NUCLEONS IN THE NUCLEAR MEDIUM

Possible Modifications and Sensitive Observables

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האוניברסיטה העברית בירושלים

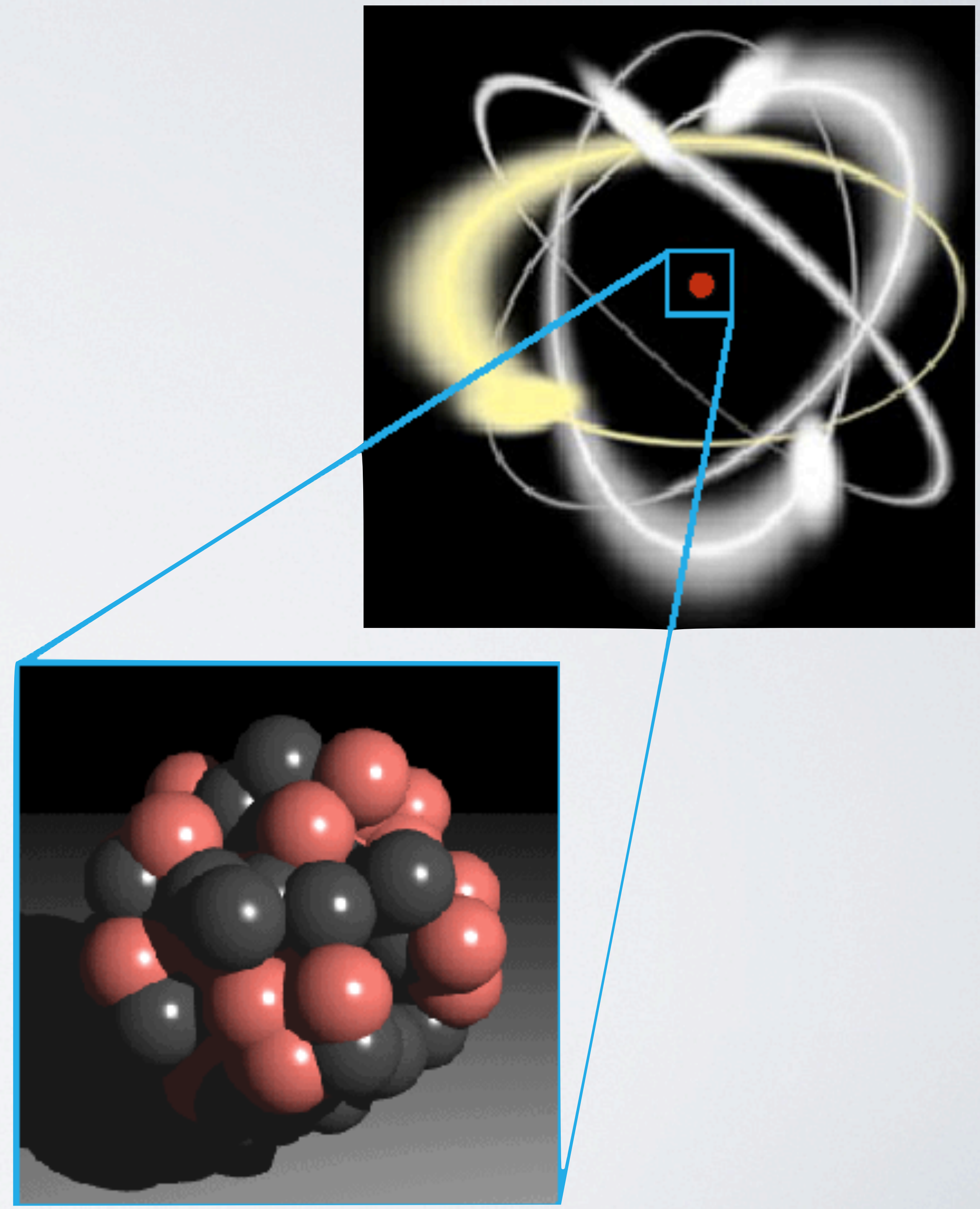
The Hebrew University of Jerusalem

With Many Thanks to S. Strauch (USC)

The Atom

Standard picture of the atom:

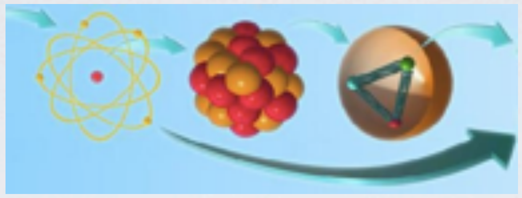
- Electrons zooming around at high velocity, drive the chemistry, interactions of the atom.
- Nuclei are small, static, and uninteresting.



Nuclei are actually complex, dynamic systems.

The Nucleus

Different Things to Different People



- Chemists ➞ Slow, Heavy, and Boring.
- Low Energy Nucl. Phys ➞ Protons + Neutrons, Complex Shell Structure, Angular Momentum.
- Medium Energy Nucl. Phys. ➞ Protons + Neutrons (typically non-interacting).
- High Energy Phys. ➞ Bag of Free Quarks.

Nuclei - Complex, Energetic and Dense

- **Nuclei are incredibly dense**
  - >99.9% of the mass of the atom
  - <1 trillionth of the volume
  - ~10^{14} times denser than normal matter (close to neutron star densities)
- **Nuclei are extremely energetic**
  - "Fast" nucleons moving at ~50% the speed of light
  - "Slow" nucleons still moving at **~10^9 cm/s**, in an object **~10^{-12} cm** in size

Simple picture is totally false, but extremely effective

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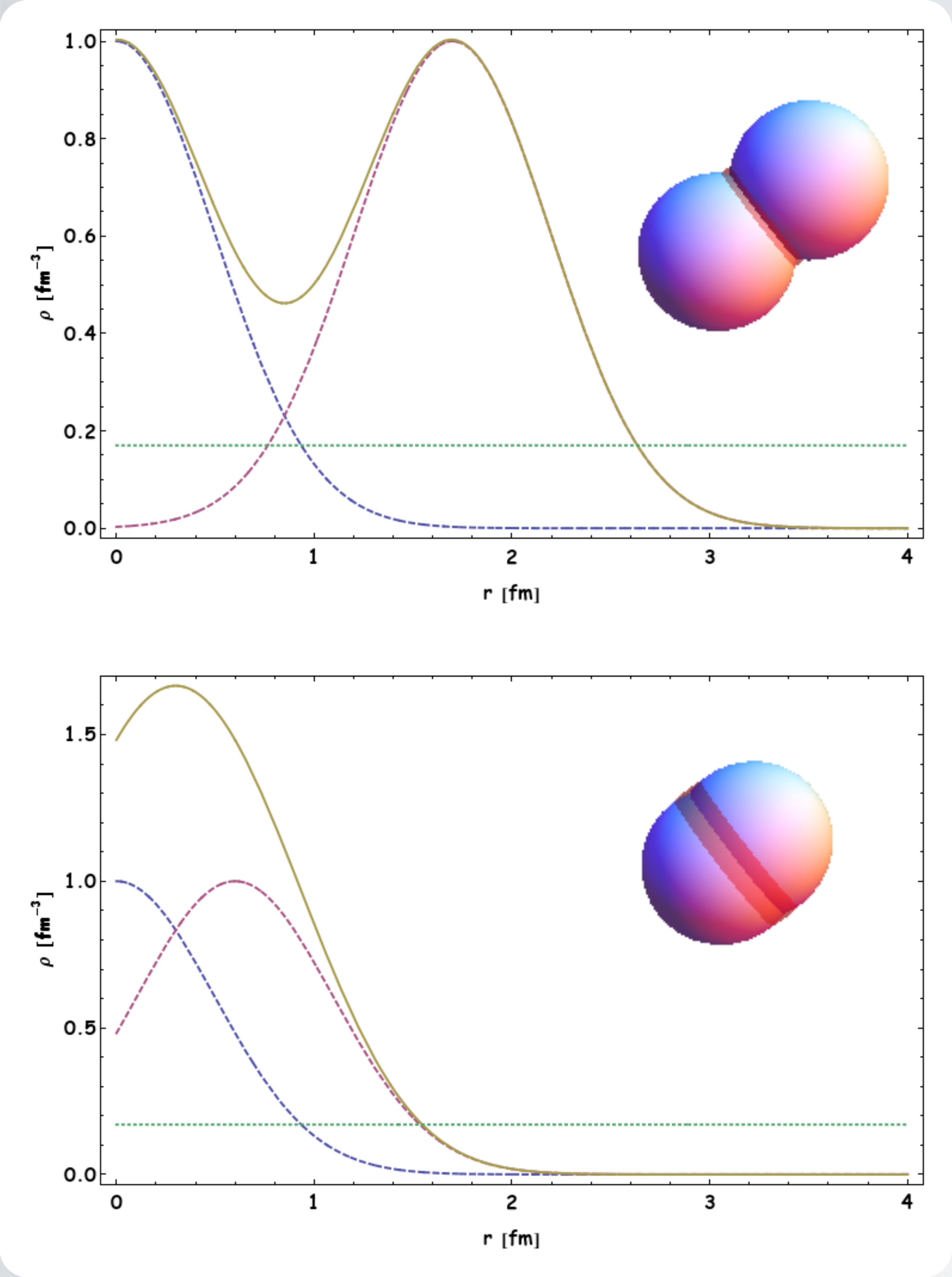
What happens to the nucleons under these conditions?

Nuclei - Complex, Energetic and Dense



Nucleons at average separation.

High momentum (short range) tail. Wavefunctions overlap.

Outline

- Medium Modification Example(s).
- Protons in the medium - some results from E03-104 (JLab).
- A prediction for the neutron
- A new proposal.

Medium Modifications

A Working Definition

- Measure some Experimental Observable for a Free Nucleon.
- Repeat for a Nucleon in a Nucleus.

Call the Difference "Medium Modification"

Nuclei Are Changed in the Nucleus

- 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 nonnucleonic degrees of freedom.
  - Are free nucleons and mesons, under every circumstance, the best quasiparticle 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?

Neutron lifetime in Medium:

Free Neutron

$$\tau_n \sim 15\mathrm{m}$$

Neutron in ^{4}He

$$\tau_n = \infty$$

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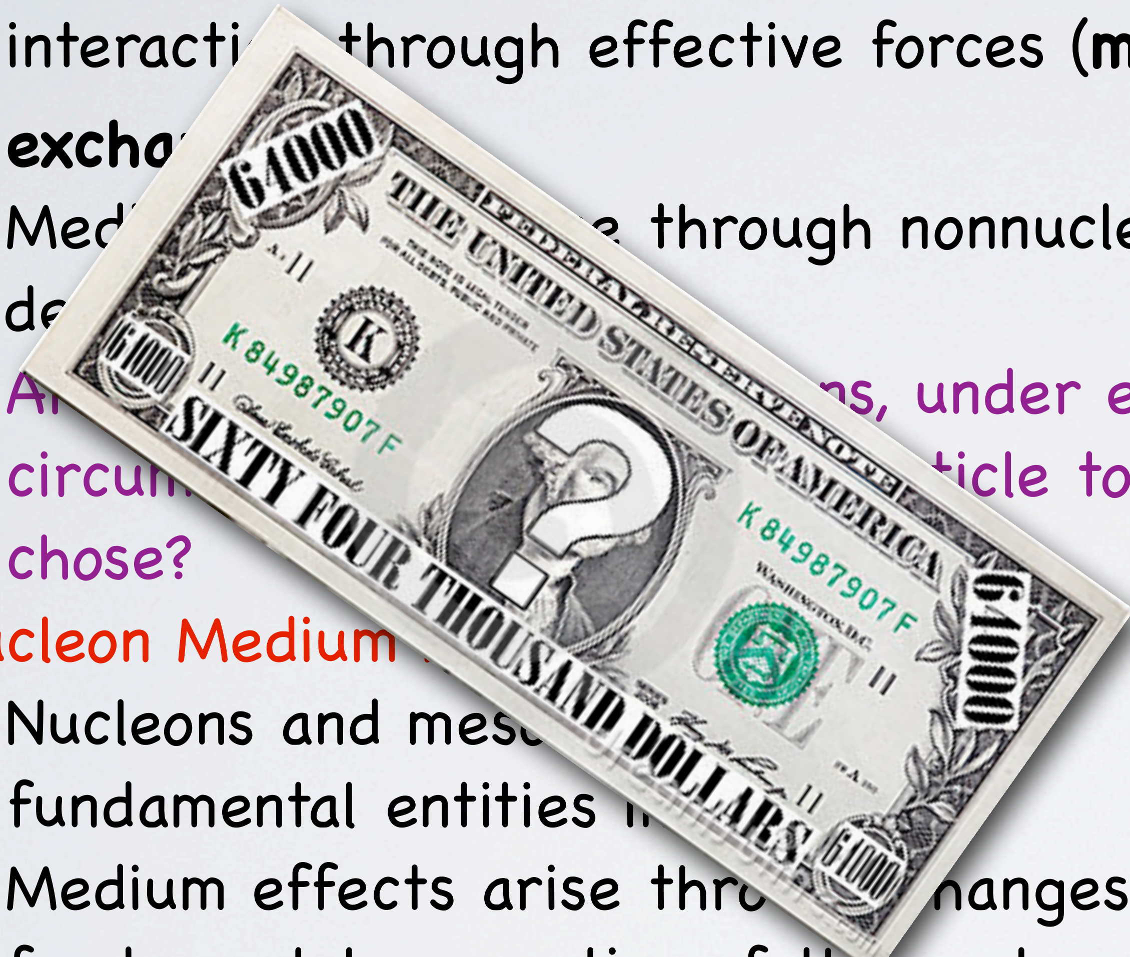

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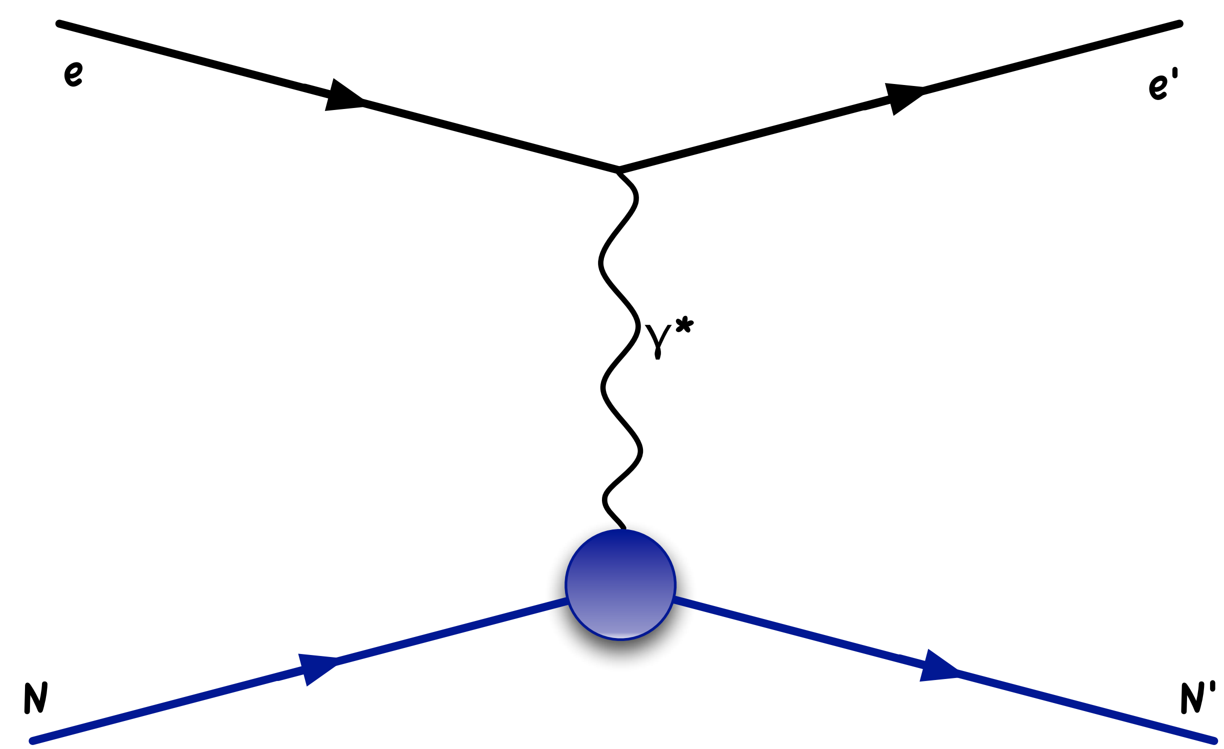
Electron Scattering Cross-Section (1-γ)

$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

Rutherford - Point-Like

$$\tau = \frac{Q^2}{4M^2},\ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$



Electron Scattering Cross-Section (1-γ)

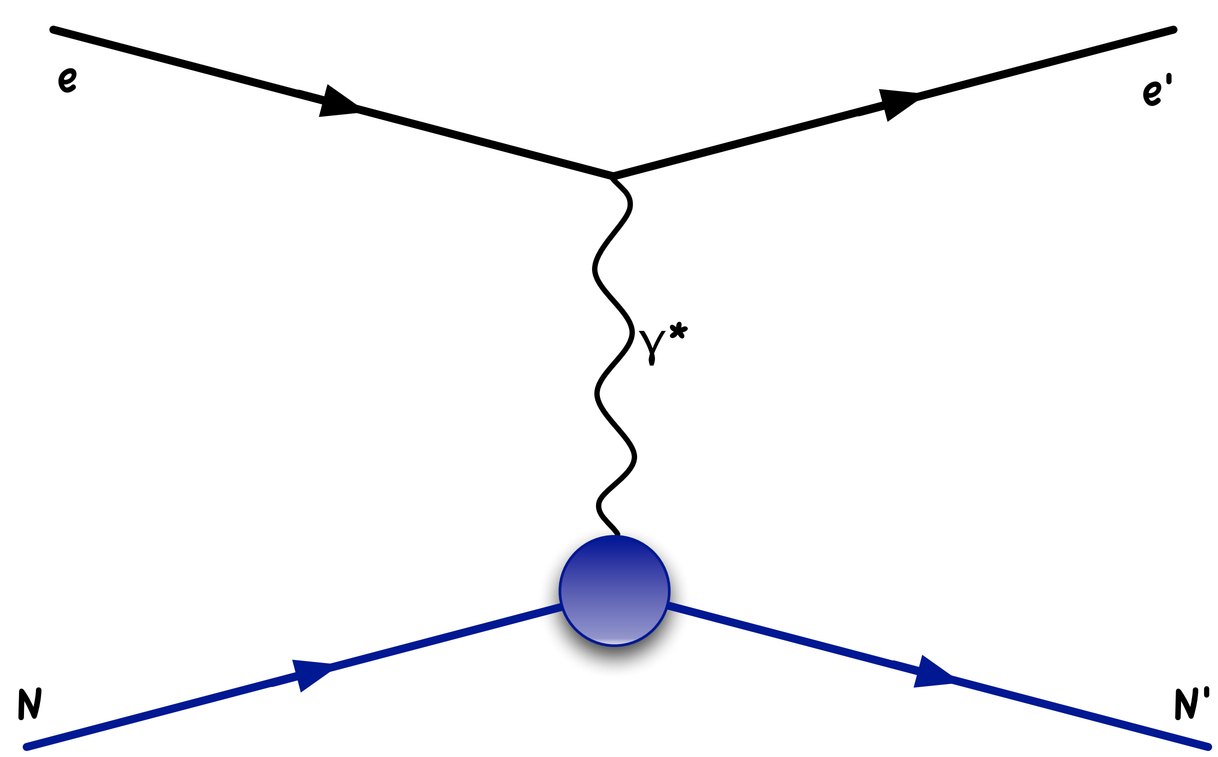
$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

Rutherford - Point-Like

$$\frac{d\sigma_M}{d\Omega} = \frac{d\sigma_R}{d\Omega} \times \left[1 + 2\tau\tan^2\frac{\theta}{2}\right]$$

Mott - Spin-1/2

$$\tau = \frac{Q^2}{4M^2},\ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$



Electron Scattering Cross-Section (1-γ)

$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

Rosenbluth - Spin-1/2 with Structure

$$\tau = \frac{Q^2}{4M^2}, \;\; \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

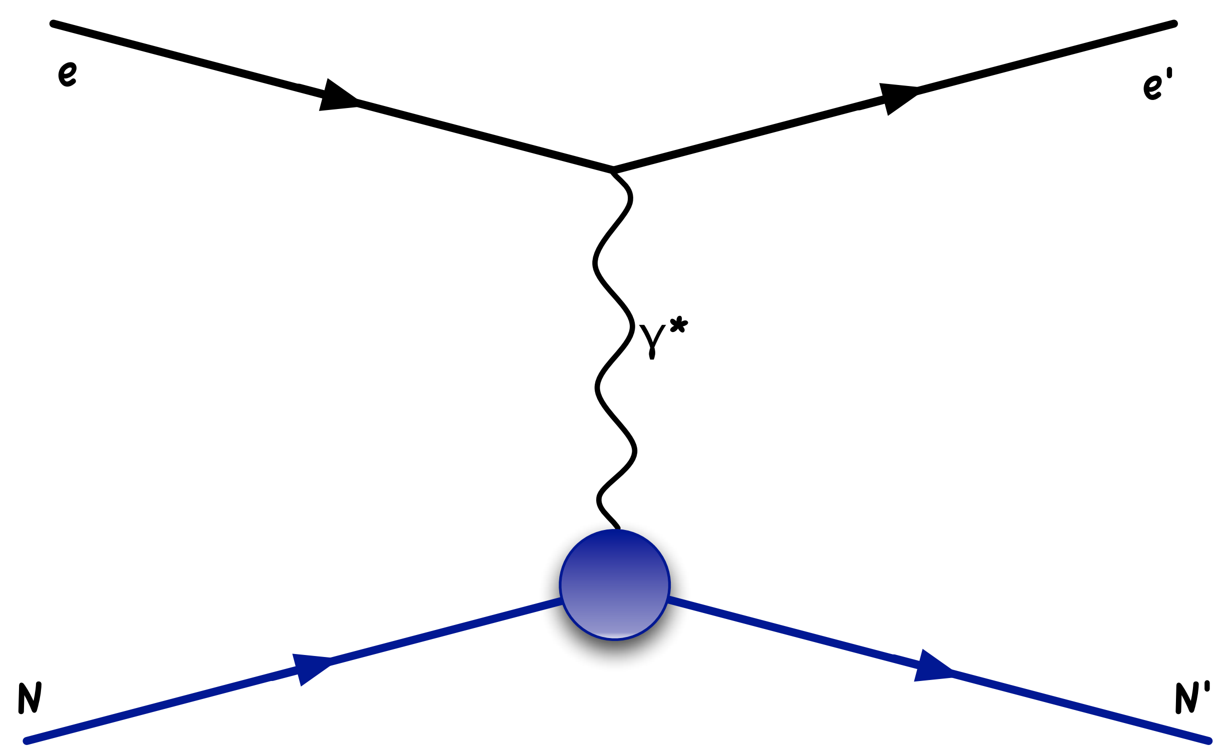
$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

$$G_M^p = 2.793 \quad G_M^n = -1.91$$

Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$



Electron Scattering Cross-Section (1-γ)

Everything we don't know goes here!

