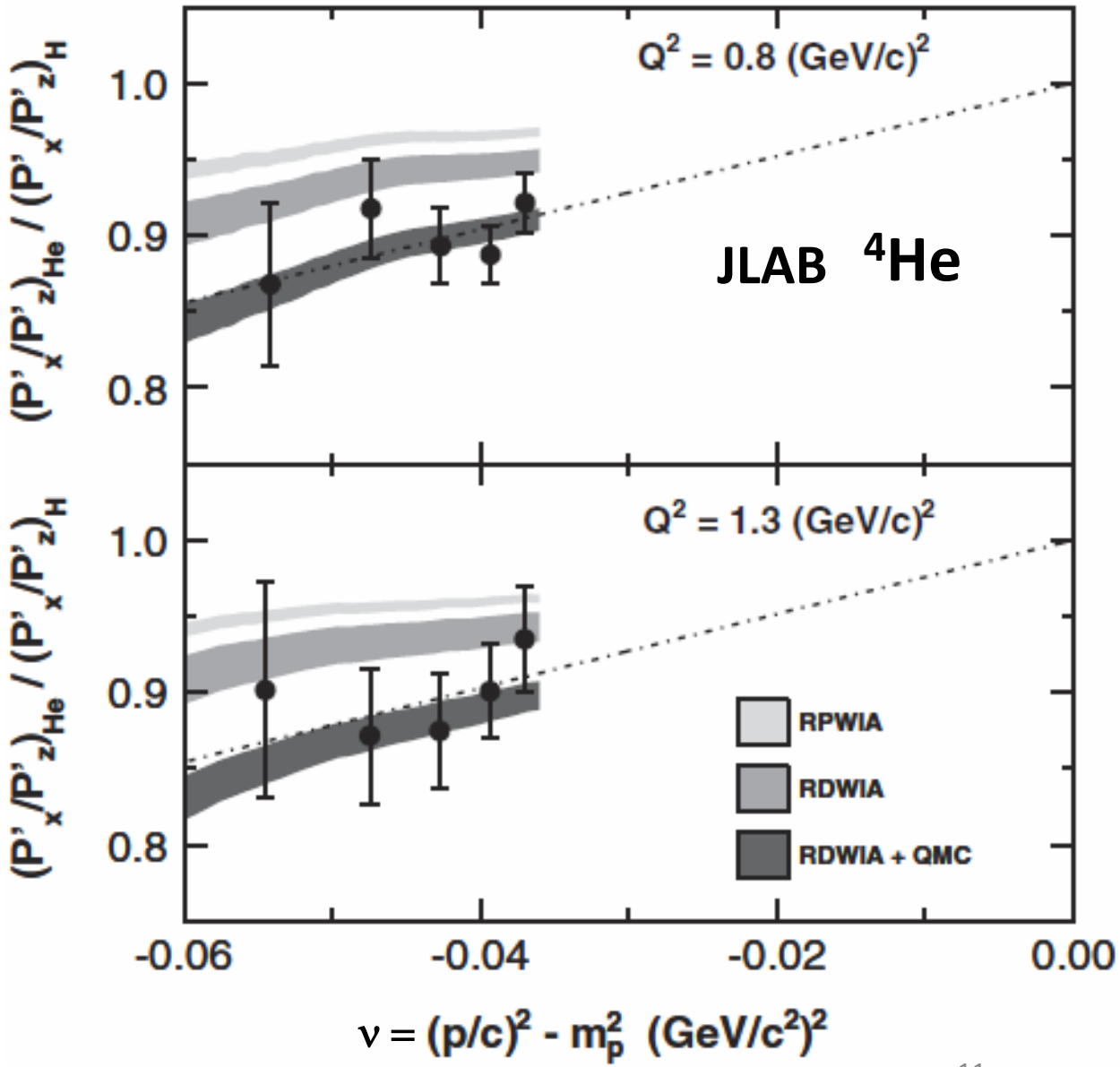
S. Strauch et al., PRL 91 (2003) 052301

Polarization transfer data (3)

M. Paolone et al., PRL 105 (2010) 072001

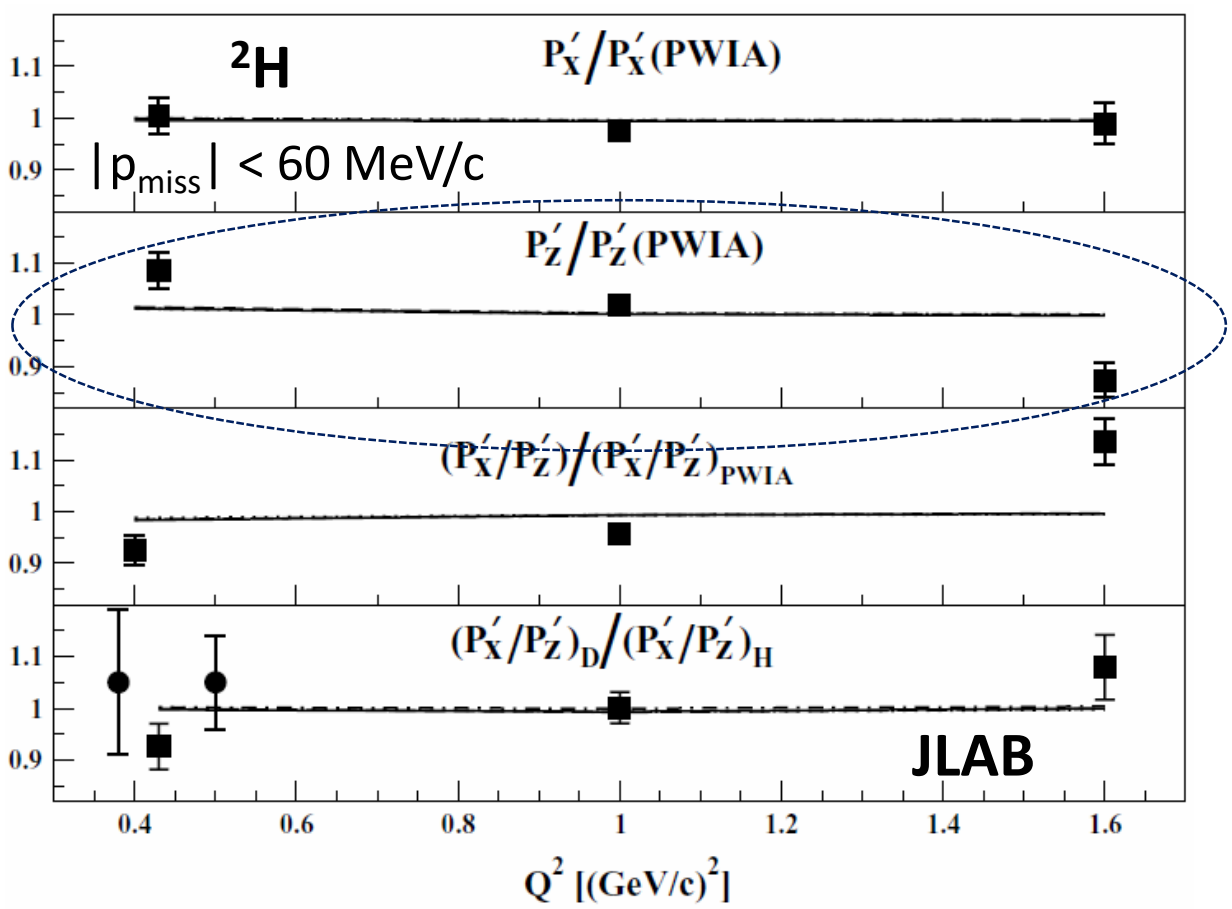
- **Q^2 independence** stays intact
- Enter presentation of data versus **virtuality**
- Results **contradict** a **relativistic DWIA**
- Results **favor** either:
  medium-modified proton FFs by QMC (Madrid)
  or **spin-dependent CX FSI (Schiavilla)**