$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right]$$

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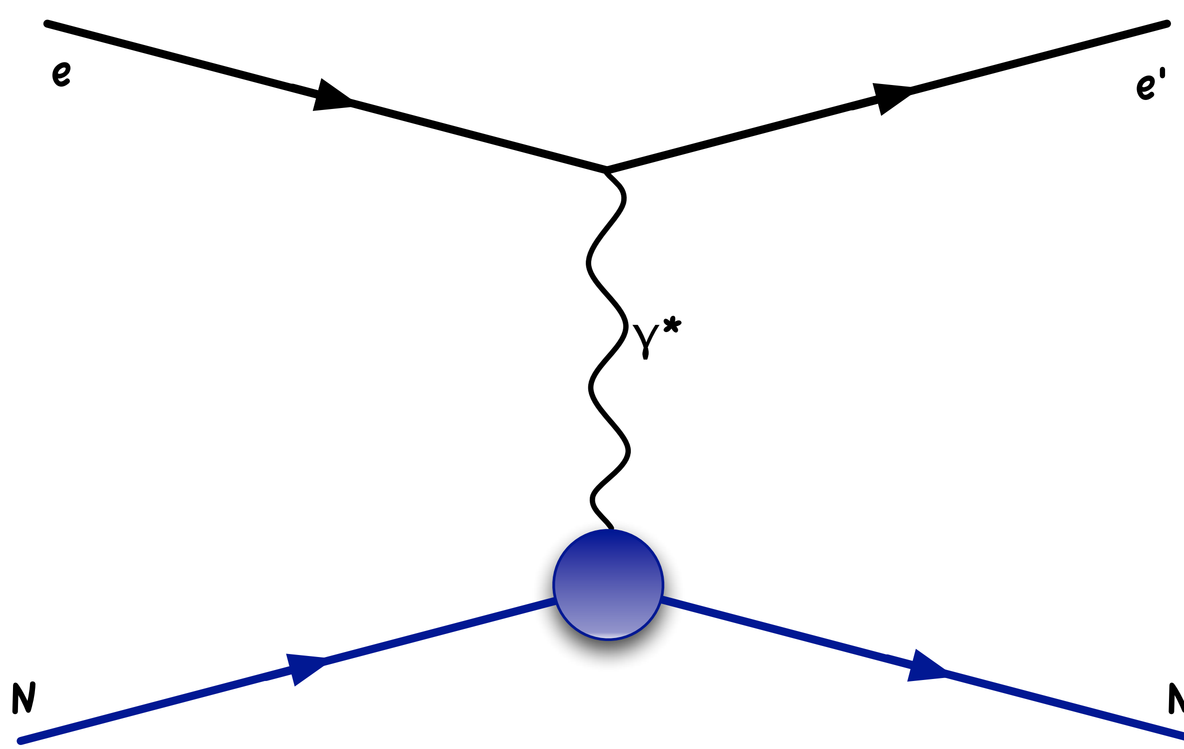
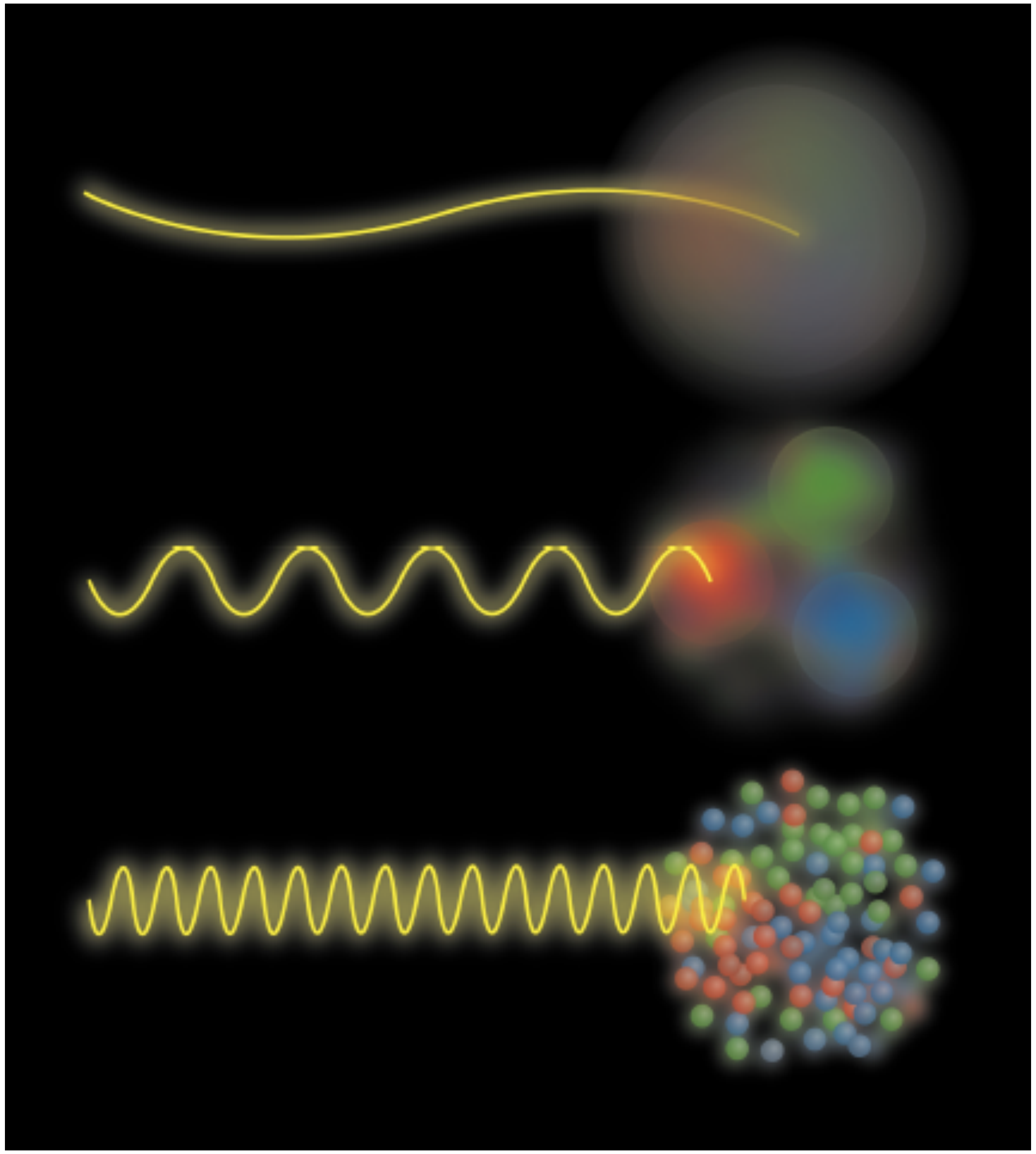




Momentum transfer:

$$k(e) - k(e') = q$$

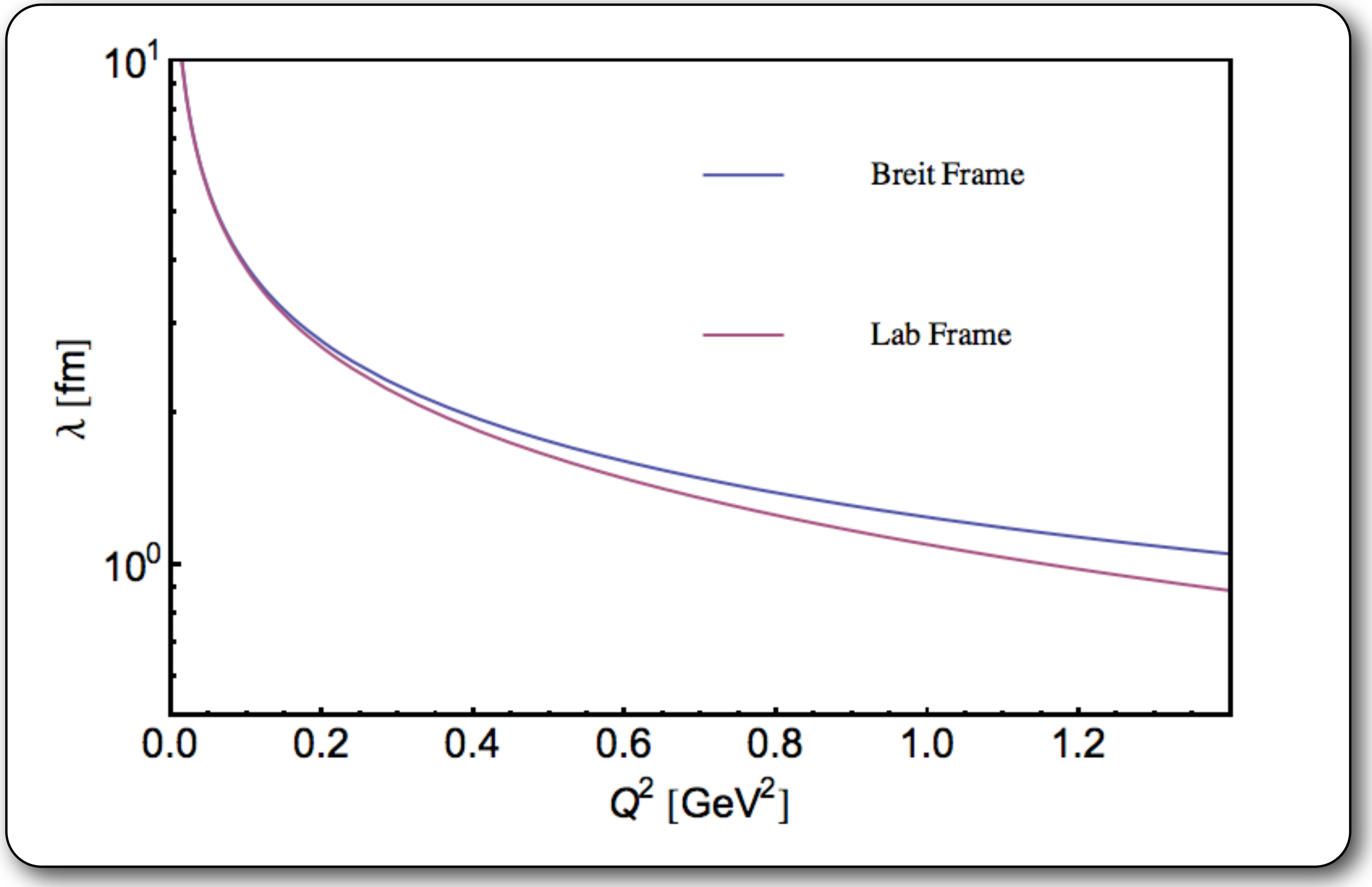
Resolving power:

$$\lambda \sim \hbar/\sqrt{Q^2} \quad (Q^2 = -q \cdot q)$$

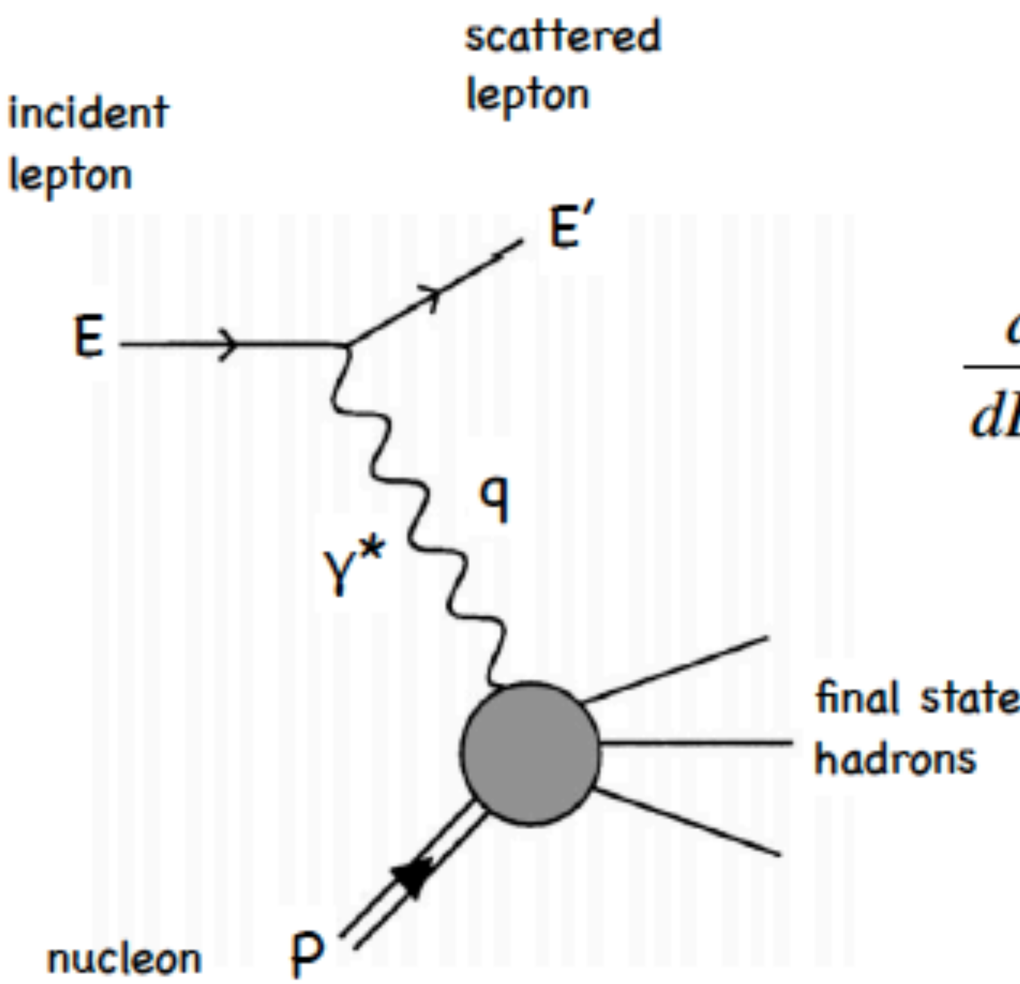
	Q^2 $(GeV/c)^2$	λ (fm)
MAMI	0.5	0.3
JLab	5	0.1
SLAC	30	0.04

THE MEANING OF Q^2

- Related to the wavelength of the virtual photon.
- Probes specific Fourier components.
- Q^2 is Lorentz-Invariant.
- Wavelength is not Lorentz Invariant.
- Roughly:
  - <0.1 GeV^2 - Static Properties.
  - 0.1 - 10 GeV^2 - Distributions (structure).
  - >~20 GeV^2 - perturbative QCD.
  - ∞ - Point Like Configuration.



Deep Inelastic Scattering



$$\frac{d^2\sigma}{dE'd\Omega} = \frac{4\alpha^2 (E')^2}{q^4}\left(\frac{F_2}{\nu}\cos^2\frac{\theta}{2} + 2\frac{F_1}{M}\sin^2\frac{\theta}{2}\right)$$

structure functions $F_1(Q^2,x)$ and $F_2(Q^2,x)$ contain all information about the structure of the target

$$\nu = E - E'$$

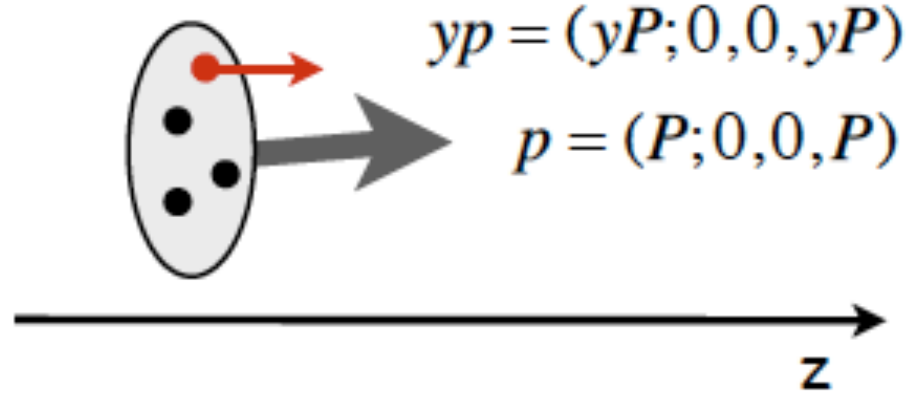
$$Q^2 = -q^2 > 0$$

$$x = Q^2 / 2M\nu$$

here: unpolarized cross section and ignoring weak interaction

Parton Model

- Infinite momentum frame



$$yp = (yP; 0, 0, yP)$$
$$p = (P; 0, 0, P)$$

$$(yp+q)^2 = (yp)^2 + 2yp\cdot q + q^2$$
$$0 \approx 2yp\cdot q - Q^2$$
$$y \approx \frac{Q^2}{2p\cdot q} = x$$

← Bjorken x gives the momentum fraction carried by the constituent

- Quark distribution q(x), number density of quarks in the target; e.g. u(x)xdx gives the fraction of momentum of u quarks in the proton with momentum between xP and (x+dx)P in the IMF

- Structure functions

$$F_1(x) = \frac{1}{2}\sum_{i=u,d,s,c,\ldots} e_i^2 (q_i(x) + \overline{q}_i(x))$$
$$F_2(x) = 2xF_1(x)$$

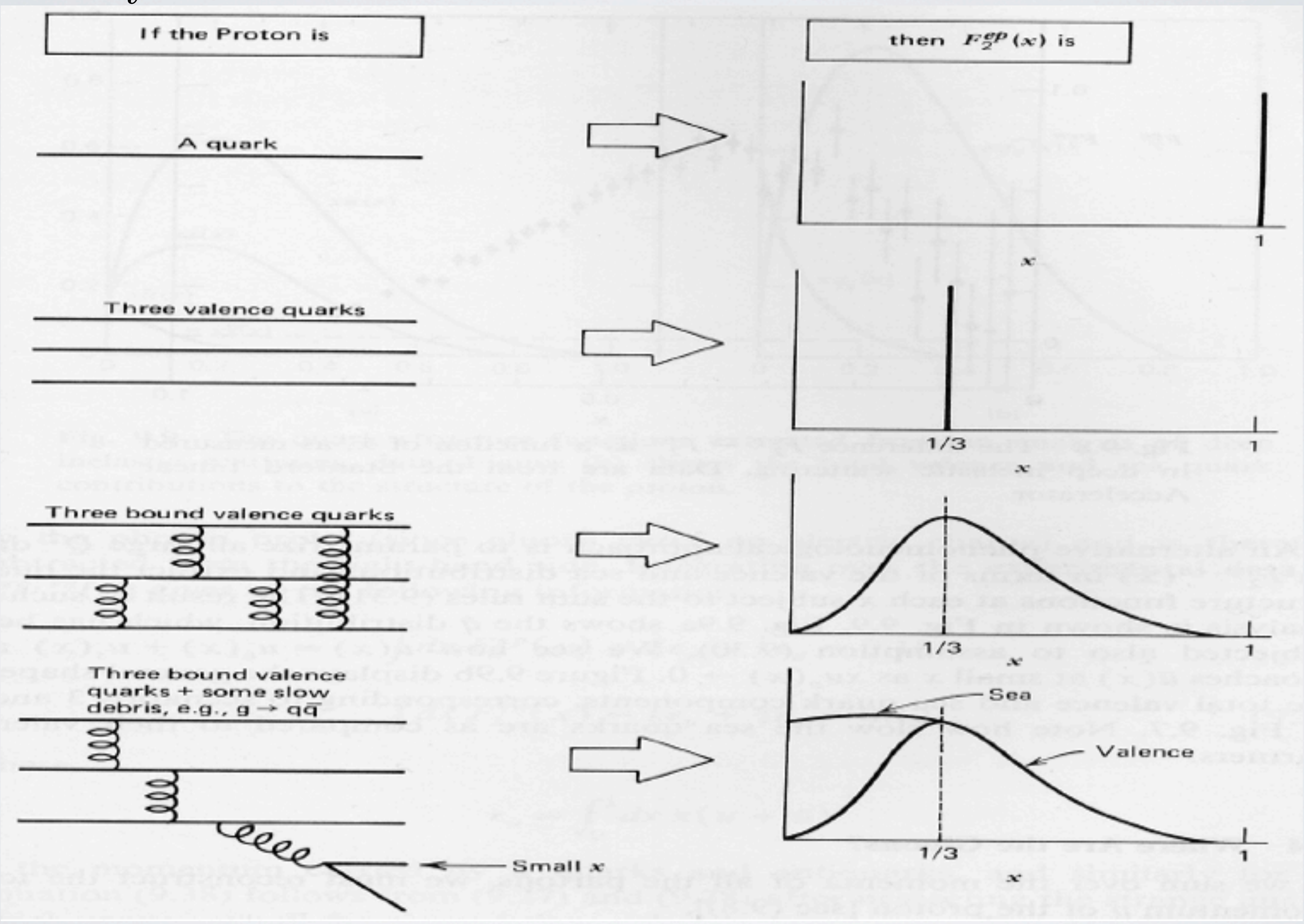
← Callan-Gross relation connecting F_1 and F_2 reflects the spin ½ nature of the quarks

D.F. Geesaman, K. Saito, A.W. Thomas, Annu. Rev. Nucl. Part. Sci. **45**, 337 (1995).

The EMC Effect

$$F_2(x) = \sum_i q_i^2 x f(x)$$

Probability of finding a quark with momentum fraction x in the nucleon.



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Naive Expectation:

$$AF_2^A = ZF_2^P + (A - Z)F_2^n$$

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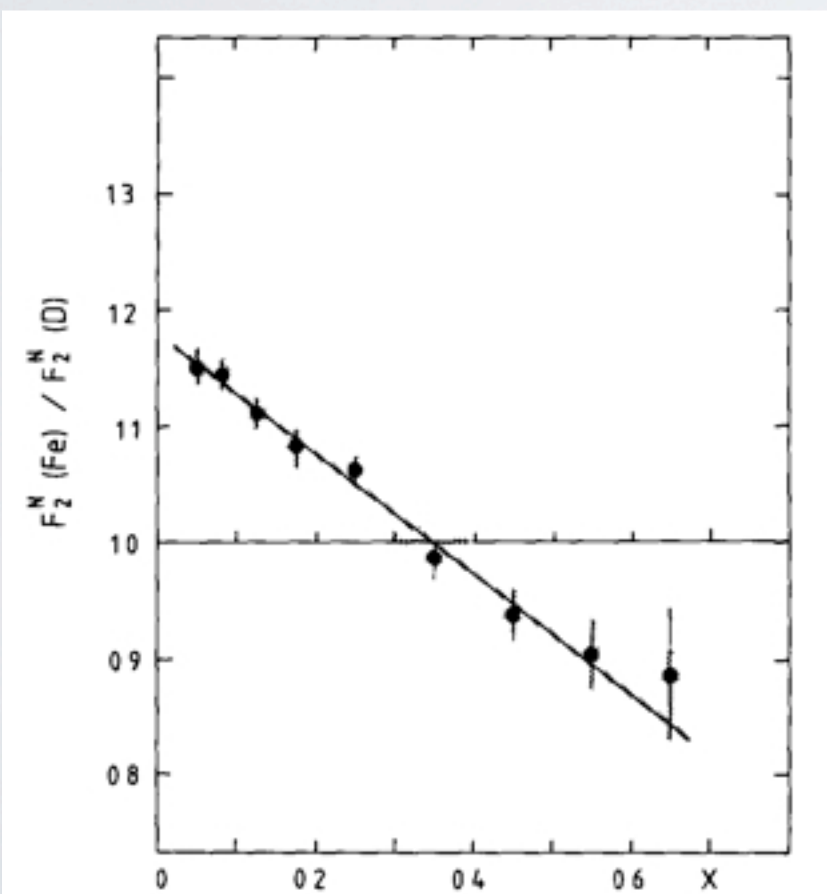
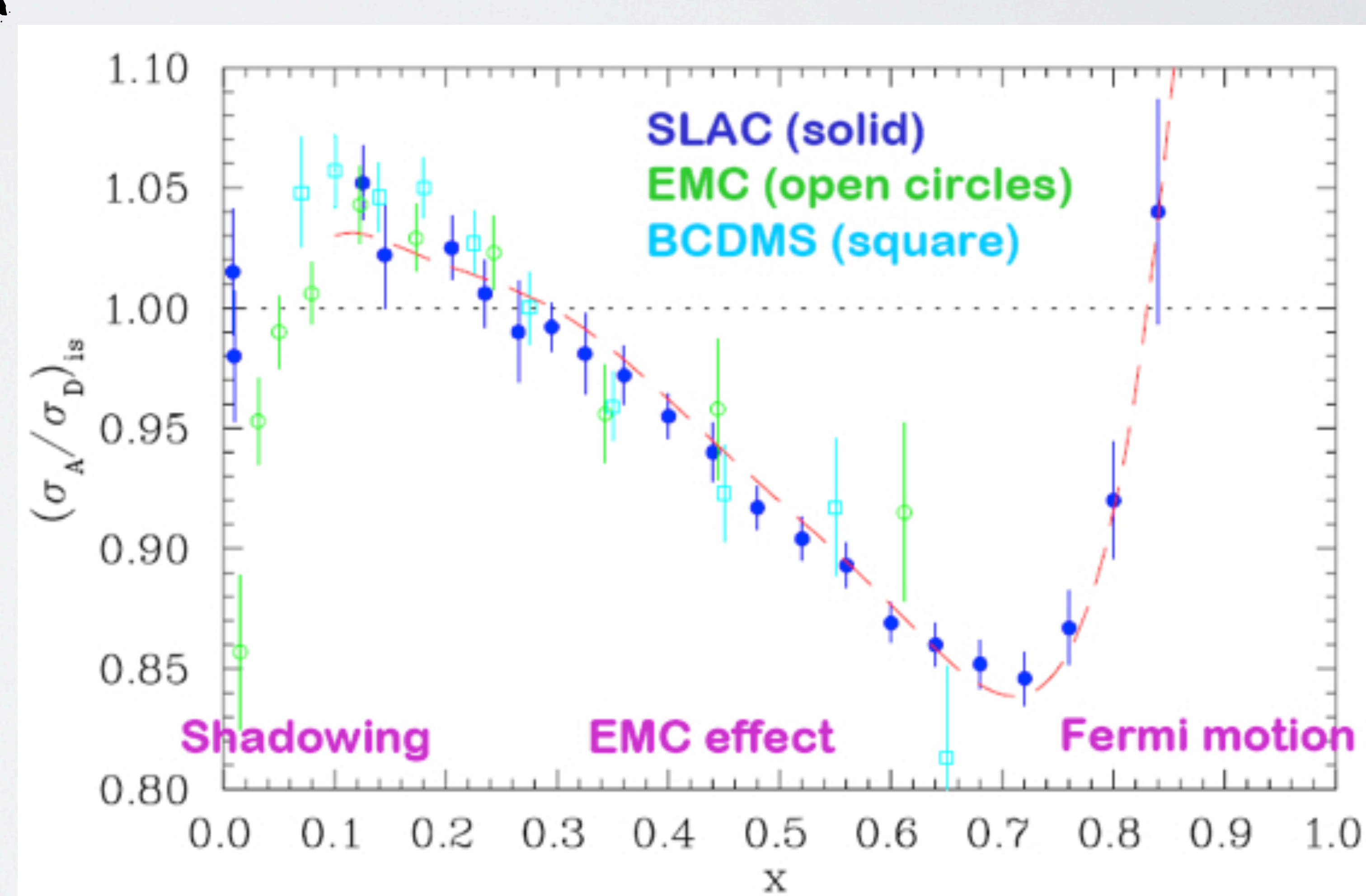
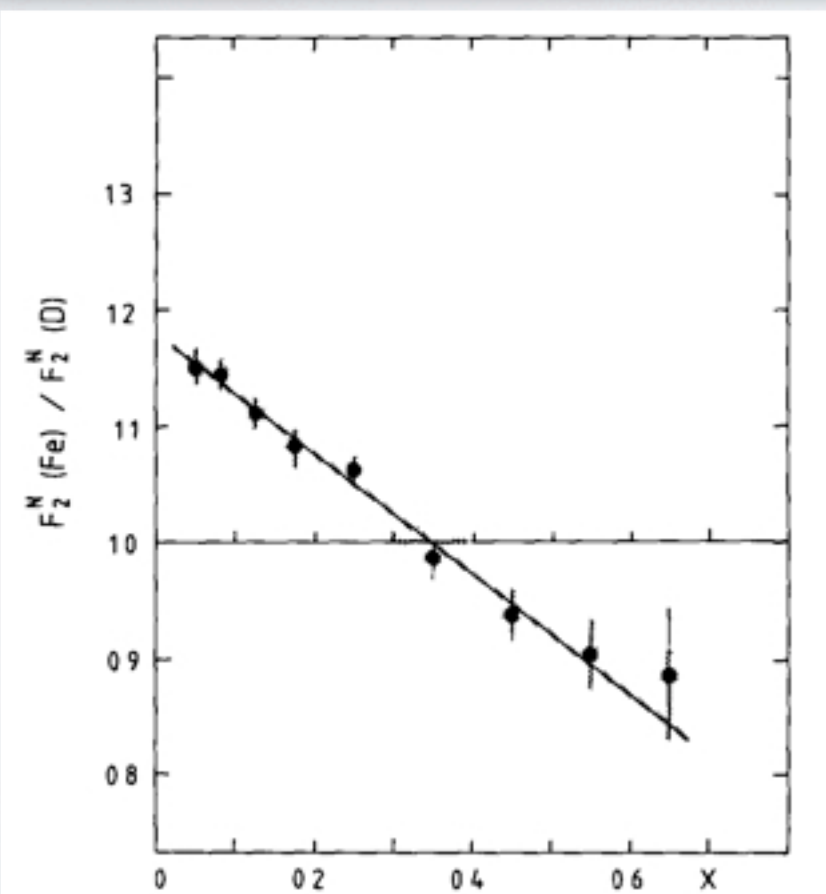


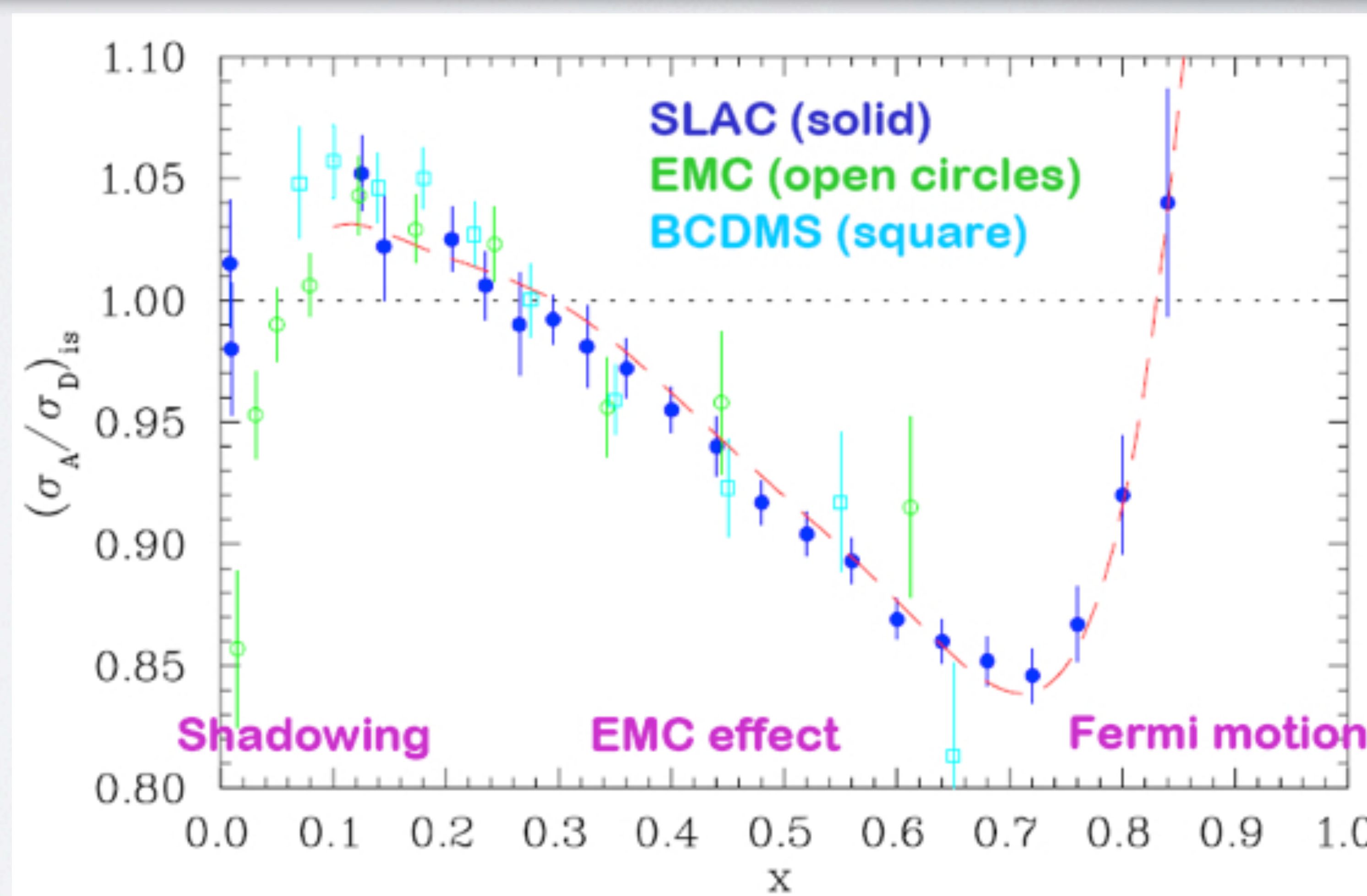


The EMC Effect

Excess of low momentum quarks and depletion of high momentum quarks in Nuclei.

Parton model interpretation: The nucleon bound in a nucleus carries less momentum than in free space.

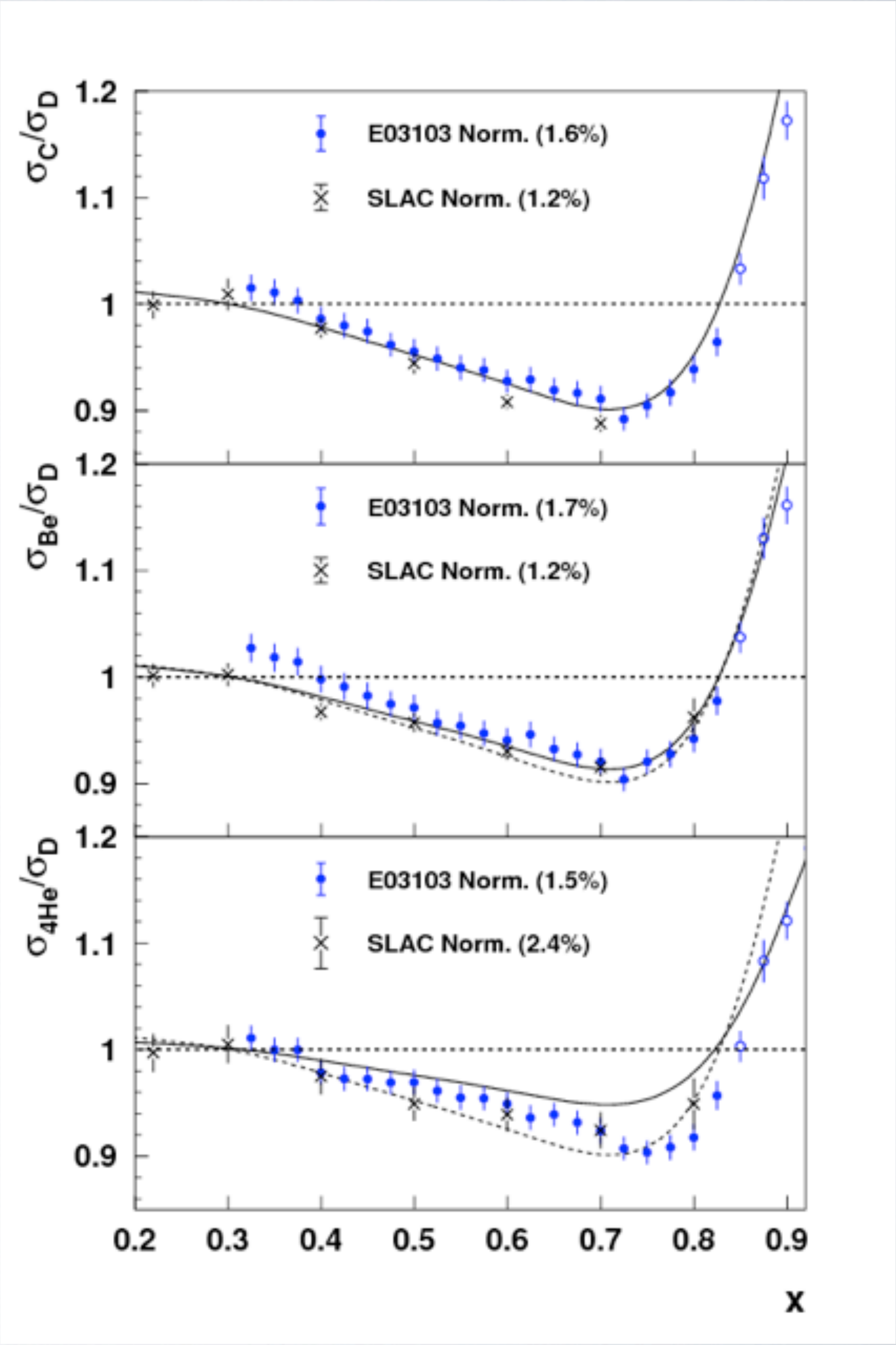




The EMC Effect

A new result

JLab experiment E03-103 (J. Arrington) measured the EMC for light nuclei (and medium-large x).
Results confirm the effect for these nuclei.