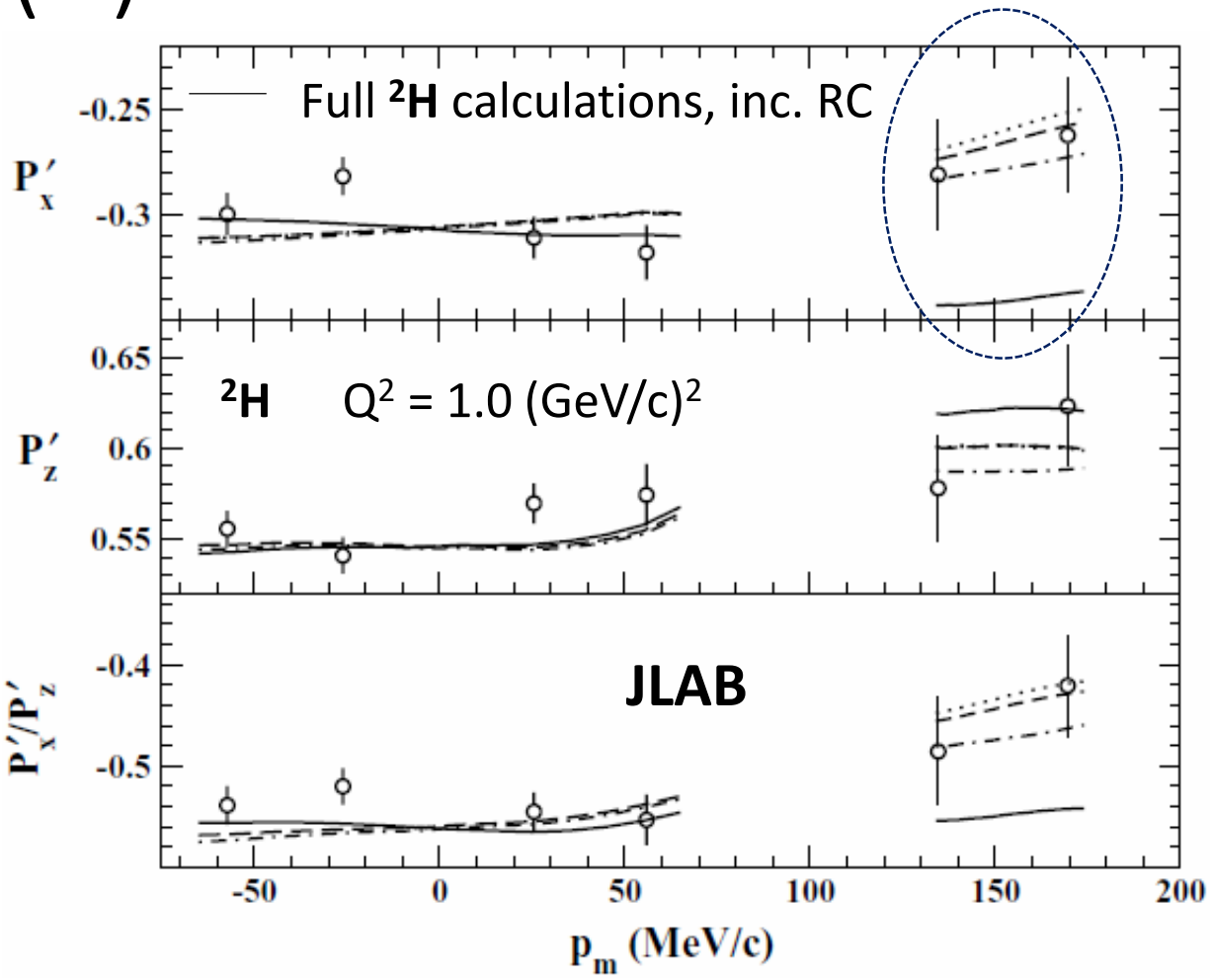




Polarization transfer data (4)

- **High p_{miss}:**
  P_x is **inconsistent** with **deuteron reaction model**
- **Low p_{miss}**: Q^2 dependence of **P_z** is **inconsistent** with **deuteron reaction model**



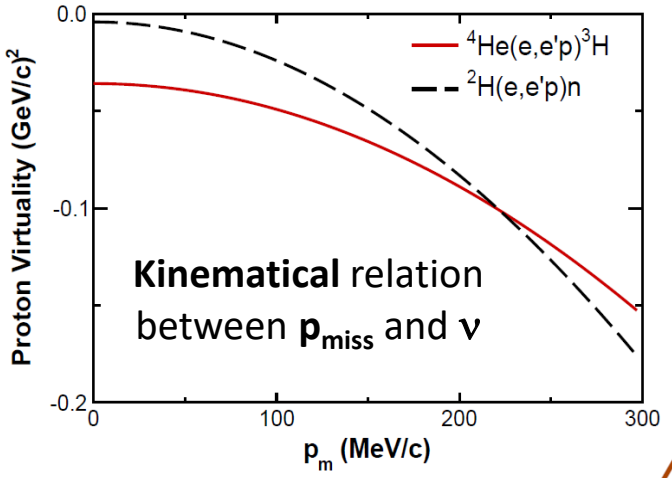


B. Hu, et al. PRC 73, 064004 (2006)
Deuteron reaction model: Arenhovel et al.

Polarization transfer data (5)