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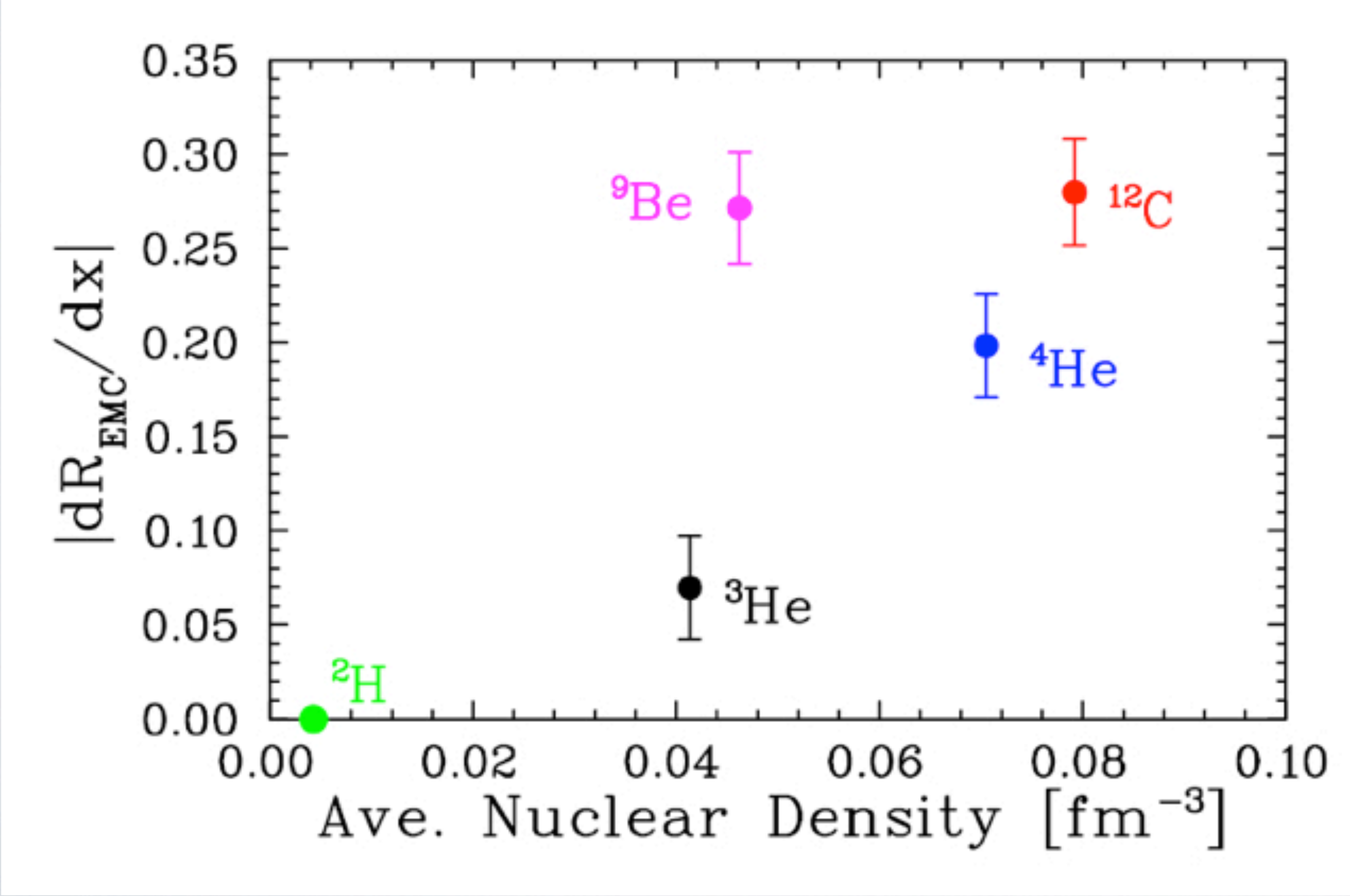

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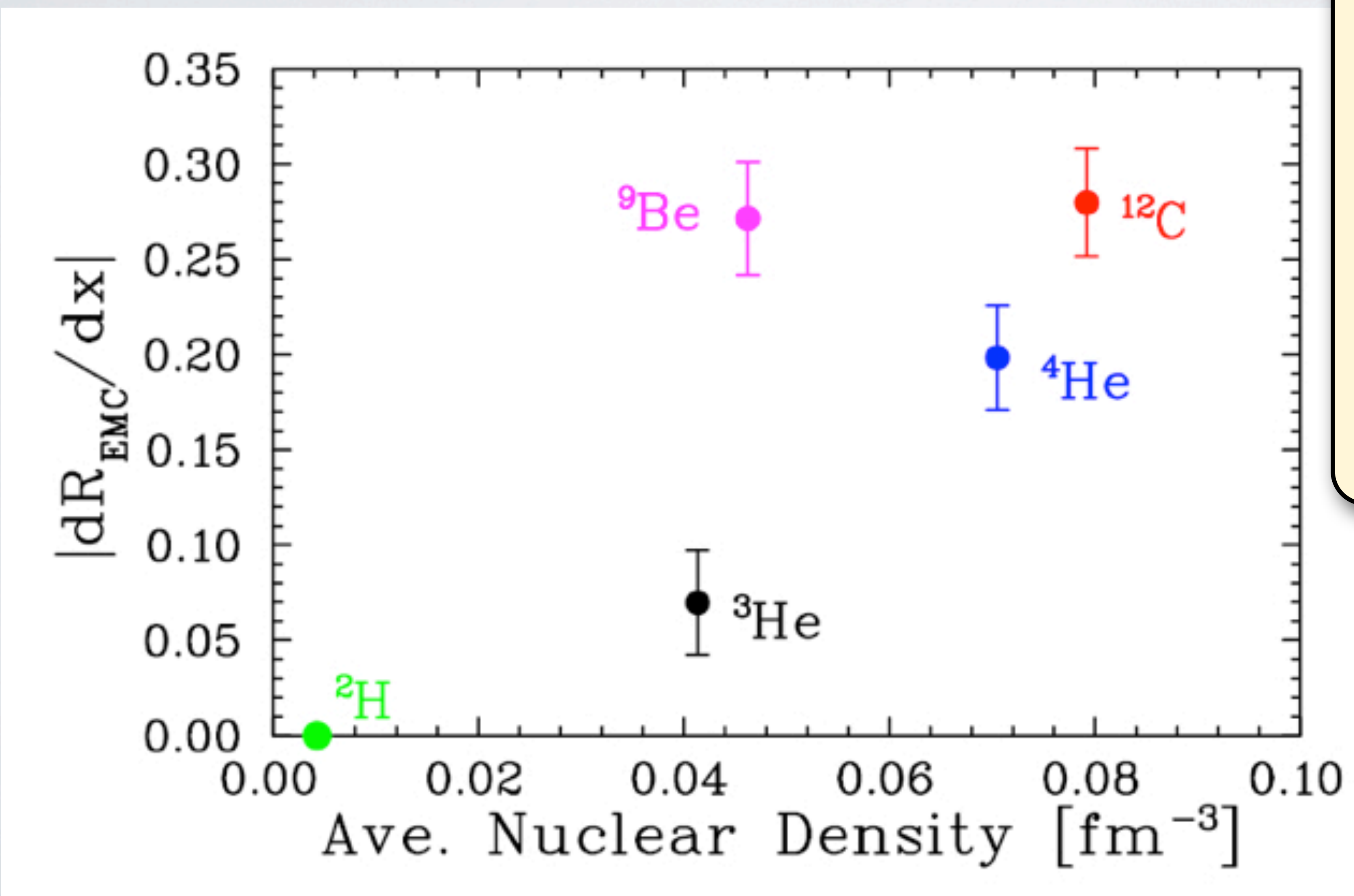

- Plot shows slope of ratio σ_A/σ_D at EMC region.
- EMC effect correlated with ρ not A.
- Local density is important, not average density.

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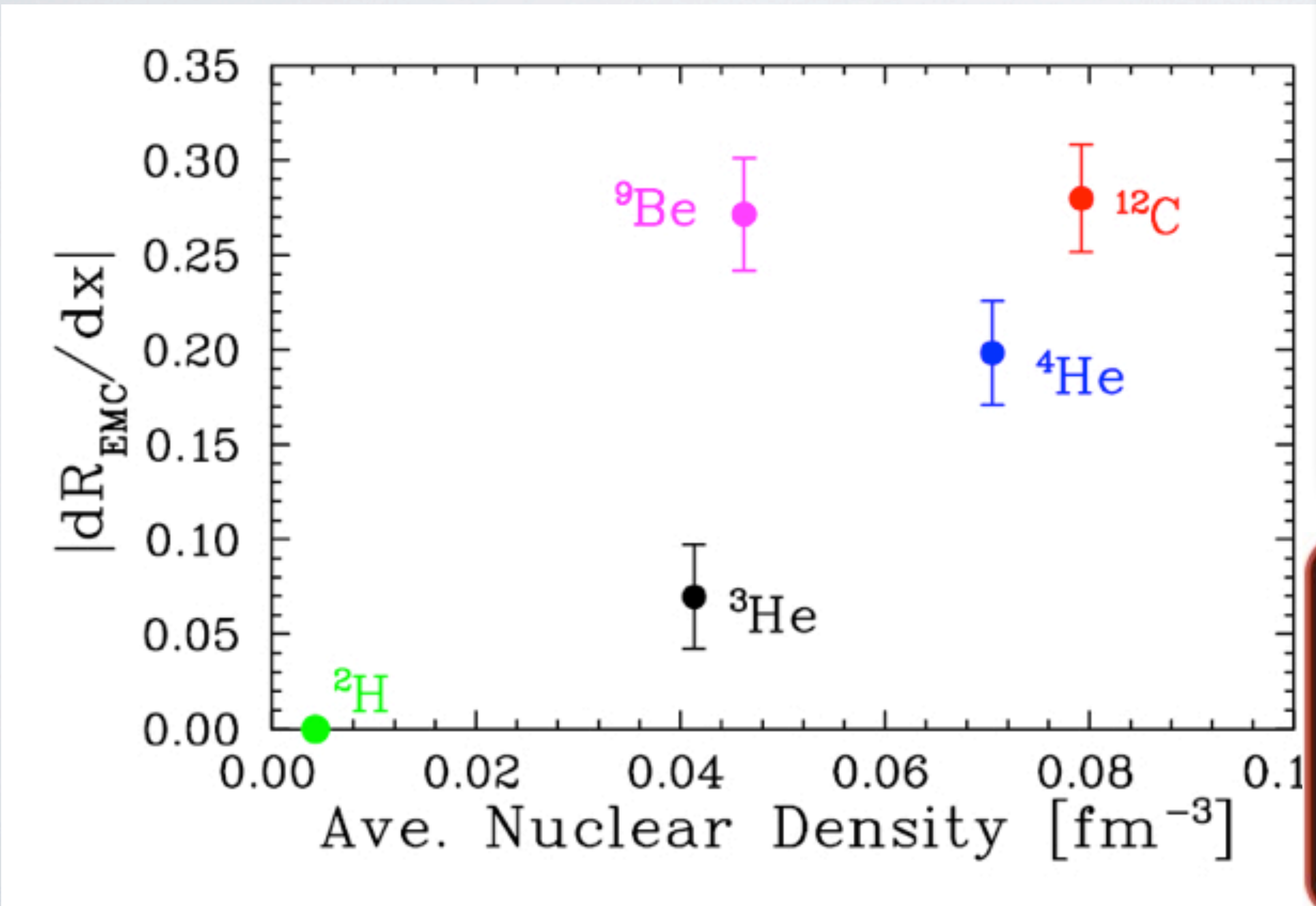

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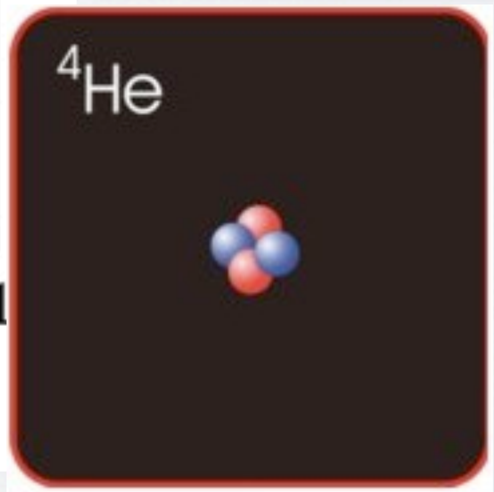

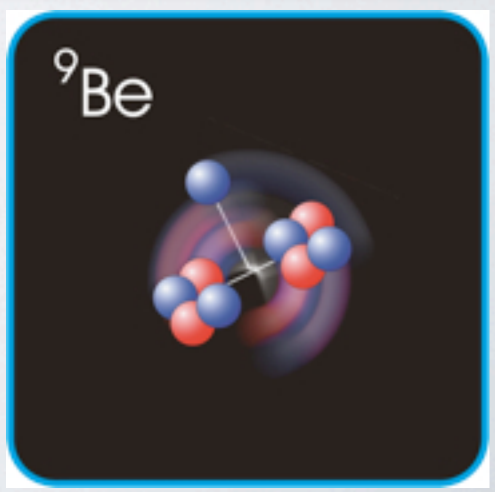

The EMC Effect (and others)

Some possible explanations

Conventional:

- Limited phase space in calculation.
- Meson exchange currents (excess pions in nuclei).
- Core polarization ($g_{N\pi\Delta}$ coupling).

Unconventional:

- Nucleon "swelling" (confinement weakened by nucleon mean color field).
- Multiquark (3n-q) clusters.
- Dynamical rescaling:
  $F_2^A(x, Q^2) = F_2^N(x, \xi_A(Q^2)Q^2)$

And many more....

More models than theorists....

No single model explains everything.

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And many more....

More models than

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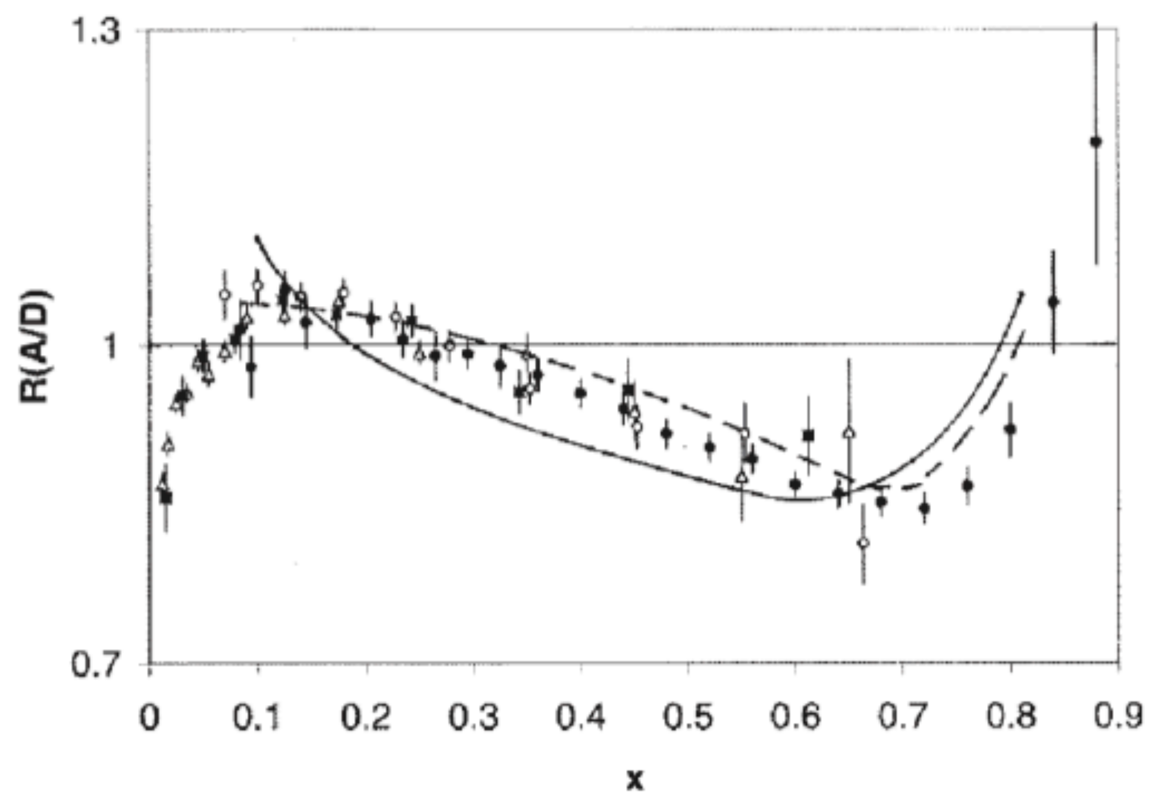
Everybody's Model is Cool
-J. Miller

No single model explains everything.

PION ENHANCEMENT?

$$F_2^A(x) = \int_x f_N(z) F_2^N\left(\frac{x}{z}\right) dz + \int_x f_\pi(z) F_2^\pi\left(\frac{x}{z}\right) dz$$

Momentum Distributions



P.R. Norton, Rep. Prog. Phys. **66**, 1253 (2003)

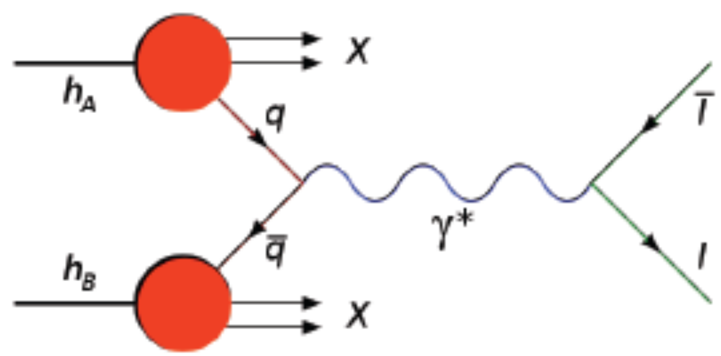
- Nucleons are bound via mesons → do not carry all the momentum.
- For stationary pion $0 < x < m_\pi/m_p$ so the pion contribution should be concentrated at low x.
- Pion model naturally predicts increase in nuclei sea (anti)quarks.

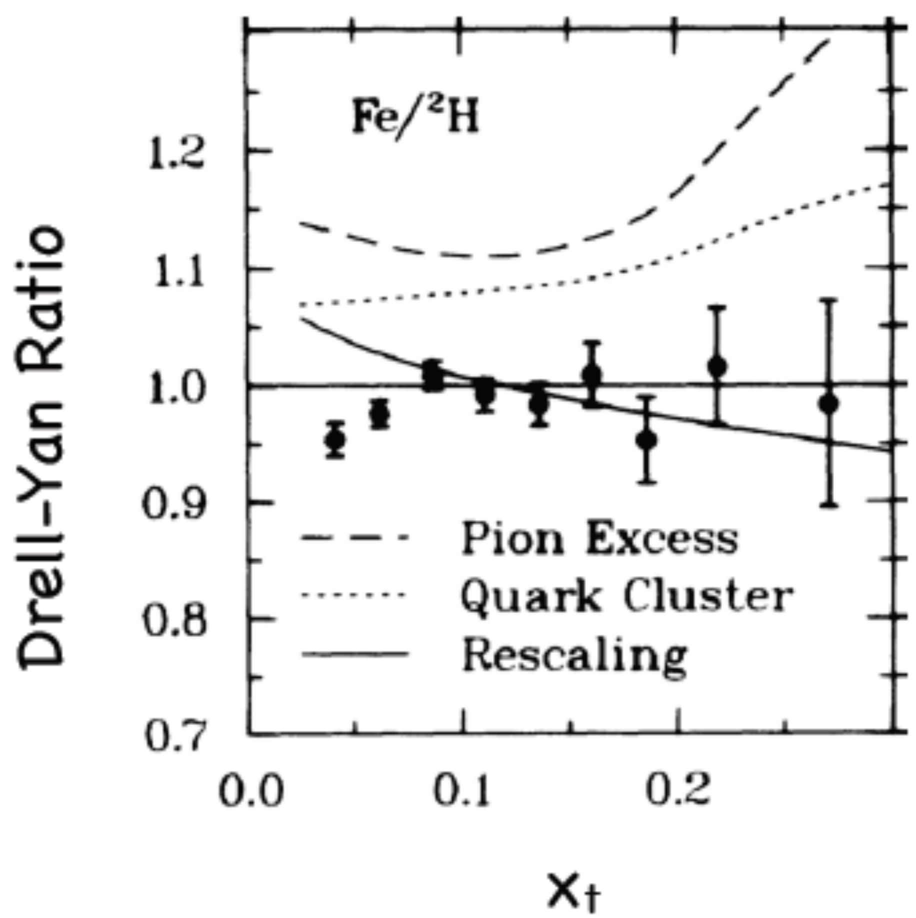
Drell-Yan Process

$$\frac{d^2\sigma}{dx_1 dx_2} = K\frac{4\pi\alpha^2}{9s}\sum_i e_i^2\{q_{iP}(x_1)\bar{q}_{iT}(x_2)+\bar{q}_{iP}(x_1)q_{iT}(x_2)\}$$

P: Projectile
T: Target

dominates for **proton** beams — dominates for **pion** beams





- Probes quark-antiquark content of beam and target.
- DY cross section ratio show now rise at low-x! (contradicting most models).

P.R. Norton, Rep. Prog. Phys. **66**, 1253 (2003);
D.M. Alde et al., Phys. Rev. Lett. **64**, 2479 (1990) - proton beam

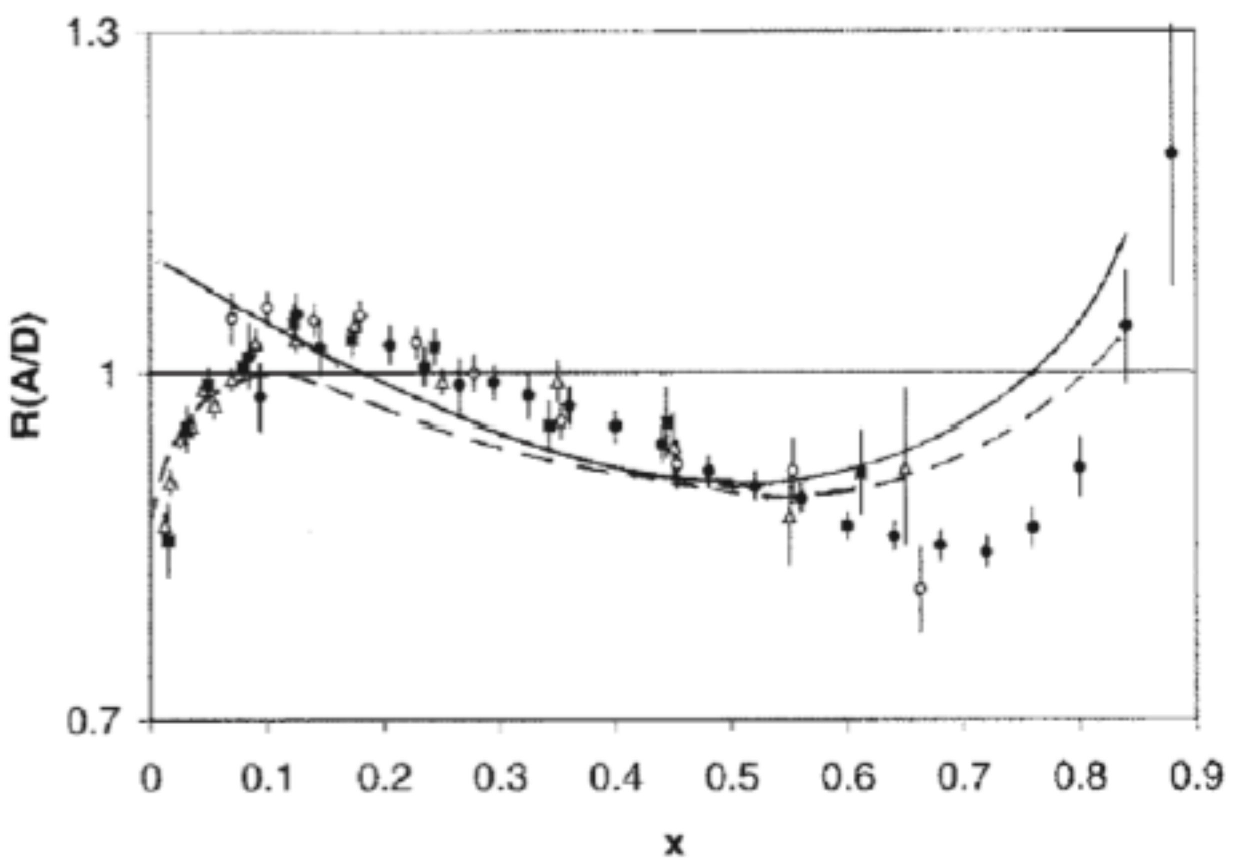
Multi-Quark Systems

$$F_2^A(x) = \int_z^A F_2^N\left(\frac{x}{z}\right)dz + \int_z^A f_6(z)F_2^6\left(\frac{x}{z}\right)dz$$

$$\int f_N(z)dz = 1-p, \int f_6(z)dx = p$$

$$F_2^6(x) \sim \left(1-\frac{x}{2}\right)^9$$

6-quark cluster



P.R. Norton, Rep. Prog. Phys. **66**, 1253 (2003)

- Tightly packed nucleons in nuclei overlap, sometimes merging to 3n quark bags.
- Color singlet 6q, 9q, 12q bags form, with probability reflecting wavefunction overlap.

Multi-Quark Systems - Simple Model

- Consider a system of N non-interacting massless quarks, the momentum being shared equally among them. The normalized distribution is given by

$$q_N(x) = \delta(x - 1/N)$$

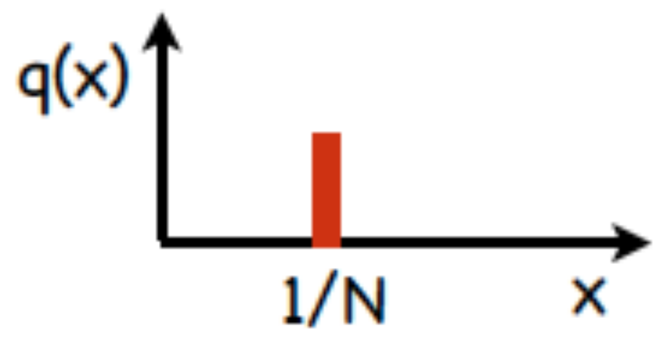
- Changing the number of quarks to N' means

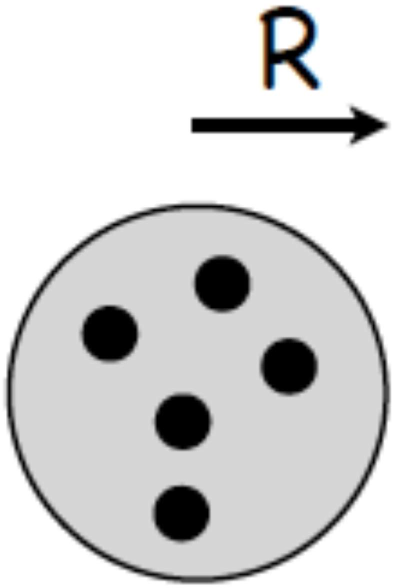
$$q_{N'}(x) = \delta(x - 1/N') = (N'/N)q_N((N'/N)x)$$
$$q_{N'}(x) = (M'R'/MR)q_N((M'R/MR)x)$$

- Allow for the fact that the primed bag carries an enhanced factor M'/M of the momentum of the unprimed bag

$$q'(x) = (R'/R)q((R'/R)x)$$

- Thus in the larger primed bag, (R'/R > 1), the quark distribution is degraded to small x, and less momentum is carried by the quarks.





$$M \propto \frac{N}{R}$$

Close et al., Phys. Lett. **129B**, 346 (1983).

Multi-Quark Systems - Simple Model

- Consider a system of N non-interacting massless quarks, the momentum being shared equally among them. The normalized distribution is given by

$$q_N(x) = \ldots$$

- Changing th…

$$q_{N'}(x) = \delta(x \ldots$$

$$q_{N'}(x) = (M \ldots$$

But this requires increase of longitudinal response function - which isn't observed!

- Allow for the fact that the primed bag carries an enhanced factor M'/M of the momentum of the unprimed bag

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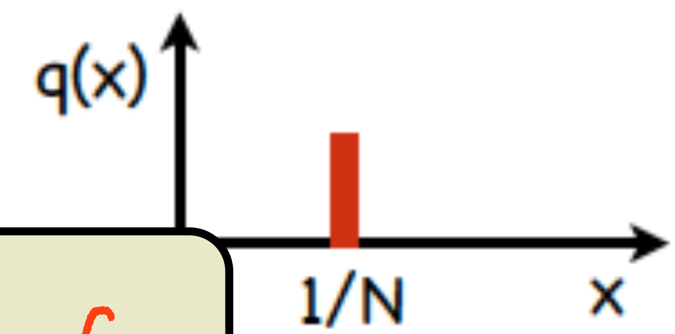

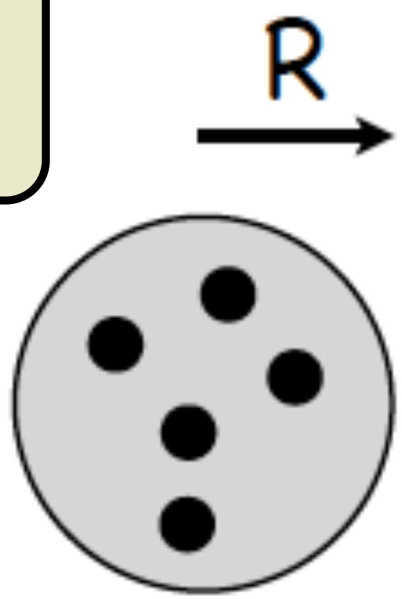

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A Way out?

What we need is…

- Observables sensitive to nucleon structure/size.
- Effect of O(10%) require observable we can measure to 2-3% or better.
- "Different" than previous measurements.

Polarization observables are…

- Related to form factors (Ch/M distributions) - for a free nucleon.
- Can be measured to great precision (<1%).
- Can be shown from calculations to be somewhat insensitive to nuclear effects (*MEC, etc…*).

J. M. Laget, Nucl Phys A579, 333 (1994)

J. J. Kelly, Phys. Rev. C 59, 3256 (1999)

A. Meucci et al., Phys. Rev. C 66, 034610 (2002)

Electron Scattering Cross-Section (1-γ)

$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

$$\frac{d\sigma_M}{d\Omega} = \frac{d\sigma_R}{d\Omega} \times \left[1 + 2\tau\tan^2\frac{\theta}{2}\right]$$

$$\frac{d\sigma_{Str}}{d\Omega} = \frac{d\sigma_M}{d\Omega} \times \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon}G_M^2(Q^2)\right]$$

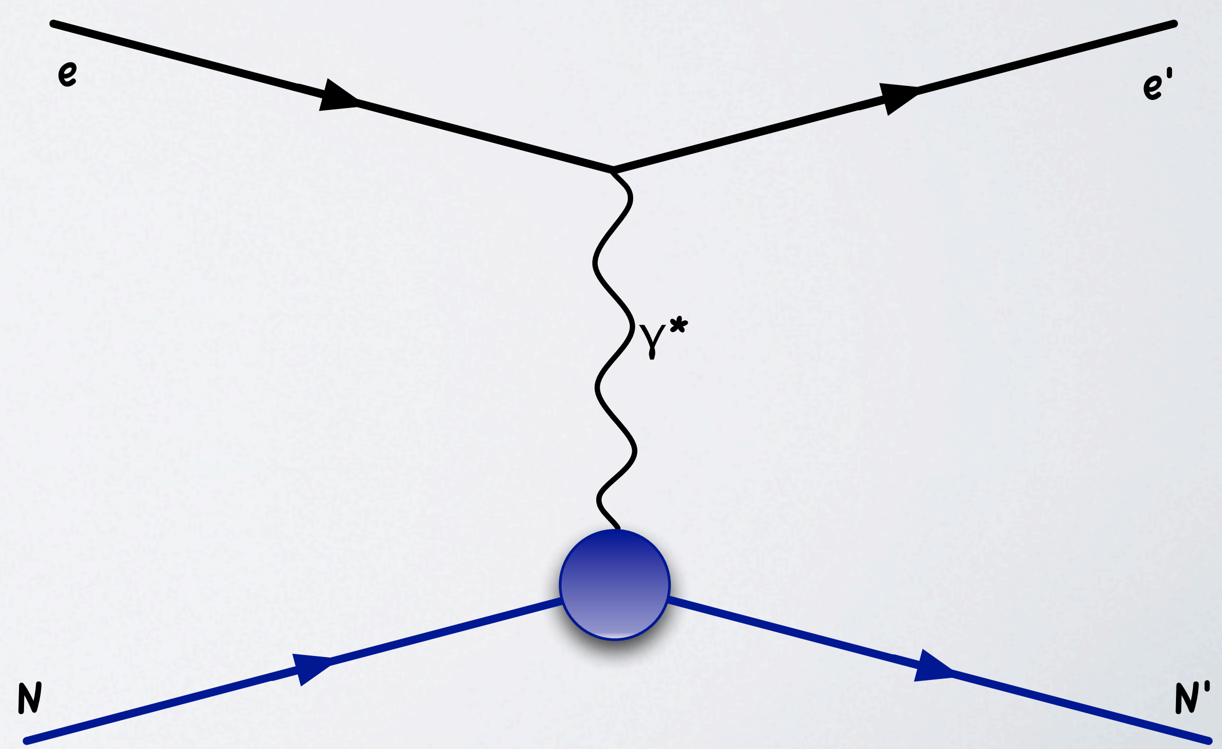
Everything we don't know goes here!

Rosenbluth - Spin-1/2 with Structure

$$\tau = \frac{Q^2}{4M^2}, \ \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

$$G_M^p = 2.793 \quad G_M^n = -1.91$$



Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$

IN THE BREIT FRAME....

It can be shown that...

The Hadronic Current

$$\mathcal{J}^0 = ie\bar{v}(p')\left[\left(F_1 + \kappa F_2\right)\gamma^0 - \frac{E_{pB}}{m}\kappa F_2\right]v(p)$$

$$\vec{\mathcal{J}} = ie\left(F_1 + \kappa F_2\right)\bar{v}(p')\vec{\gamma}v(p)$$

Explicitly

$$\mathcal{J}^0 = ie2m\chi'^{\dagger}\chi\left(F_1 - \tau\kappa F_2\right) = ie2m\chi'^{\dagger}\chi G_E$$

$$\vec{\mathcal{J}} = -e\chi'^{\dagger}\left(\vec{\sigma}\times\vec{q}_B\right)\chi\left(F_1 + \kappa F_2\right) = -e\chi'^{\dagger}\left(\vec{\sigma}\times\vec{q}_B\right)\chi G_M$$

Sachs Form Factors related to electric and magnetic part of the interaction - in the Breit Frame.

THE NAIVE INTERPRETATION

$$
\begin{aligned}
G_E(Q^2) &= \int \rho_{Ch}(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3r \\
&\sim \int \rho_{Ch}(\vec{r}) d^3r - \frac{q^2}{6} \int \rho_{Ch}(\vec{r}) \vec{r}^2 d^3r + \cdots \\
&\sim Ch - \frac{q^2}{6} \left\langle r^2 \right\rangle_{Ch} + \cdots \\
G_M(Q^2) &= \int \rho(\vec{r})_M e^{i\vec{q}\cdot\vec{r}} d^3r \\
&\sim \mu - \frac{q^2}{6} \left\langle r^2 \right\rangle_M + \cdots
\end{aligned}
$$

As wrong as you can be while still being somewhat right...

Measurement Techniques

Rosenbluth Separation

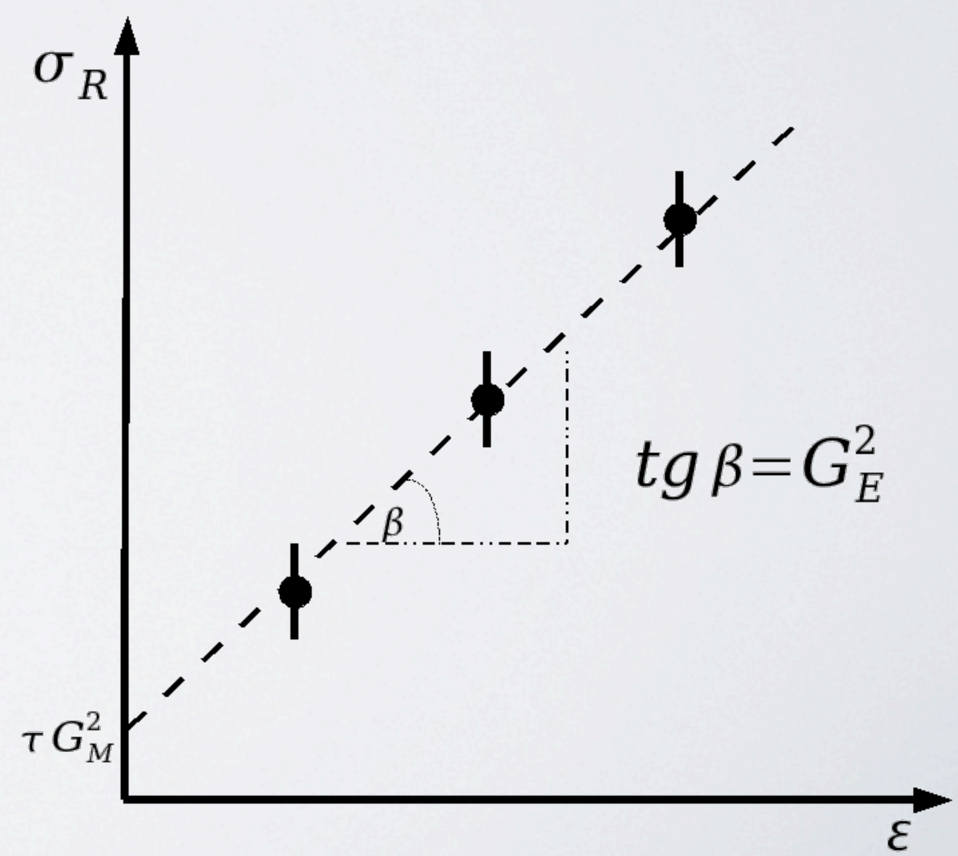
$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\mathrm{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

- Measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q2 fixed.

- Linear fit to get intercept and slope.

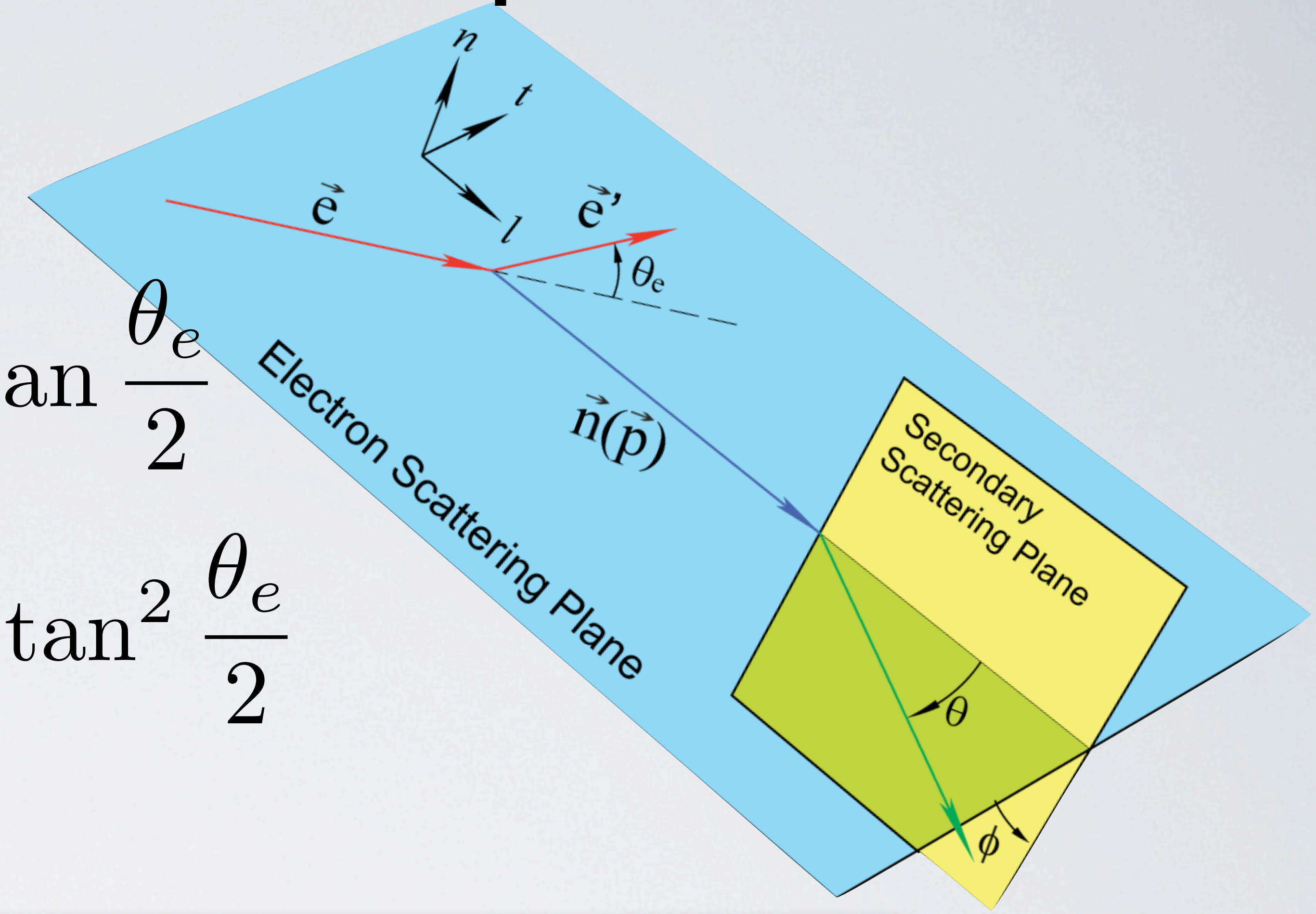
- But... G_M suppressed for low Q^2 (and G_E for high).

- Also normalization issues/ acceptance issues/etc. make it hard to get high precision.