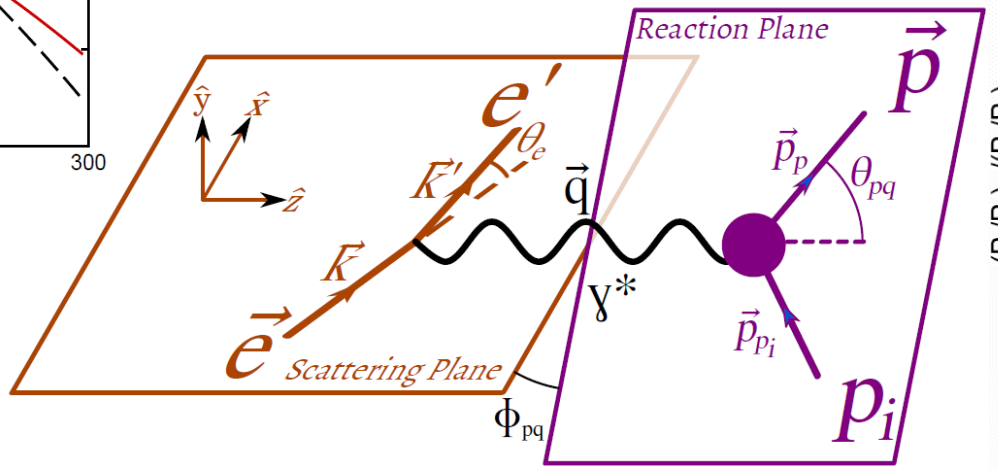
I. Yaron et al., PLB 769 (2017) 21–24

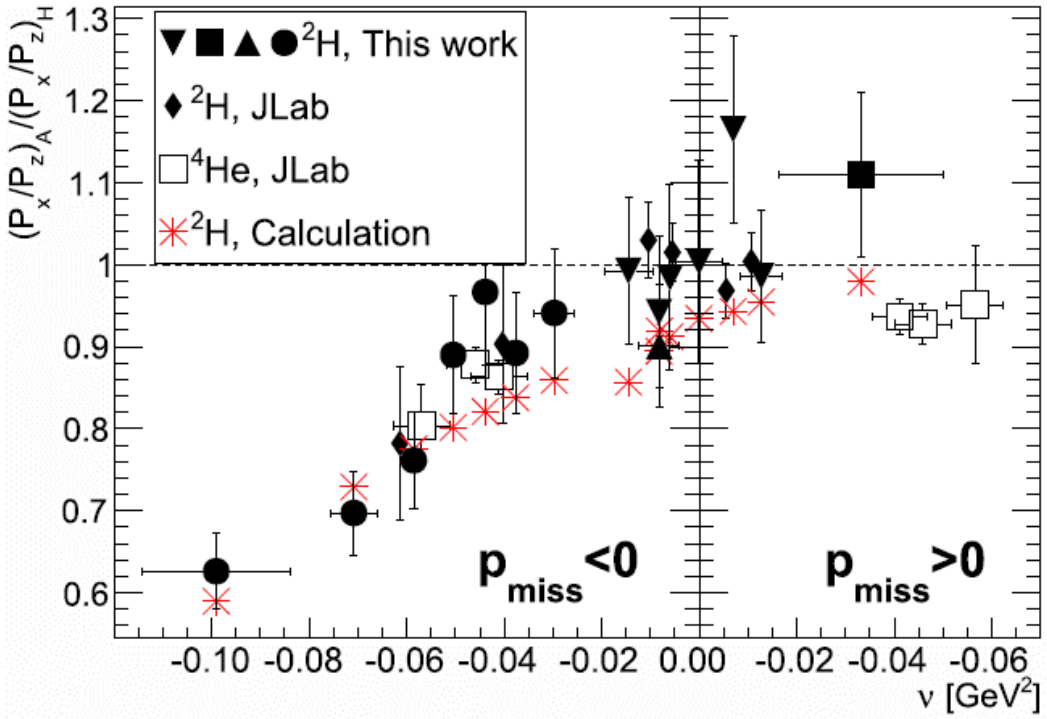
- $\left(\frac{P_x}{P_z}\right)_{2H} / \left(\frac{P_x}{P_z}\right)_{1H}$ and $\left(\frac{P_x}{P_z}\right)_{4He} / \left(\frac{P_x}{P_z}\right)_{1H}$ behave **similarly**
- **Nuclear effect:** function of **virtuality** of the knock-out proton and the $\mathbf{p_{miss}}$ **direction**
- Seems **independent** of the average **nuclear density** and **Q^2**
- **General agreement** between data and full calculations, which assume **free proton form factors**

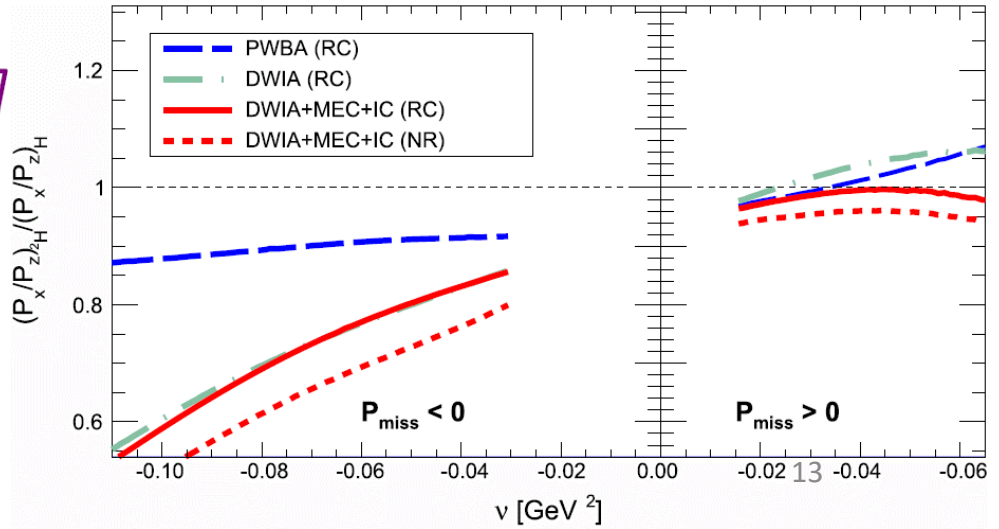


$\vec{p}_{miss} > 0 \leftrightarrow$ has a component ∥ to $\vec{q}$

$\vec{p}_{miss} < 0 \leftrightarrow$ has a component ∥ to $-\vec{q}$



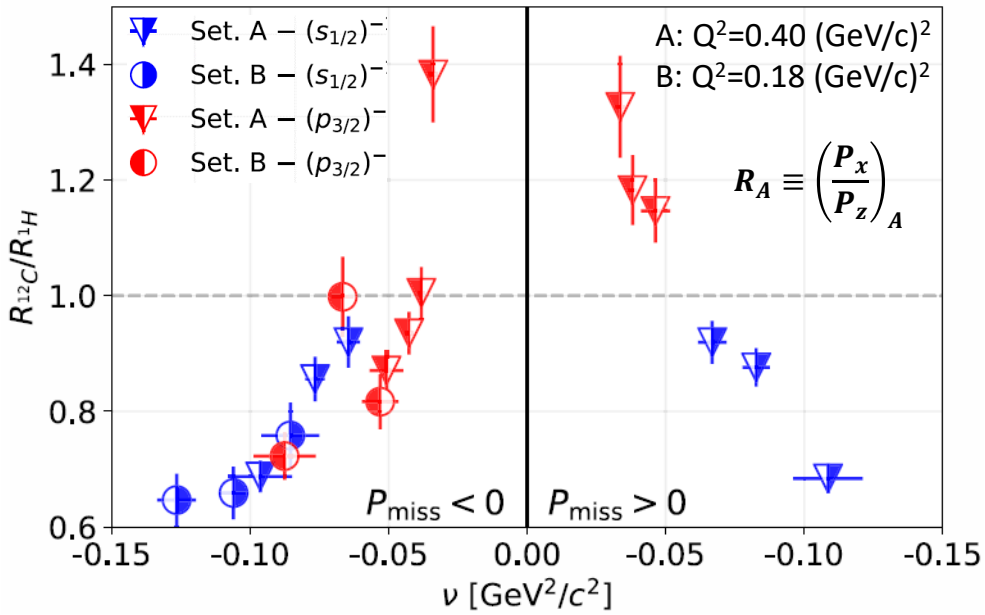




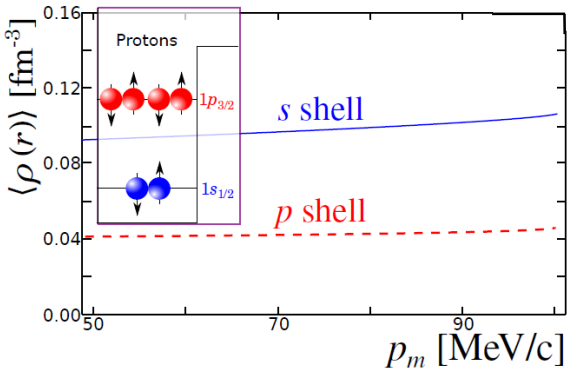
Polarization transfer data (6)

D. Izraeli et al., PLB 781 (2018) 95–98

- Enter **^{12}C**. Data from **different density regions** by separating knockout protons from **S-** and **P-shells**
- **R_A/R_{1H}** for **^{2}H**, **^{4}He**, **^{12}C(S)**, **^{12}C(P)** are consistent, even when obtained in different kinematics.
- Data suggest **universal behavior**, independent of **average local density** and **Q^2**.