Measurement Techniques

Recoil Polarization



$$I_0 P_t = -2\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_l = \frac{E_e + E_{e'}}{M}\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta_e}{2}$$

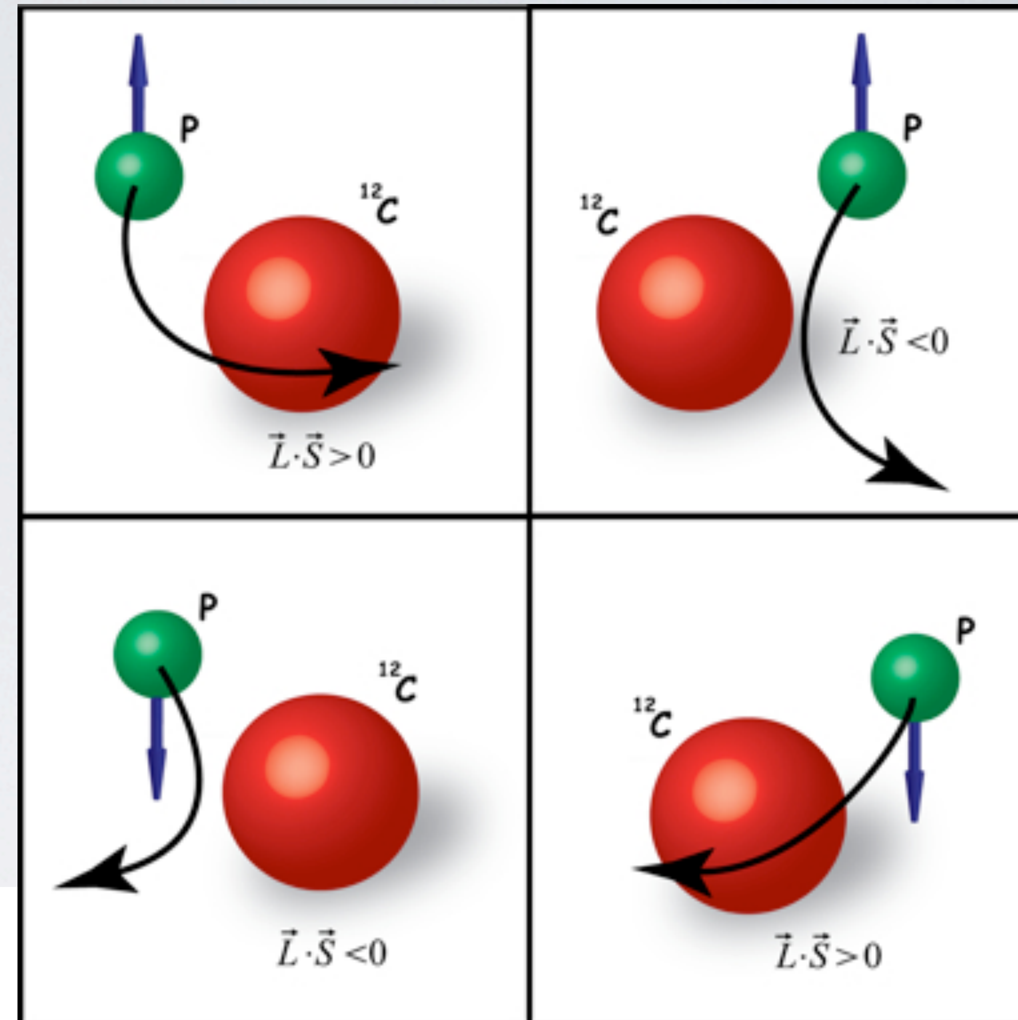
$$P_n = 0 \ (1\gamma)$$

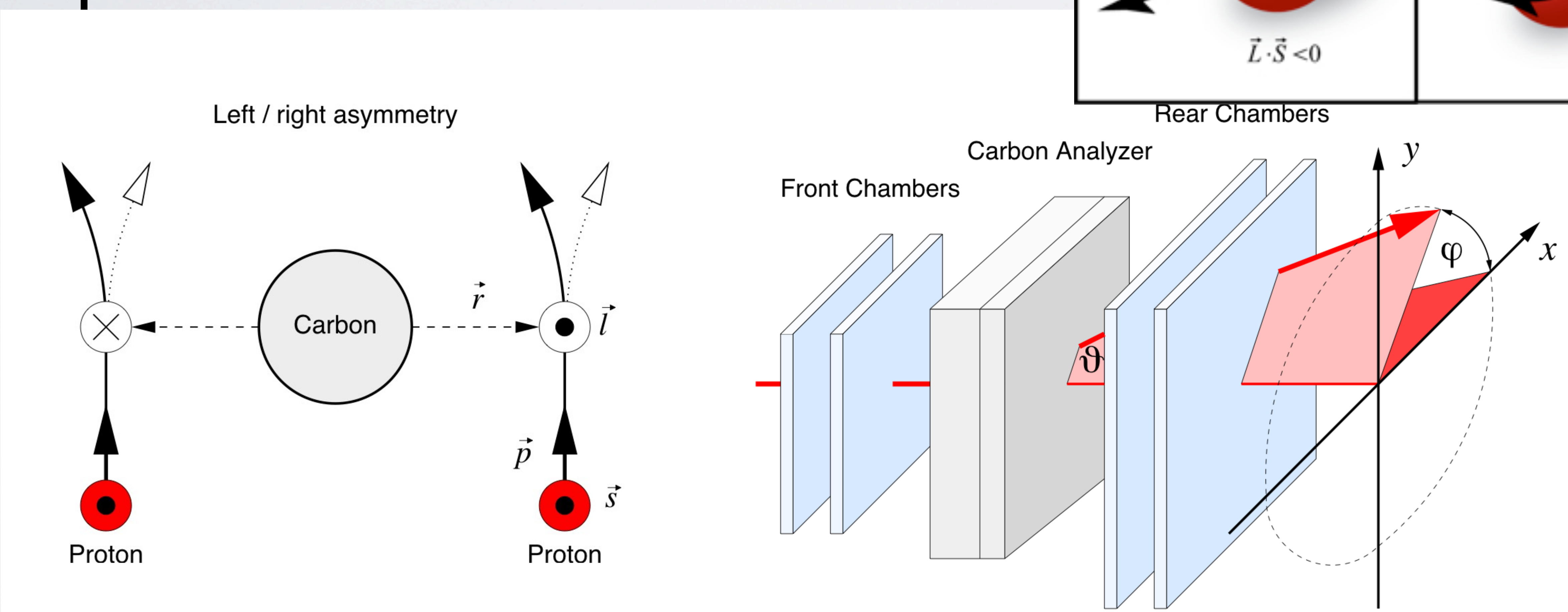
$$\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\frac{\theta_e}{2}$$

- A single measurement gives ratio of form factors.
- Interference of "small" and "large" terms allow measurement at practically all values of Q^2.
- Does not require a measurement of the cross sections.

How to measure the polarization

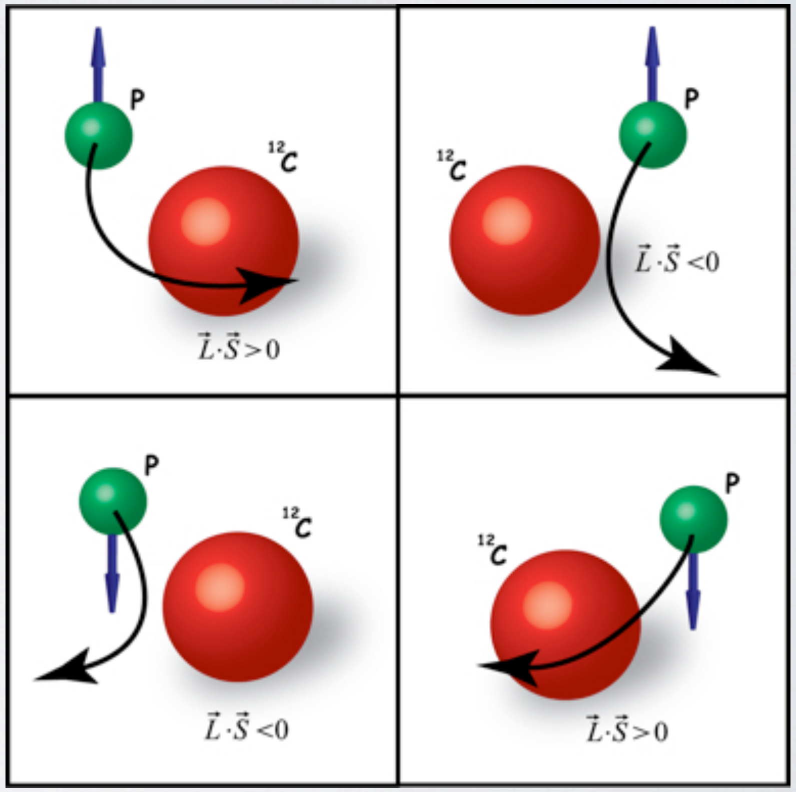
- Scatter recoil nucleons off a nucleus (carbon/ hydrogen/ ...).
- Spin-Orbit coupling causes angular dependence on spin.





How to measure the polarization

$$N_0(\theta,\phi) \;=\; N_0(\theta)\varepsilon(\theta)\left\{1+\left[hA_y(\theta)P_t^{fpp}+a_{instr}\right]sin\phi-\left[hA_y(\theta)P_n^{fpp}+b_{instr}\right]cos\phi\right\}$$



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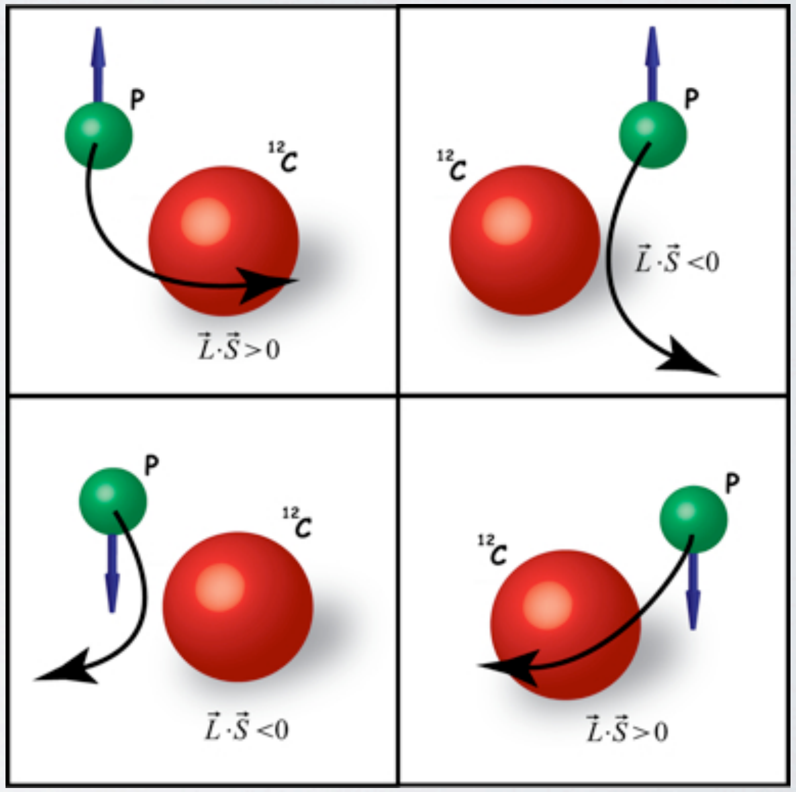
$$N_+ - N_- \quad = \quad N_0(\theta)\varepsilon(\theta) \left\{hA_y(\theta)P_t^{fpp}sin\phi - hA_y(\theta)P_n^{fpp}cos\phi\right\}$$



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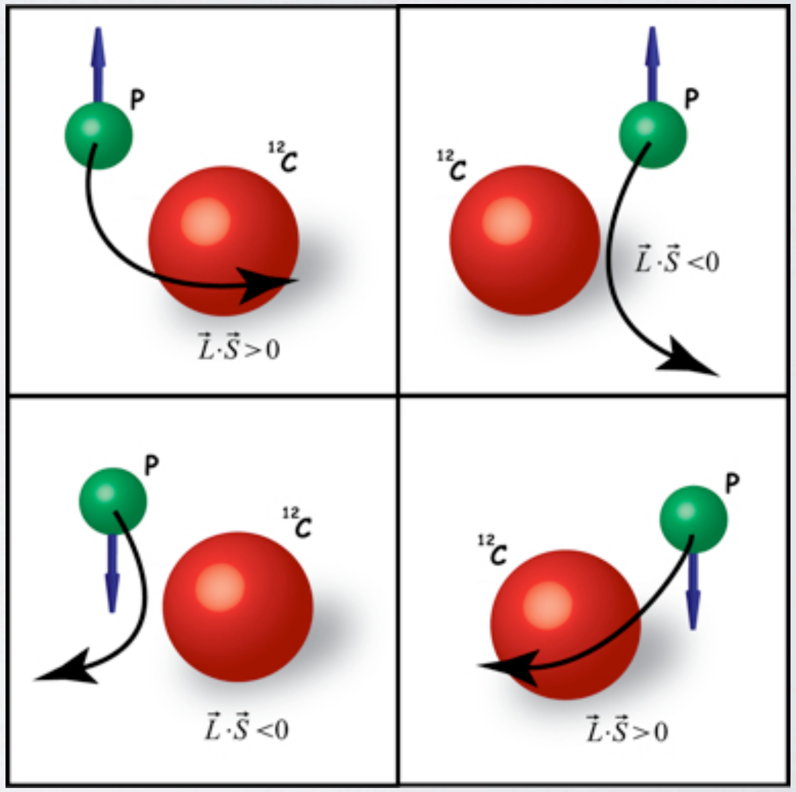
$$\frac{N_0(\theta)\varepsilon(\theta)hA_y(\theta)P_n^{fpp}}{N_0(\theta)\varepsilon(\theta)hA_y(\theta)P_t^{fpp}} = \frac{P_n^{fpp}}{P_t^{fpp}} \propto \frac{G_E}{G_M}$$



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$$\begin{aligned} N_+ - N_- \quad = \quad & N_0(\theta)\varepsilon(\theta) \\ & \left\{hA_y(\theta)P_t^{fpp}sin\phi - hA_y(\theta)P_n^{fpp}cos\phi\right\} \end{aligned}$$

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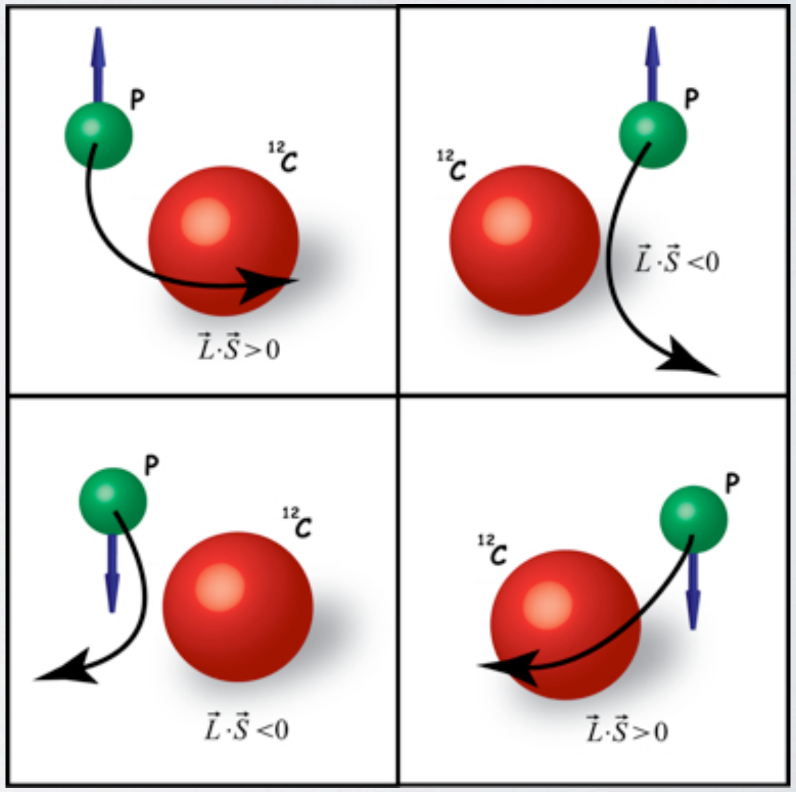
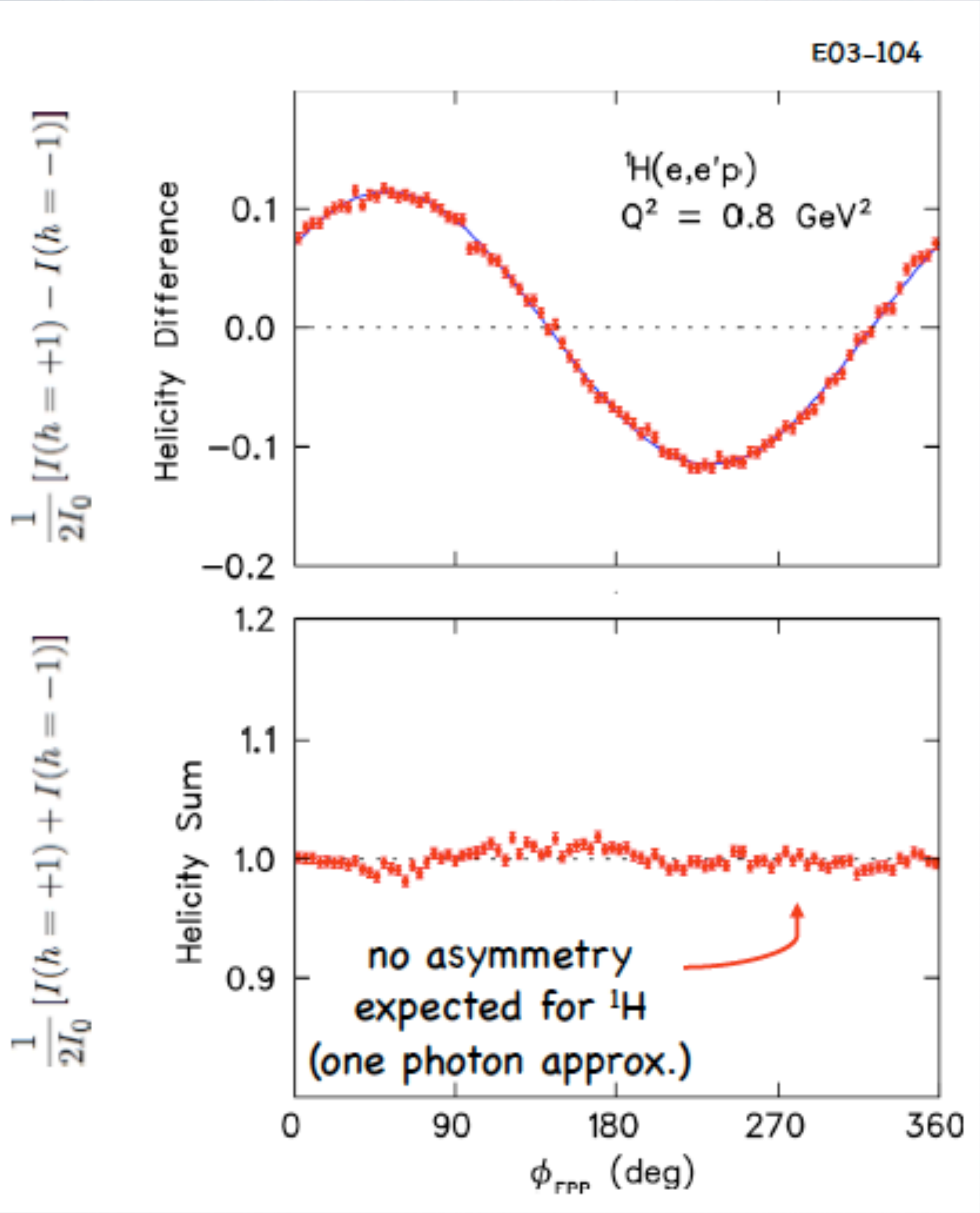


Systematic uncertainties cancel out (to ~0.5%)!

$$\sigma_{stat.} = \sqrt{\frac{2}{N}}$$

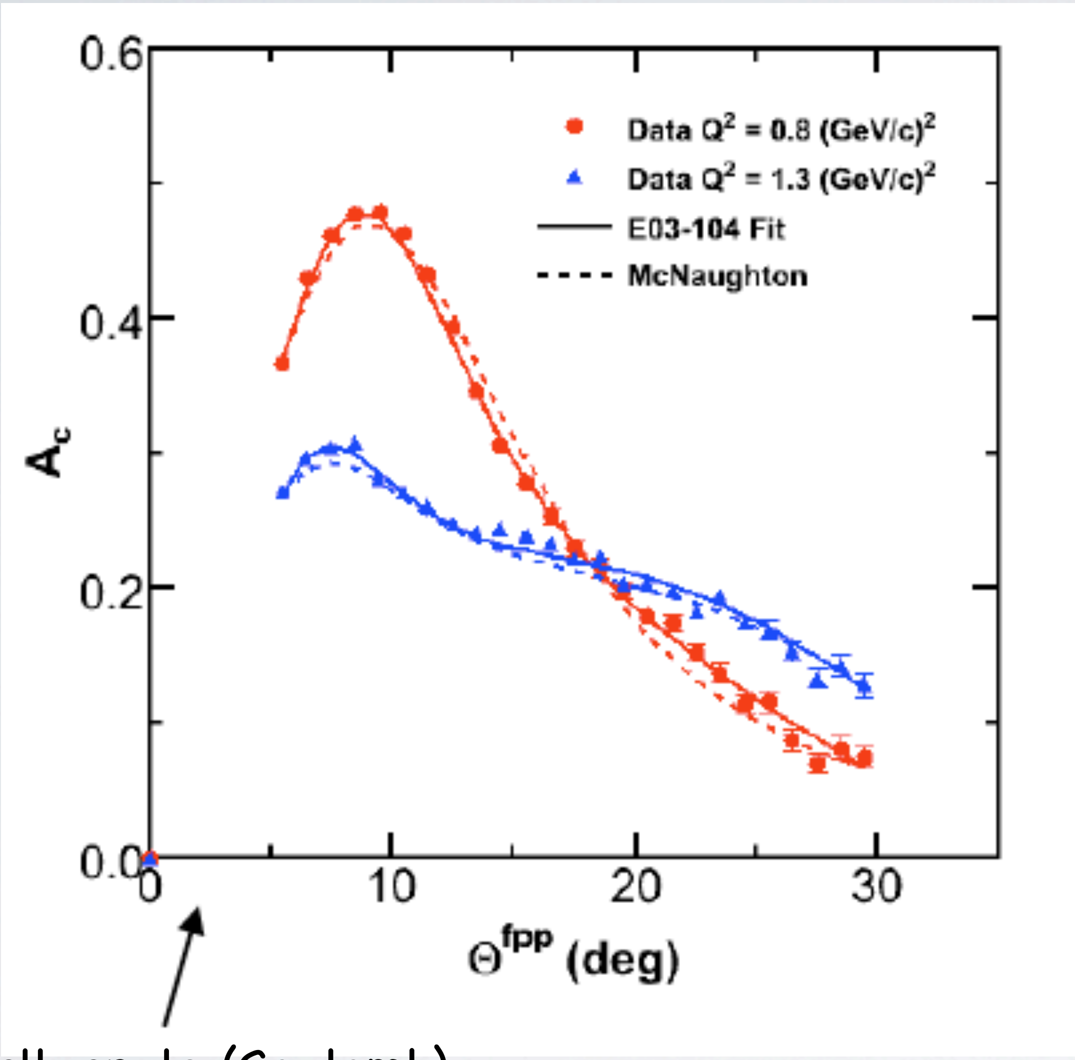
Observed Angular Distribution



- Excellent control of systematic uncertainties for polarization transfer observables
- Instrumental asymmetries complicate the extraction of induced polarization
  - Detector misalignment
  - Detector inefficiencies
  - Tracking problems