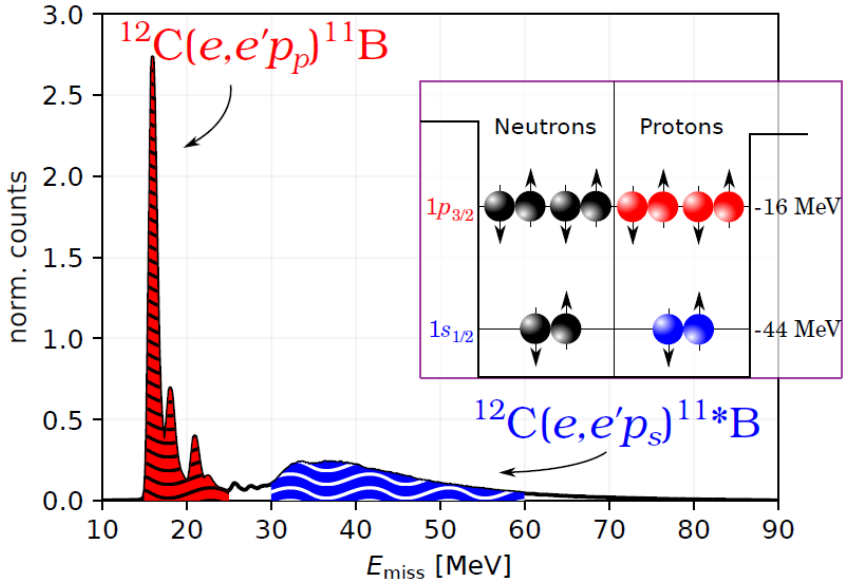


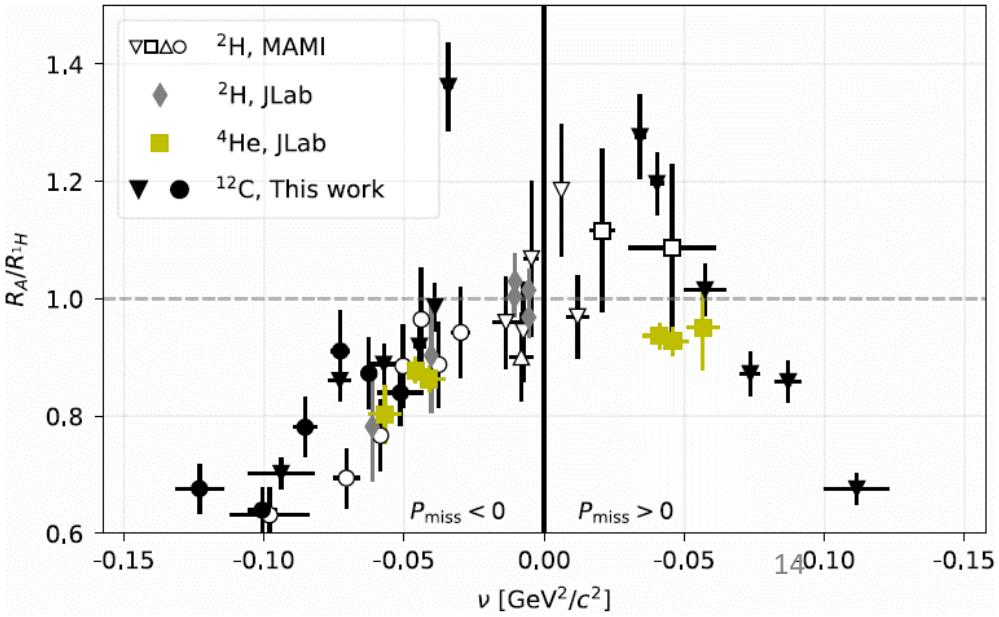
E_{miss} < 28 MeV:
p-shell knockout
28 < E_{miss} < 50 MeV:
s-shell and **multi-particle** knockout



G. Ron et al., PRC 87, 028202 (2013)

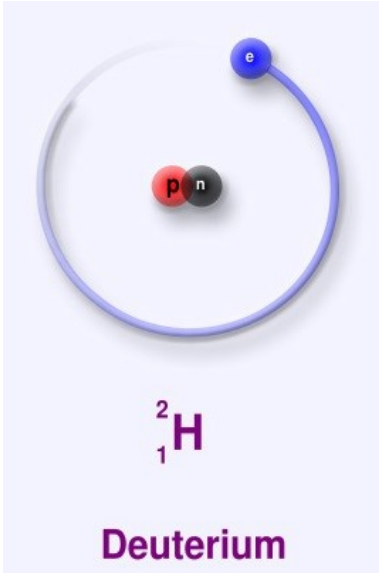
$$E_{miss} = \omega - T_p - T_{11B}$$



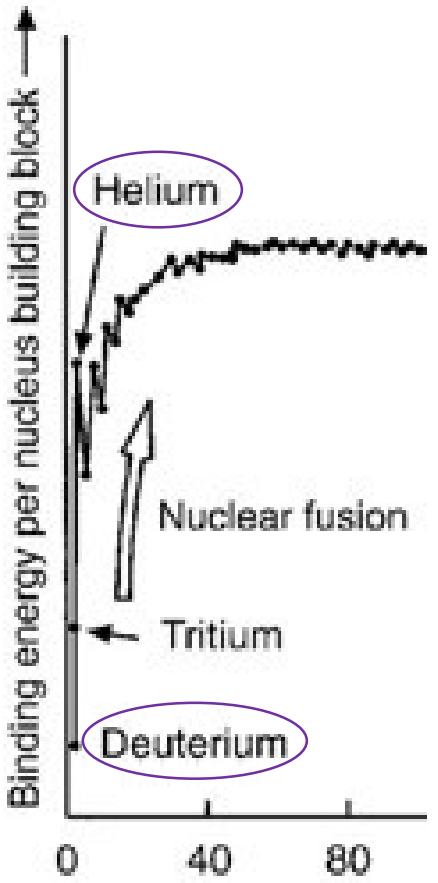


Deeper investigation of the deuteron

- The **most loose** nuclear system
  - Often used as a **'free neutron'** target
- Nevertheless, **bound nucleons** can still be **'off-shell'**
- No local nuclear density changes
- Perform experiments as low Q^2 - nucleon radius
- Good calculations (H. Arenhövel et al.*)
  - Meson Exchange Currents (MEC)
  - Isobar Configuration (IC)
  - Relativistic Correction (RC)
  - Final State Interactions (FSI)
  - Free proton EM Form Factors



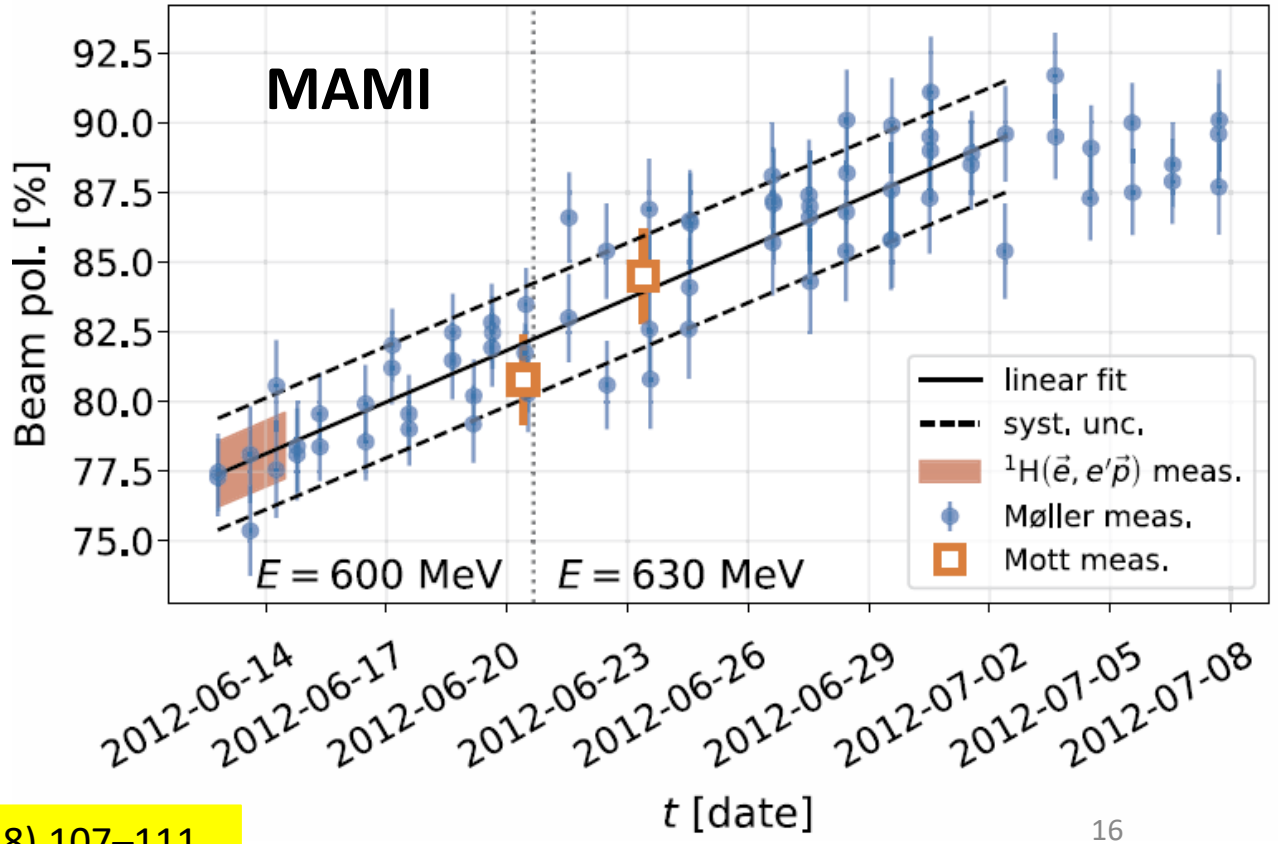
B. E. (^{2}H) = 2.2 MeV
B. E. (^{4}He) = 28.3 MeV



*H. Arenhövel et al., Eur. Phys. J. A 23 (2005) 147–190

Extraction of ^{2}H polarization transfer components (1)

- Precise determination of e^- beam polarization
  → reduced systematic uncertainties on the components
- Enabled detailed comparison to Arenhövel's calculation using free-proton EM FFs
- Used fitted beam-polarization instead of fluctuating periodic measurements
- Overall normalization determined by $^1H(\vec{e}, e'\vec{p})$ measurements
- Beam-polarization uncertainty significantly reduced

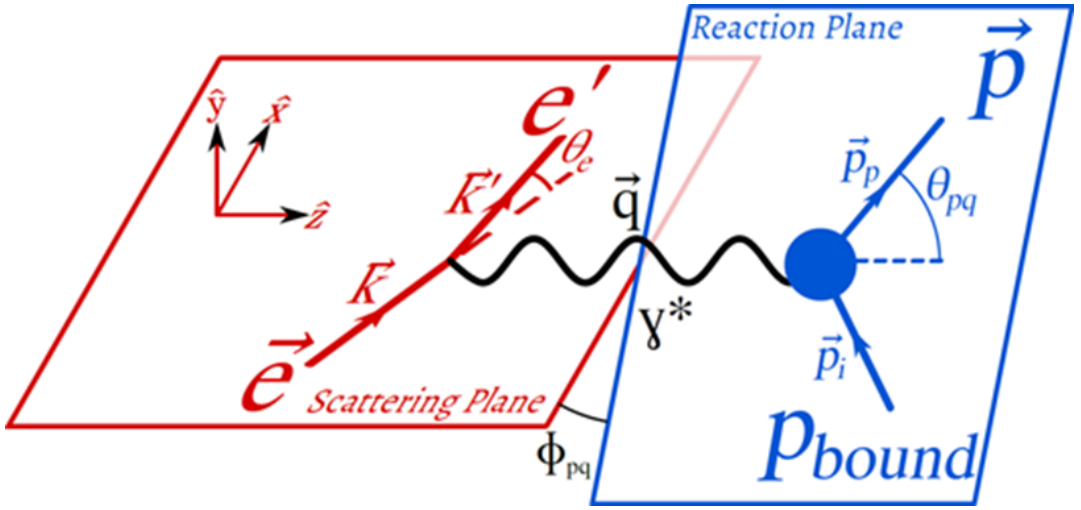


D. Izraeli et al., PLB 781 (2018) 107–111

Extraction of ^{2}H polarization transfer components (2)

- Beam polarization was precise enough for extracting polarization transfer components with the required uncertainty (not only P_x/P_z)
- P_y component determined as well
- For ^{1}H, P_y=0 → P_y can be compared only to calculations

- While **P_x/P_z** is sensitive (almost linearly) to **G_E/G_M**, some **nuclear effects may cancel out** in the ratio.
- The measured individual **polarization transfer components** may provide a **more stringent test** of the **calculation**



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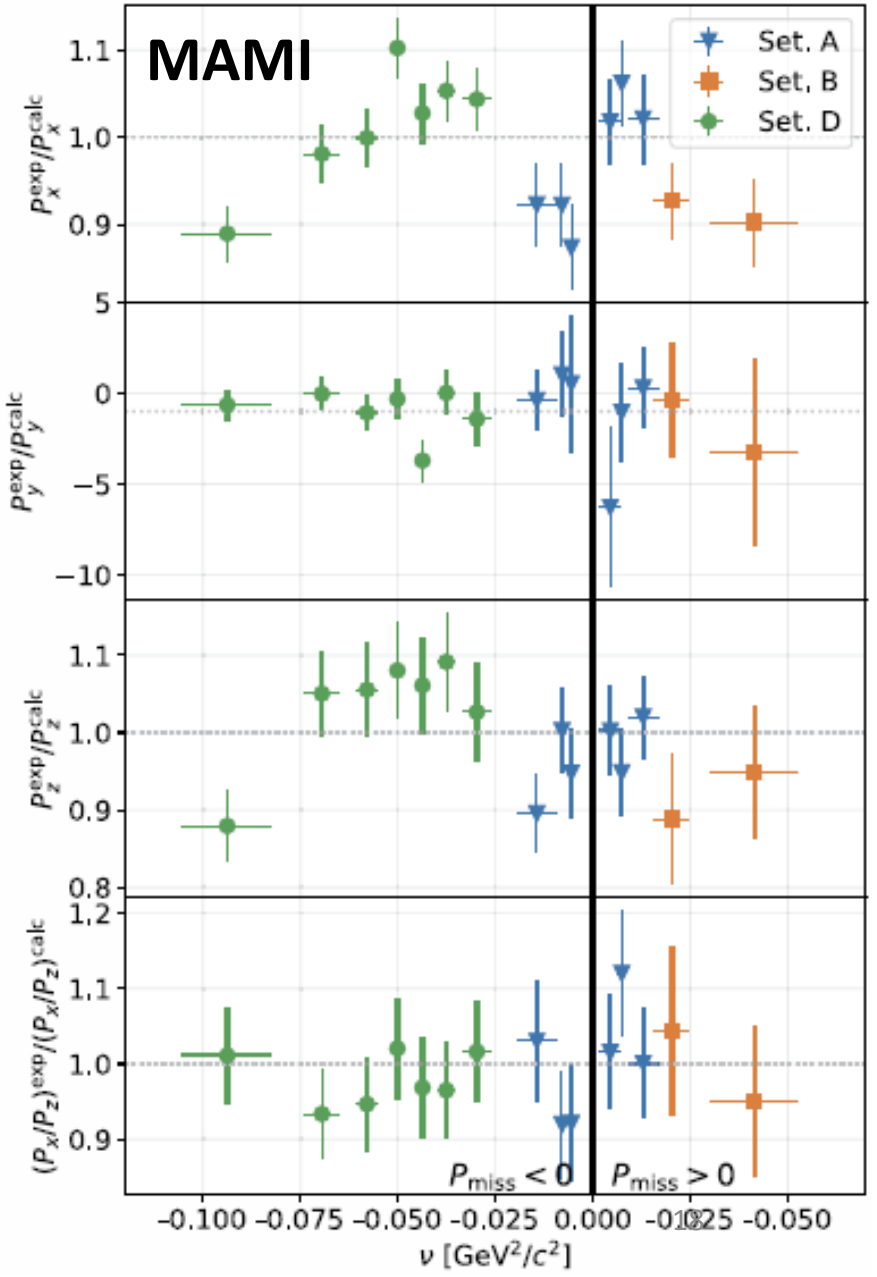
^{2}H polarization transfer components results (1)

Kinematic	Setting		
	A	B	D
Q^2 [GeV^2/c^2]	0.40	0.4	0.18
E_{beam} [MeV]	600	600	630
p_{miss} [MeV/c]	−80 to 75	75 to 175	−220 to −130

- Exp/Calc ratios were extracted event-by-event over the entire data set
- **P_x/P_z agrees** highly significantly with the **calculation** (**p = 0.91**)
- This indicates **no need for modifications in G_E/G_M**
- Experimental **P_x** and **P_z** values **differ** from **calc,** especially at **high p_{miss}**
- **Py** differs highly, maybe due to division of very small numbers
- Modifications in **G_E** and **G_M** are thus possible, but only if they keep the ratio **G_E/G_M** intact
- Excluding **FF** modifications, deviations of **P_x** and **P_z** suggest that nuclear effects and/or RC included in the calculation should be improved