Courtesy S. Strauch

Analyzing Power



Small-angle (Coulomb) scattering – no analyzing power

Analyzing power connects asymmetry with polarization:

$$\varepsilon = hA_yP$$

Determination of the analyzing power from 1H(e,e'p) data and electron beam polarization:

$$\varepsilon_x, \varepsilon_z \rightarrow G_E/G_M$$

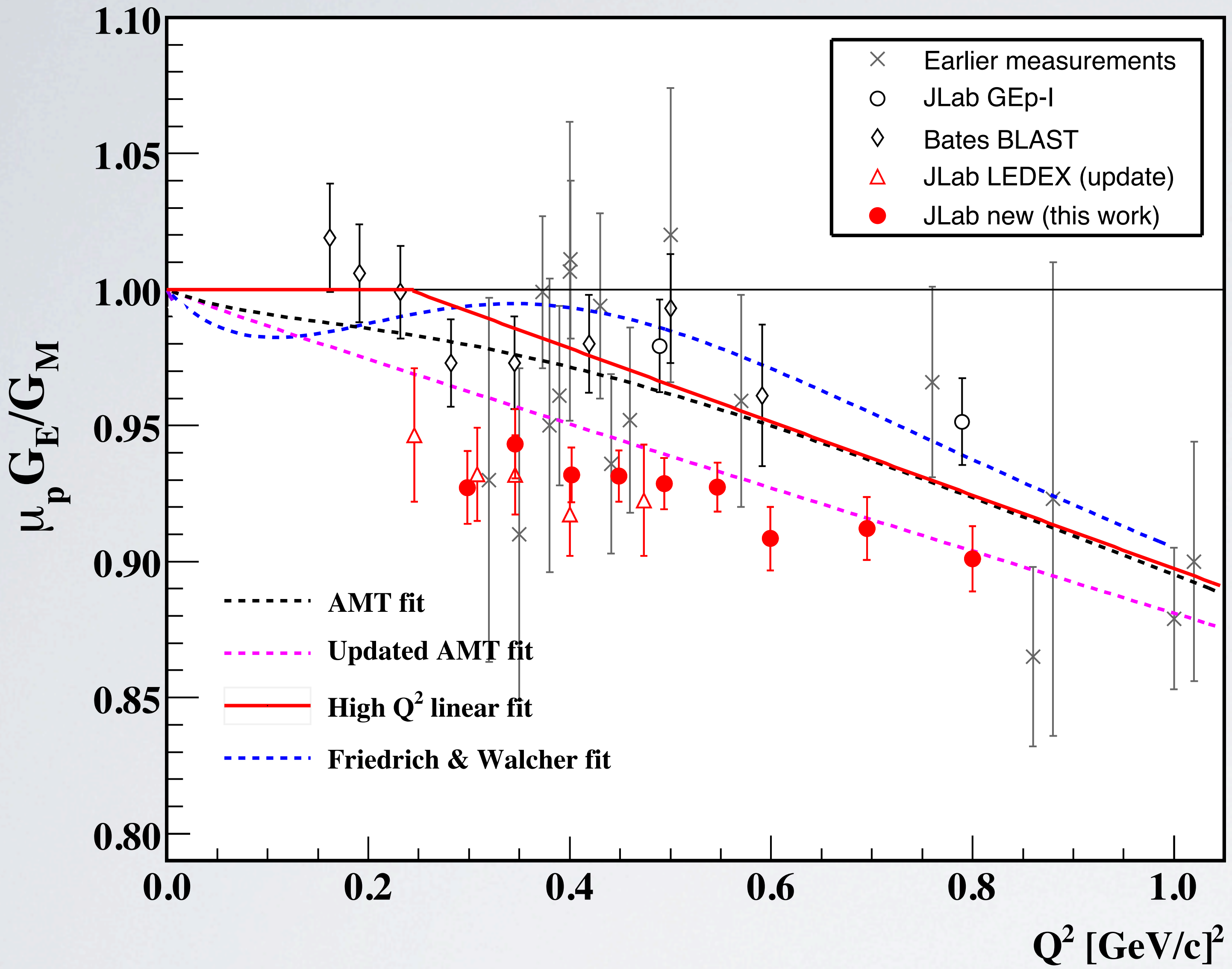
$$G_E/G_M \rightarrow P'_x/P'_y$$

$$\frac{1}{h}\sqrt{\frac{\varepsilon_x^2\varepsilon_y^2}{P_x'^2 + P_z'^2}} \rightarrow A$$

Use to extract P_y (induced polarization)

Courtesy S. Strauch

How well can we do this?



About 1% uncertainties for the proton.

Largest uncertainty from spin precession in the spectrometer.

X. Zhan et al., To be published in PLB (+ PhD Thesis)

The General Idea

Experiment

- Measure ratio of polarization components for a free nucleon.
- Measure ratio of polarization components for a nucleon extracted from the nucleus in quasi-free scattering.
- Take the super-ratio to remove systematic effects.

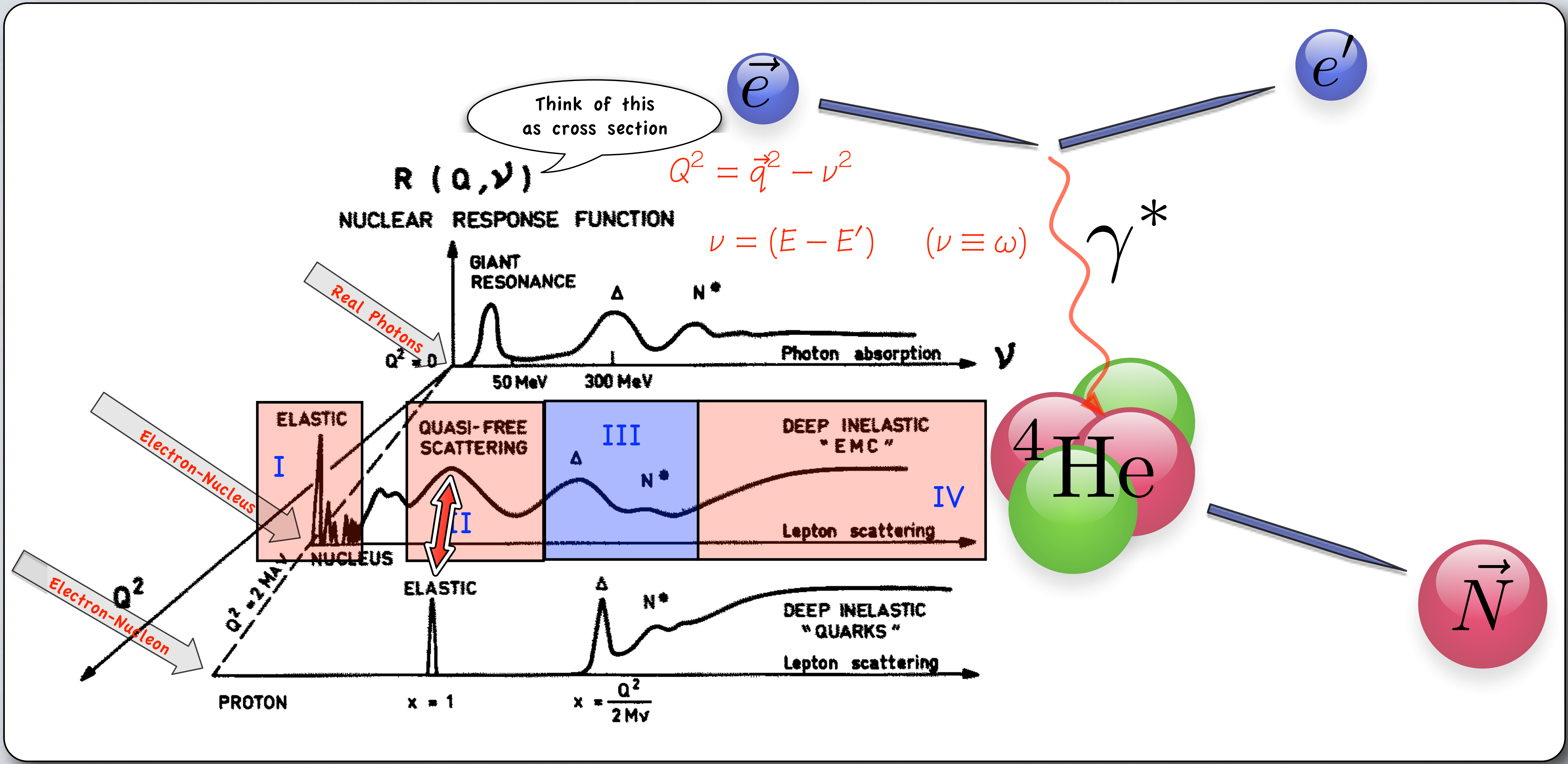
Theory

- Using some model calculate density dependent form factors.
- Integrate over density dist. to get medium modified FF (MMFF).
- Use MMFF to calculate polarization components.
- Add in Final State Interactions, etc...

COMPARE.....

Quasi-Free Scattering

- Electron scatters off Nucleon in the nucleus.
- Data selected to include nucleons with no initial state interactions (i.e., are Quasi-Free).

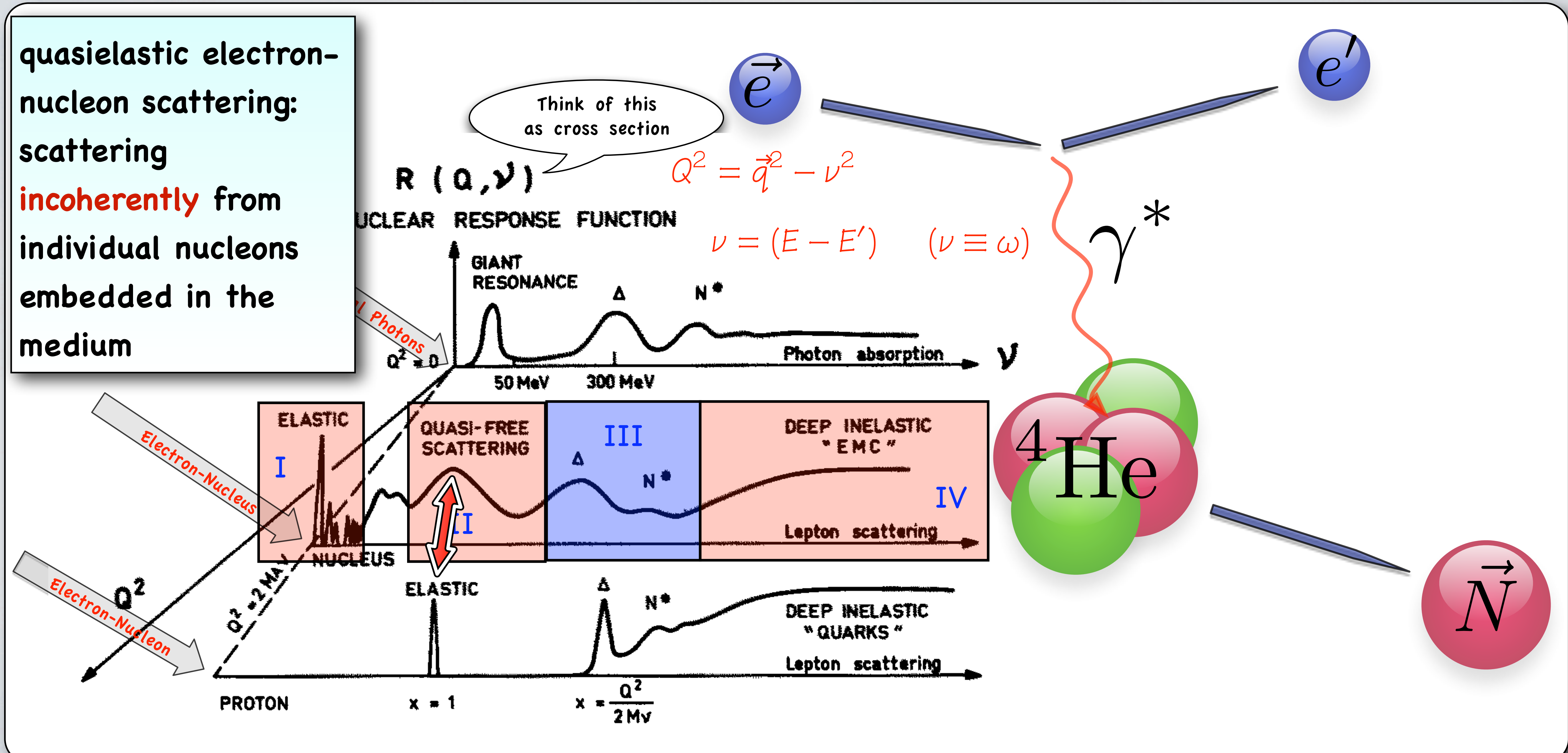


Quasi-Free Scattering

- Electron scatters off Nucleon in the nucleus

Effectively a "free" nucleon in the mean-field of the nucleus.

interactions (i.e., are Quasi-Free).



QE Scattering From Bound Nuclei

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

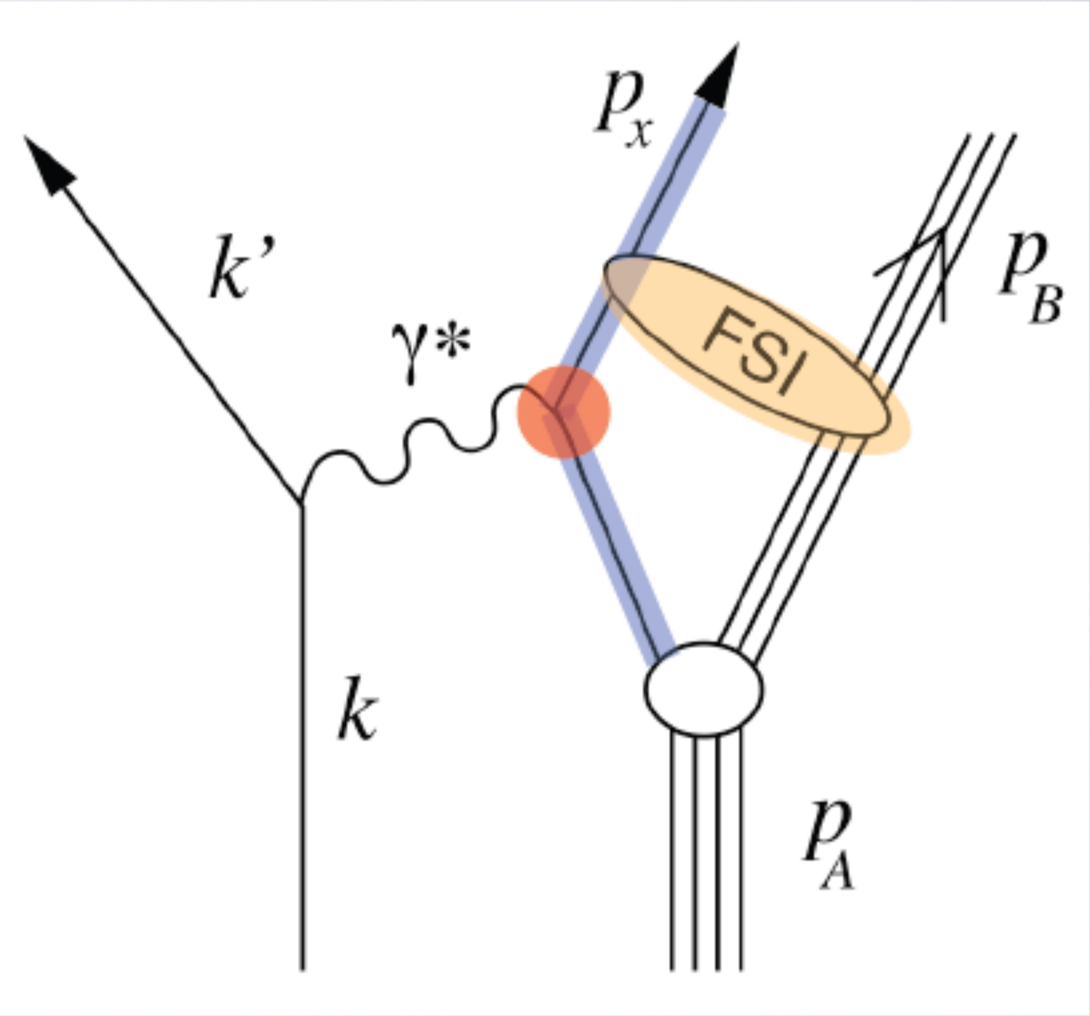
$$J_N^\mu(\omega,\vec{q}) = \int d\vec{p}\,\bar{\psi}_F(\vec{p}+\vec{q})\hat{J}_N^\mu(\omega,\vec{q})\psi_B(\vec{p})$$

Wave functions for initial bound, ψ_B, and final outgoing, ψ_F, nucleons

Final state interactions, FSI; optical potentials

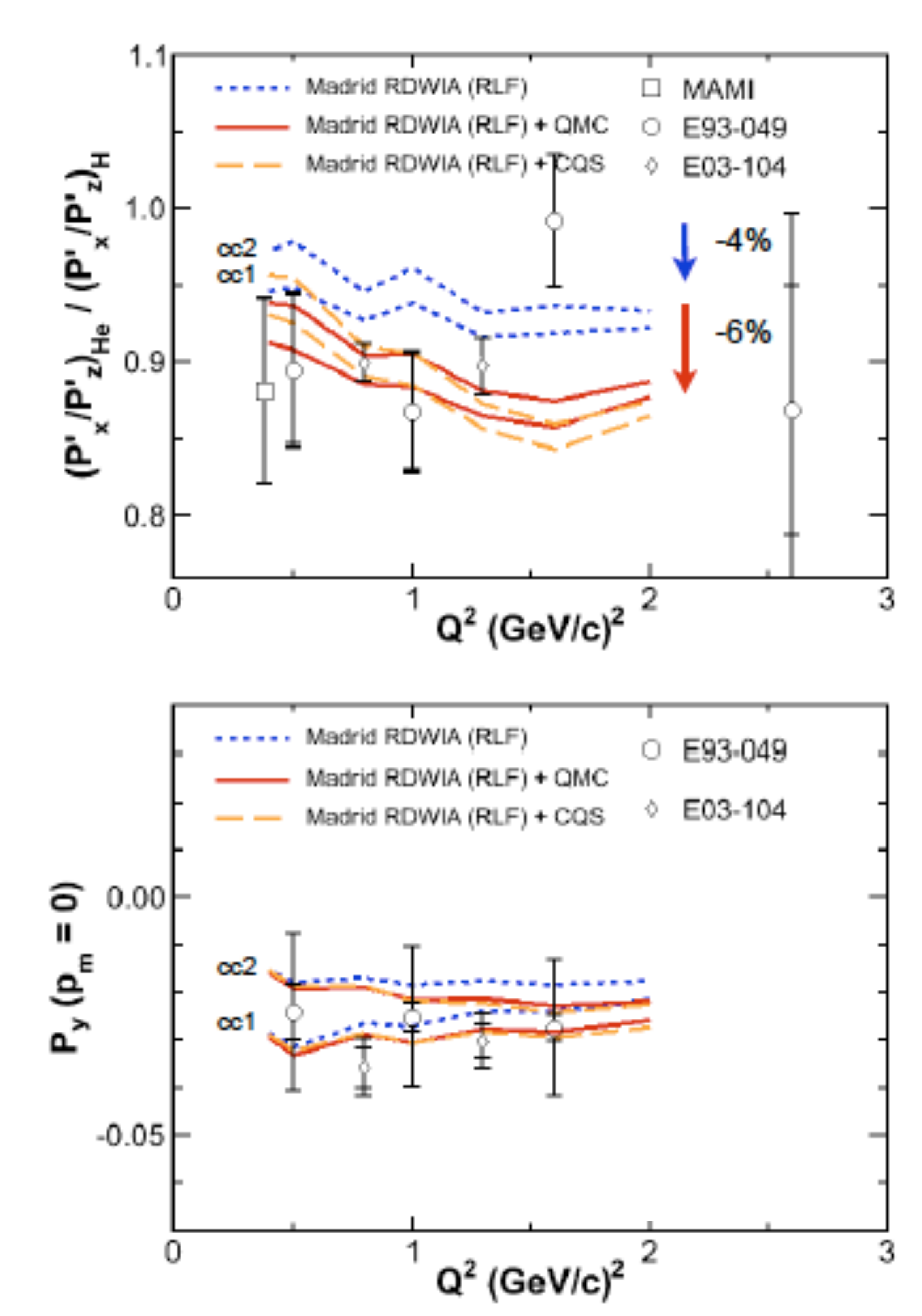
Relativistic nucleon current operator of cc1 or cc2 forms; possible medium-modified form factors enter here.