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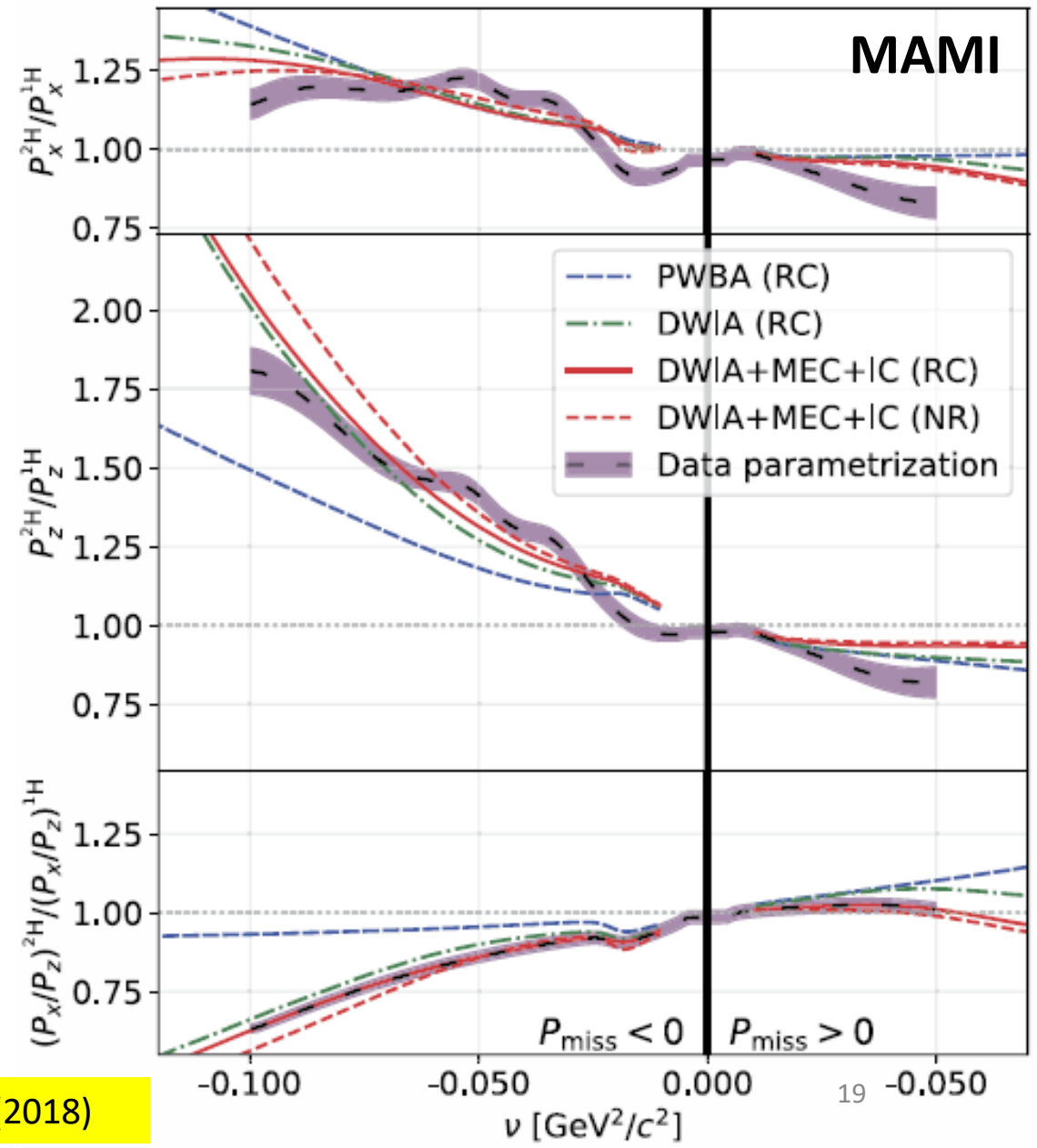
^{2}H polarization transfer components results (2)

- A **continuous parametrization** of the data (avoids losing information due to averaging within bins) was derived for ^{2}H polarization transfer ratios to ^{1}H
- Done by a **novel method***, relating the data to a realistic model of the deuteron
- This process requires extraction of experimental polarization transfer components
- Number of parameters was optimized to avoid over-fitting
- **Main deviation** from the free proton is due to **FSI** (compare **PWBA** and **DWIA**)
- Observed deviation of P_x/P_z is **mainly due to P_z**, which seems to be **more sensitive** to **FSI** and **RC** than P_x



D. Izraeli et al., PLB 781 (2018) 107–111

*D. Izraeli et al., JINST 13 P07209 (2018)

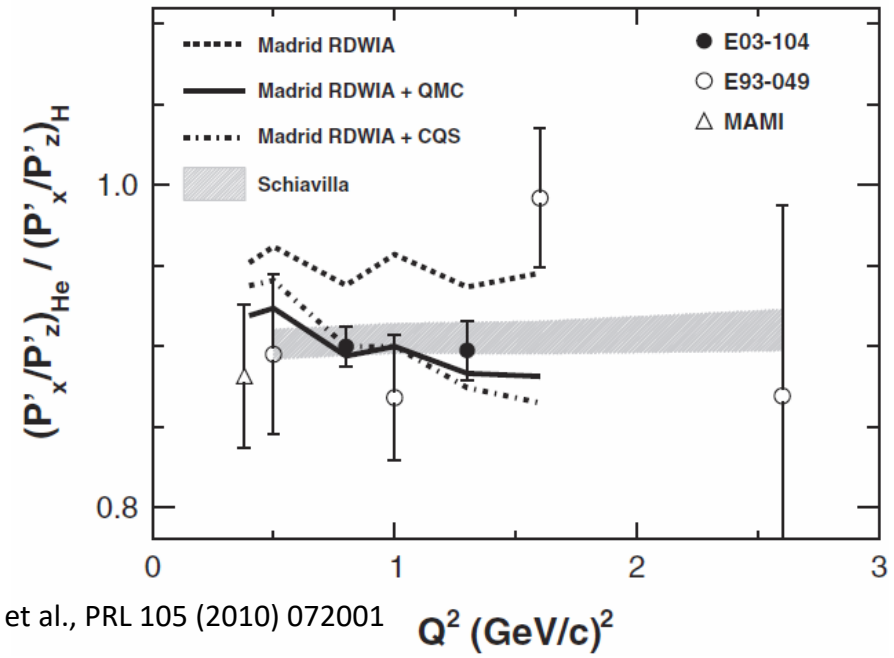
Physics Motivation – stock taking so far

- Are nucleon global properties (mass, radius) modified inside nuclei?
  - Do their EM form factors $G_E(Q^2)$, $G_M(Q^2)$ change?
- If so, how do these changes depend on:
  - The nucleus size
  - Nuclear density
  - Q^2
- Can one disentangle inter-nucleon effects (FSI, nucleon-nucleon interactions) from intra-nucleon medium modifications?

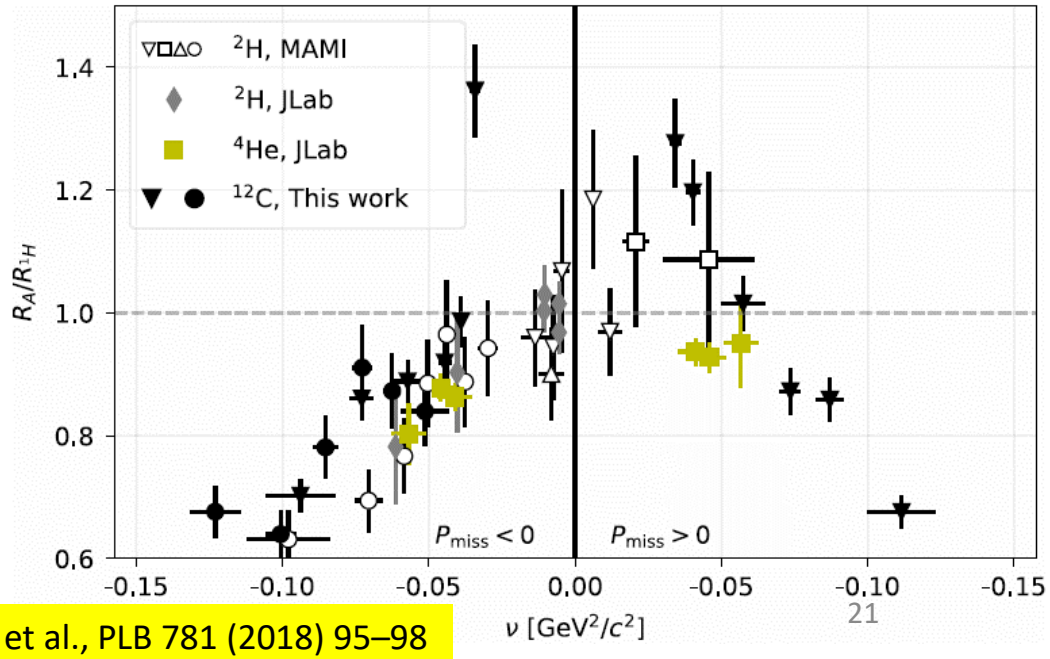
- Some ^{4}He data may suggest it, but no smoking gun yet
- Apparently, relevant measured variables are independent of all 3
- Models are seemingly able to separate 'regular' nuclear effects from medium modifications

Summary and conclusions (1)

- Polarization transfer for **^{2}H**, **^{4}He** and **^{12}C** was collected at relatively wide kinematic conditions (**Q^2 = 0.18 – 2.6 (GeV/c)^2**)
  - 2.6 (GeV/c)^2 point is with a large error
- Still no polarization transfer measurement that **requires medium-modified EM FFs** for its theoretical interpretation
- Nuclear models give good handles in **disentangling** inter-nuclear effects from intra-nucleon effects. **RC** and **FSI** are required for good interpretation
- Polarization transfer ratios seem to be **independent** of the **nuclear size**, **nuclear density** and **Q^2**, in the measured ranges



M. Paolone et al., PRL 105 (2010) 072001



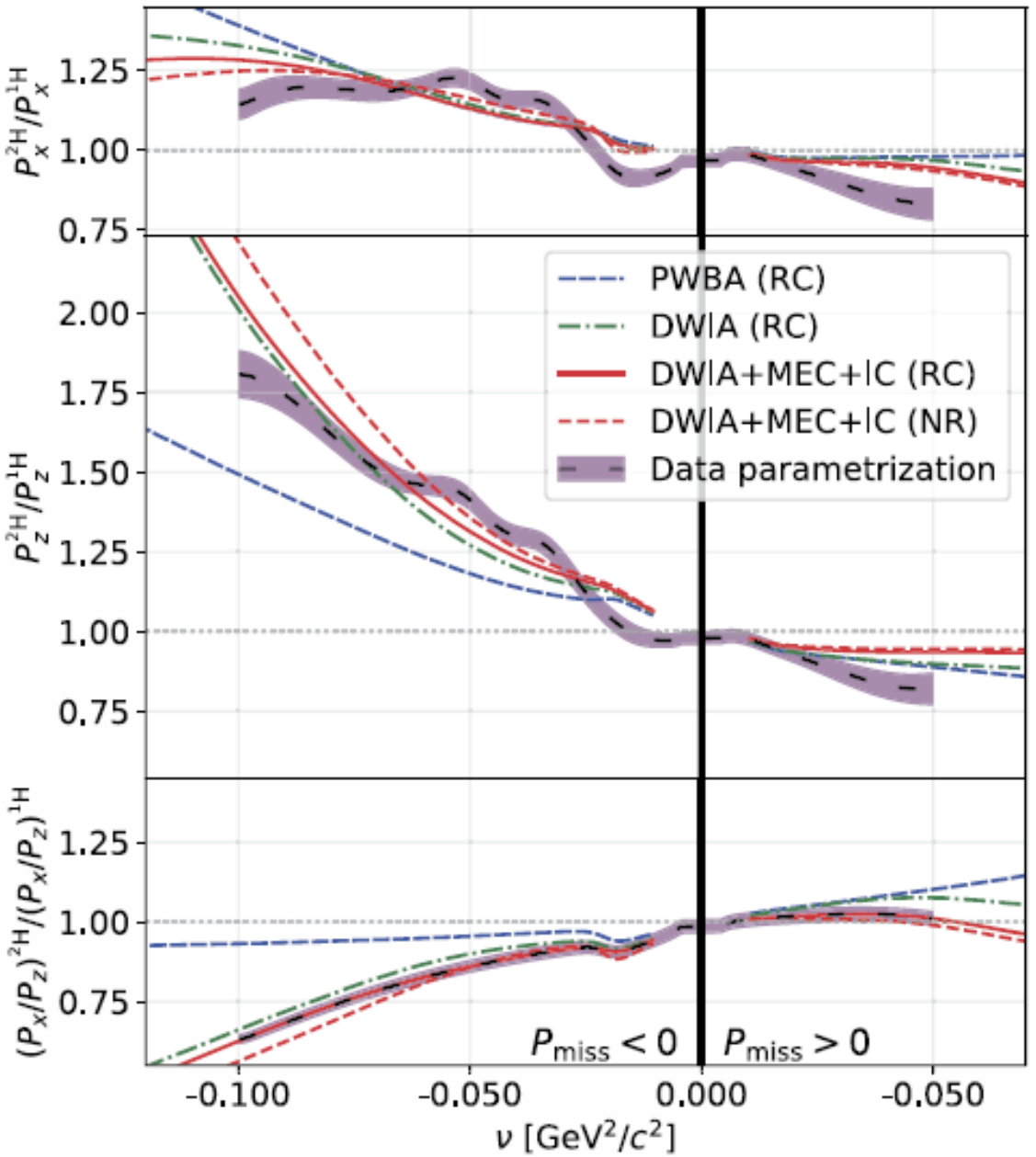
D. Izraeli et al., PLB 781 (2018) 95–98

Summary and conclusions (2)

- Polarization transfer has a **universal smooth behavior** in **virtuality**. This behavior is reconstructed by calculations

- It is possible to select events from **specific local density regions within certain nuclei**, by controlling the **nuclear shell of the knocked-out proton**, via **cuts on** the **missing energy**

- Polarization **components** may provide **more stringent tests** on calculations, since in **ratios** some of the **nuclear effects might cancel out**



D. Izraeli et al., PLB 781 (2018) 107–111

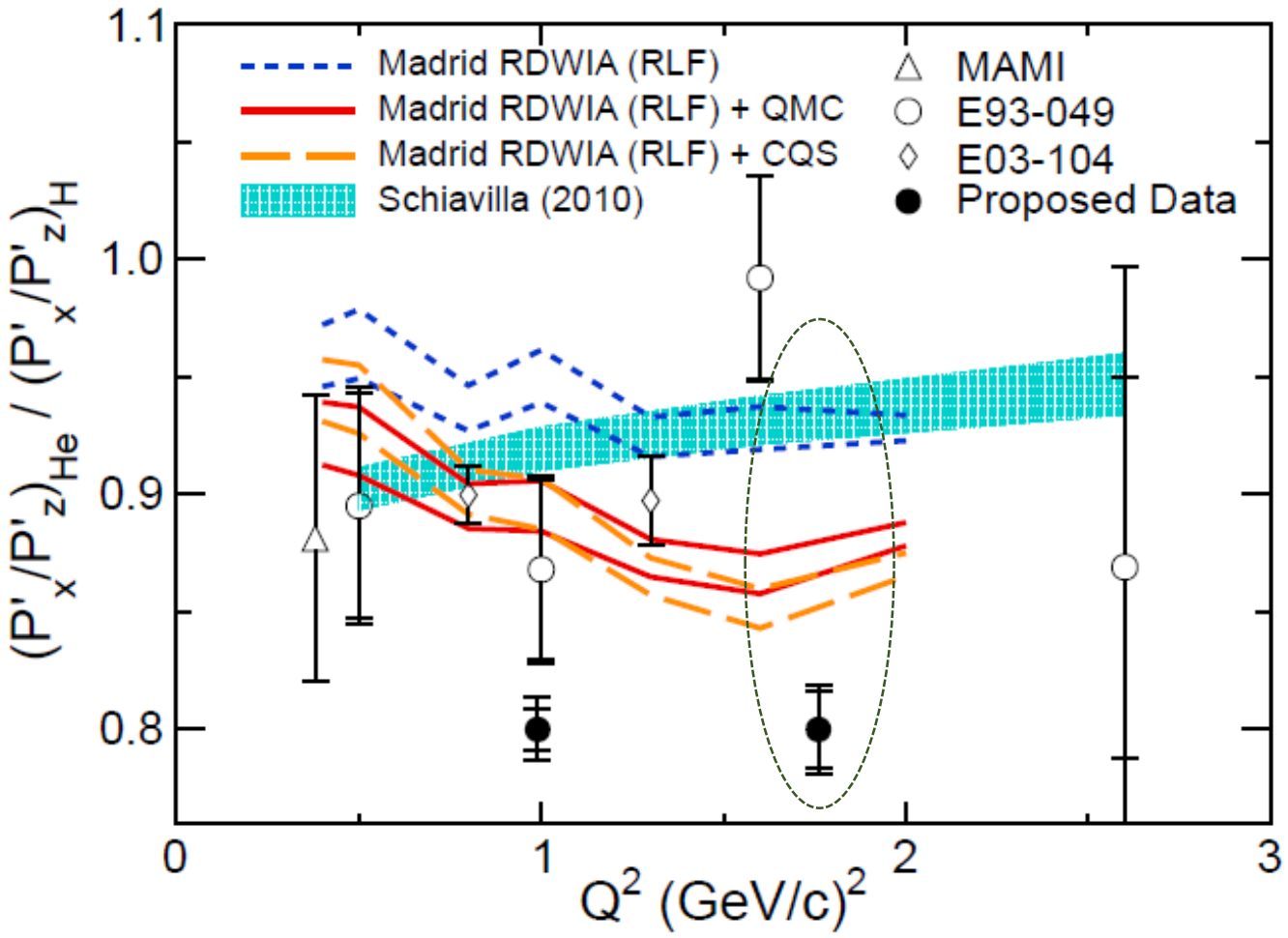
Outlook (1)

- To verify whether medium modifications of nucleons occur or not, **more polarization transfer measurements are required**

- Measurements on **^{2}H, ^{4}He and ^{12}C** should be extended to **higher virtuality (p_{miss})**

  - Approved at JLAB: $^{4}\boldsymbol{He}(\vec{e}, e'\vec{p})$ @ **Q^2 = 1.0, 1.8 (GeV/c)^2**, **-200 < p_{miss} < +300 MeV/c**

  - Nuclear **medium effects** are expected to **increase with virtuality**



S. Strauch et al., JLAB E12-11-002

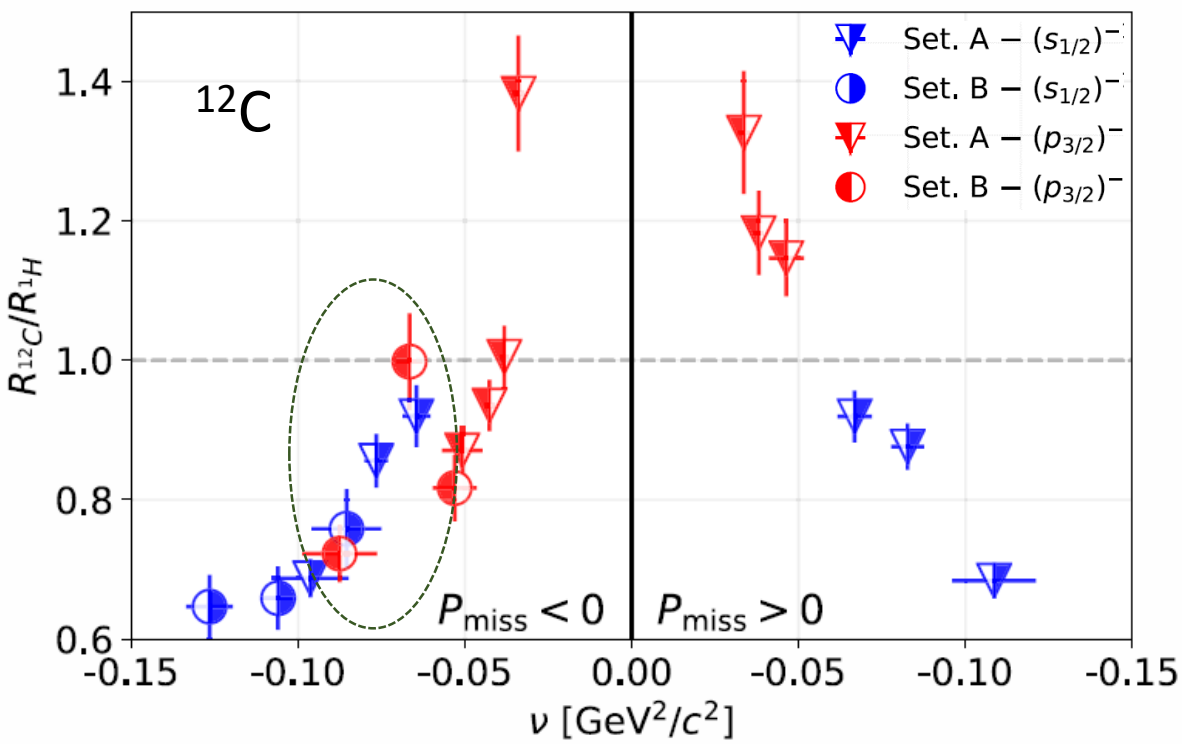
Outlook (2)

- Elaborate measurements on **specific nuclear shells** (s, p in ^{12}C). Especially compare **s and p** results at **same virtuality and kinematics**

- Continue measuring **polarization components**, and not only ratios. Specifically, **compare components at different shells**

- Measure **specific nuclear shells at high Q^2** – in this regime, the contribution of **multi-nucleon reactions** to deep-shell single proton knockout **may be reduced**

- The effect of FSI on polarization transfer may be investigated by measuring **heavier nuclei**



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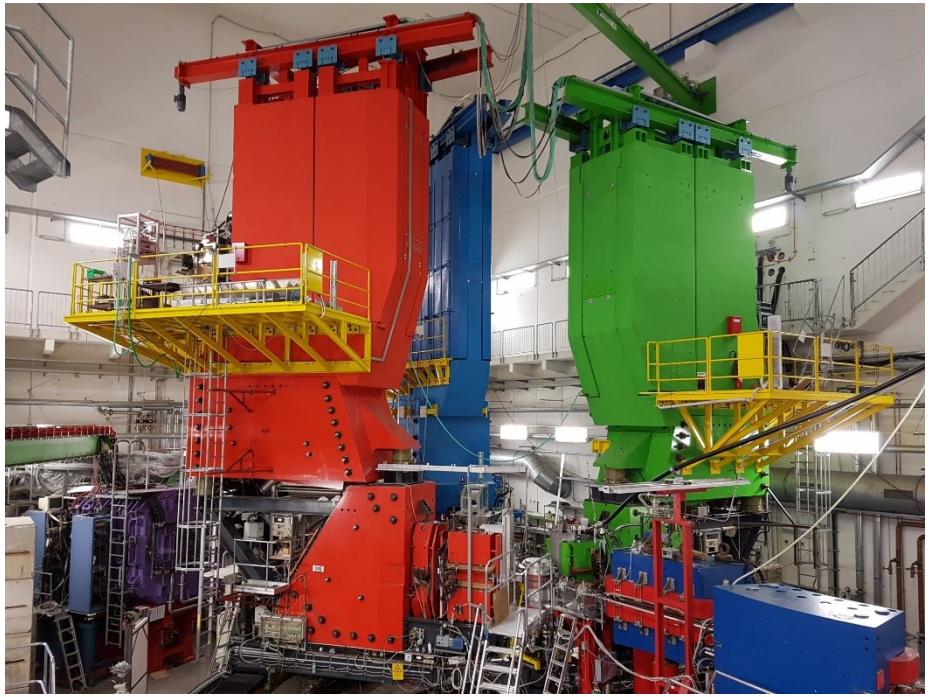

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