$$G(Q^2,\rho) = G(Q^2)\frac{G_{\rm QMC}(Q^2,\rho)}{G_{\rm QMC}(Q^2)}$$



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

Madrid RDWIA

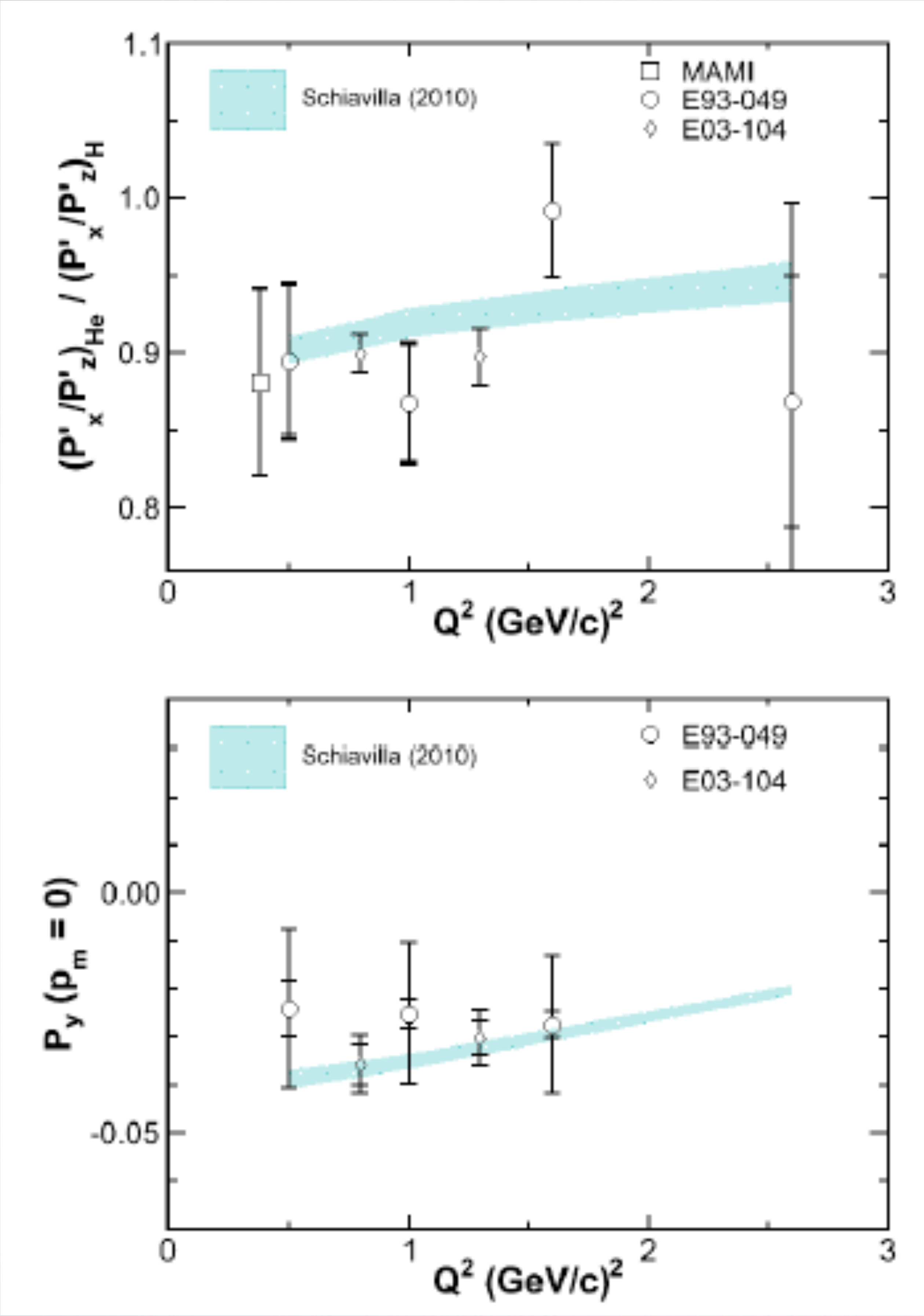


- Relativistic calculation in distorted-wave impulse approximation **(RDWIA)** overestimates R
- Density-dependent in-medium form factors were evaluated at the local density ρ(r)

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

- Both, the **QMC** and **CQS** models give reduction in R by about 6% and are in very good agreement with data
- Induced polarization, Py, is almost exclusively sensitive to FSI
- **RLF optical potential** along with cc1 current operator results in excellent description of Py within the Madrid model

FSI? - 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 Py 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)

A Hand Waving Prediction

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

For the proton:

$$G_E^p(Q^2) \sim 1 - \frac{Q^2}{6} R_{Ep}^2$$

$$G_M^p(Q^2) \sim \mu_p \left[1 - \frac{Q^2}{6} R_{Mp}^2\right]$$

$$\mathcal{R} \equiv \frac{G_E^p}{G_M^p} \sim \frac{1}{\mu_p}\left[1 - \frac{Q^2}{6}\left(R_{Ep}^2 - R_{Mp}^2\right)\right]$$

Can change radius or magnetic moment in the medium.

$R_E^p \sim R_M^p$, $\Delta R_E \sim \Delta R_M$

μ_p grows in the medium:

$$\mu_p \propto \frac{R_{E/M}}{M}$$

$R^* > R$, $M^* < M$ (binding)

$$\frac{\mathcal{R}^*}{\mathcal{R}} \propto \frac{\mu_p}{\mu_p^*}$$

Consistent with experimental results

The Neutron - A Hand Waving Prediction

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

For the neutron:

$$G_E^n(Q^2) \sim 0 - \frac{Q^2}{6} R_{En}^2$$

$$G_E^n(Q^2) \sim \mu_n \left[1 - \frac{Q^2}{6} R_{Mn}^2\right]$$

$$\mathcal{R} \equiv \frac{G_E^n}{G_M^n} \sim -\frac{1}{\mu_n}\frac{Q^2}{6} R_{En}^2$$

Can change radius or magnetic moment in the medium.

$G_E^n(0) = 0,\ \Delta R_E \sim \Delta R_M$

μ_n grows in the medium:

$$\mu_n \propto \frac{R_{E/M}}{M}$$

$R^* > R,\ M^* < M$ (binding)

$$\frac{\mathcal{R}^*}{\mathcal{R}} \propto \frac{\mu_p}{\mu_p^*} \frac{{R_E^{n*}}^2}{{R_E^n}^2} > 1$$

Radius enters quadratically.

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$G_E^n(0) = 0,\ \Delta R_E \sim \Delta R_M$

μ_n grows in the medium:

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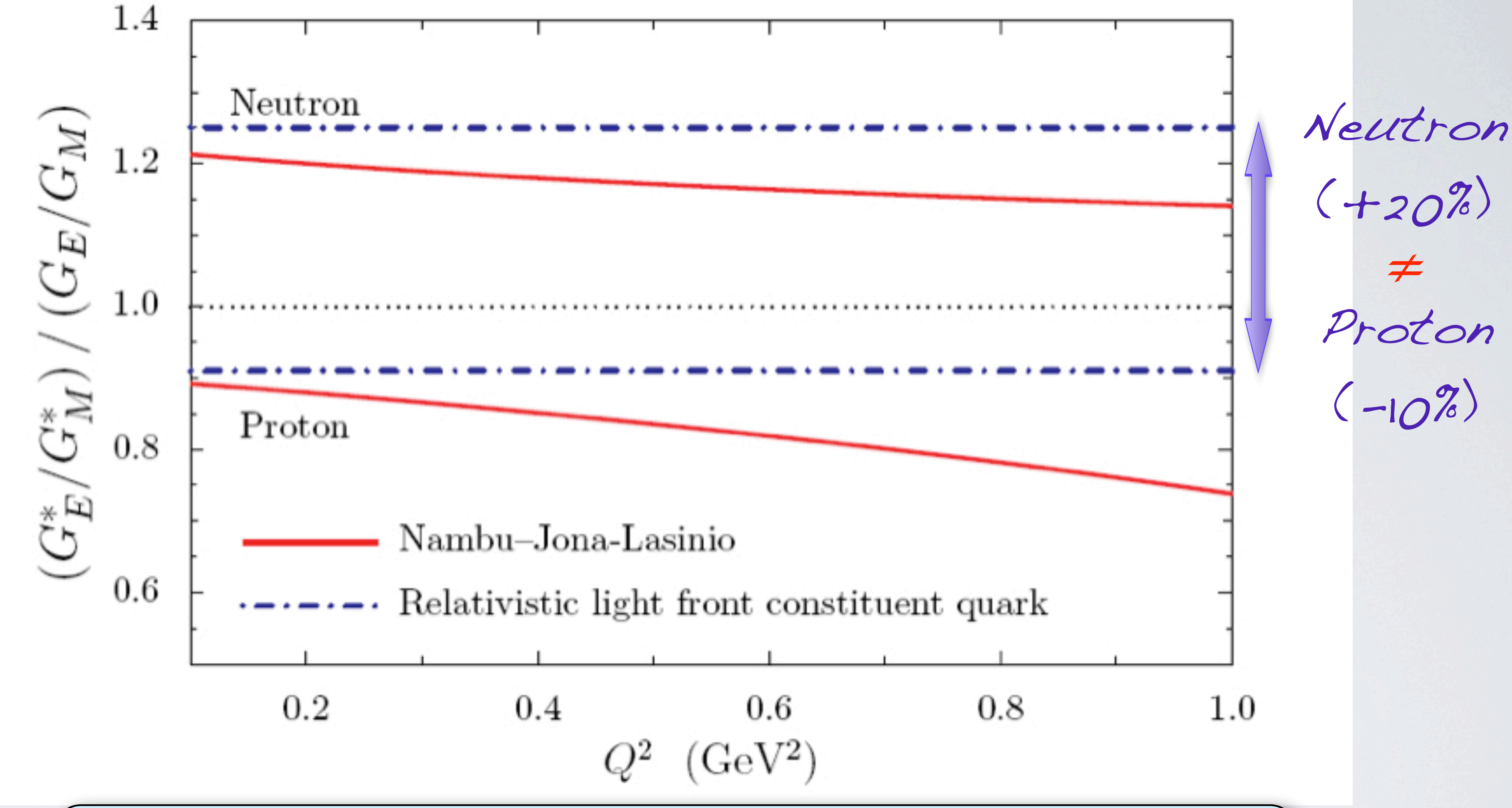
$R^* > R,\ M^* < M$ (binding)

Is this just handwaving????

The Neutron - A theory calculation

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



Different models for medium modification all give same result:

Effect on neutron form factor ratio very different from the proton!

Are we looking in the Wrong Place?

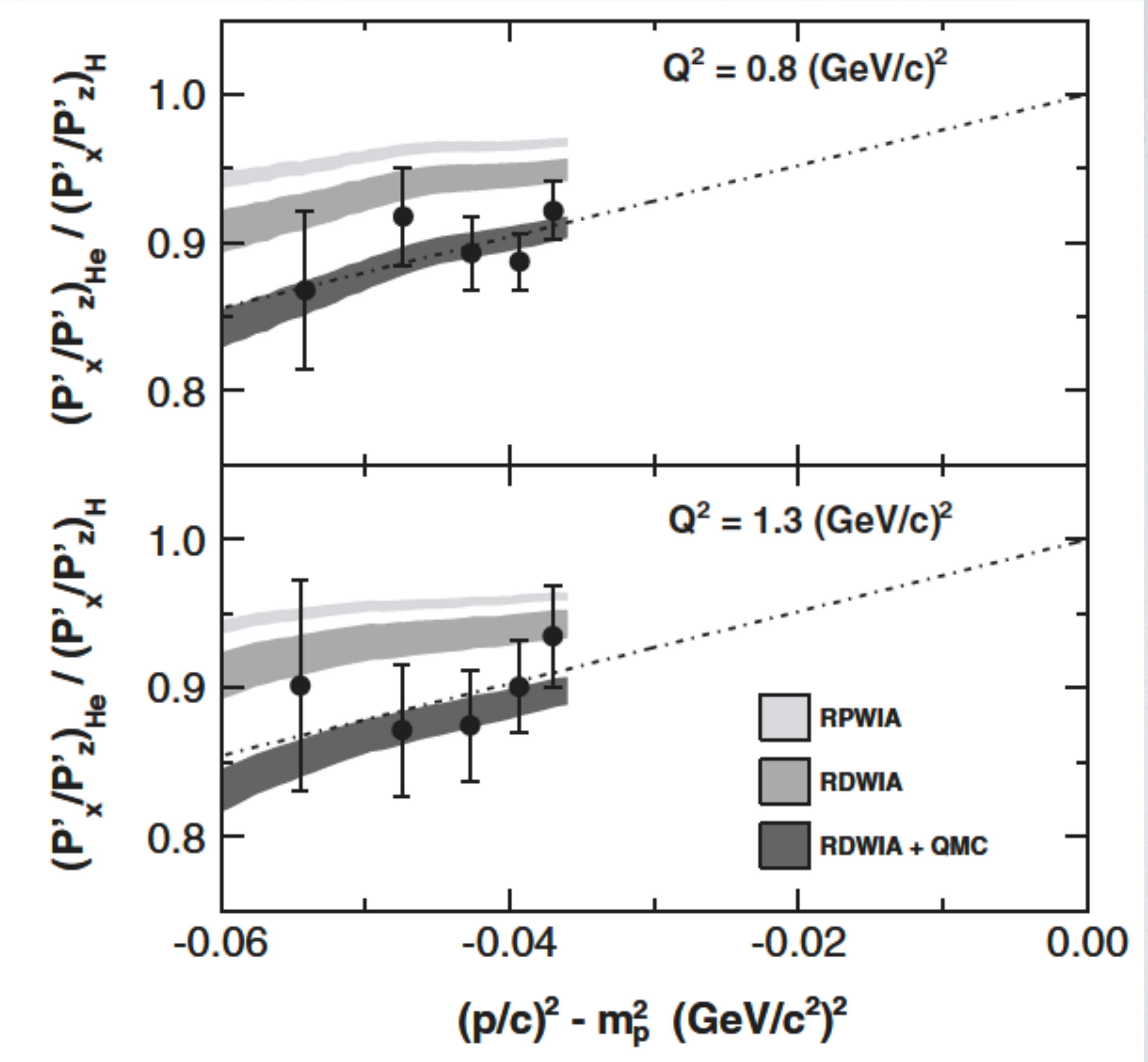
Nucleon Virtuality

- Point Like Configurations (PLCs) suppressed in the medium, leading to dependence of medium modification on nucleon virtuality (related to missing momentum).

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

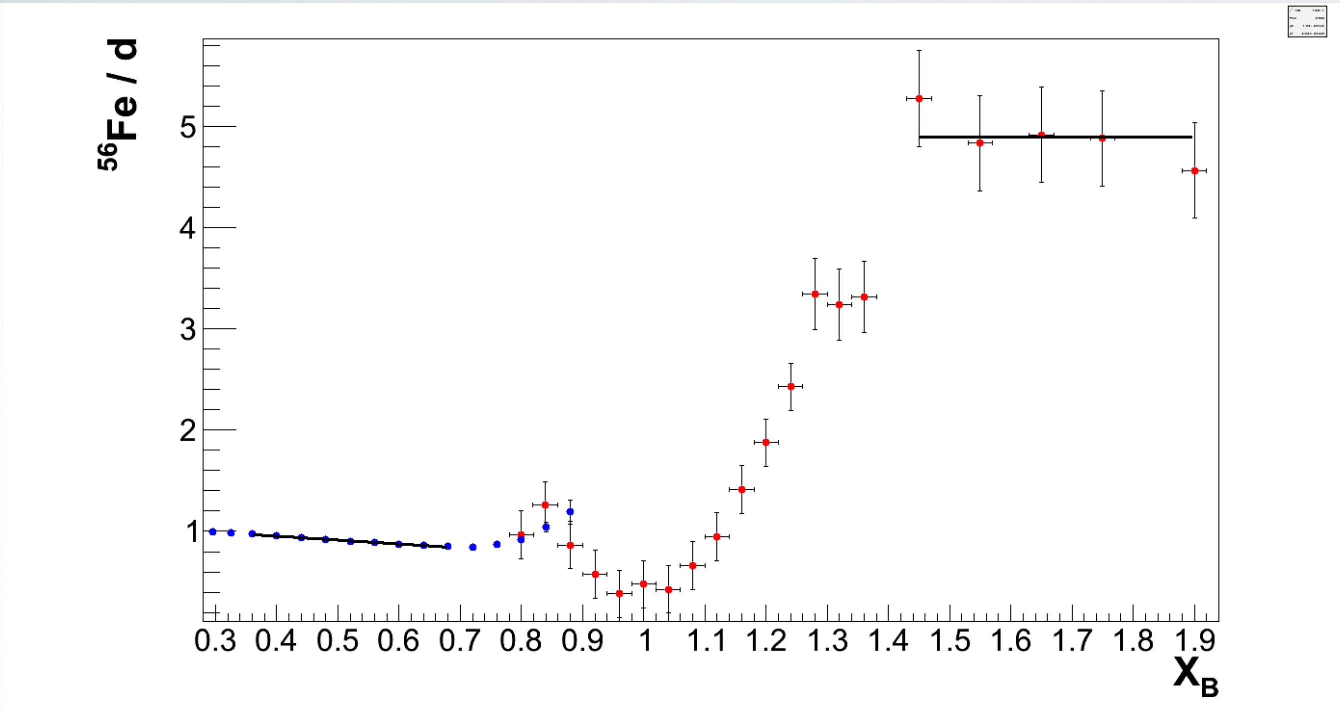
- If that's the case, we should look for modification in the large virtuality regime (large MM, off-shellness).

- Preliminary data agree with expected trend, but would like better data.

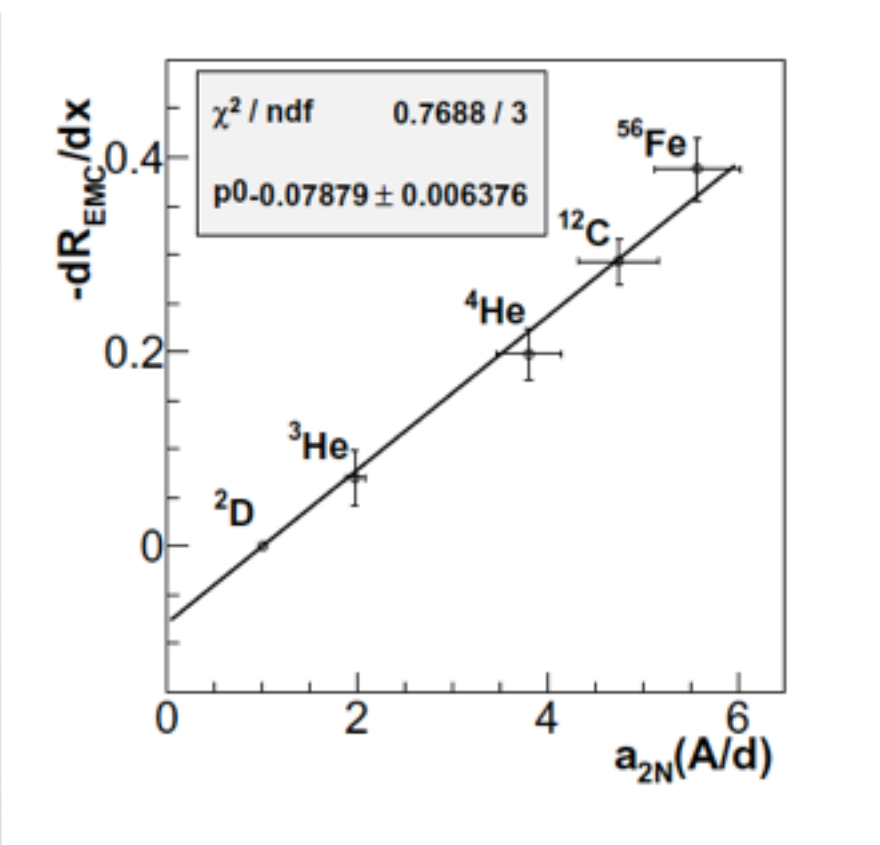


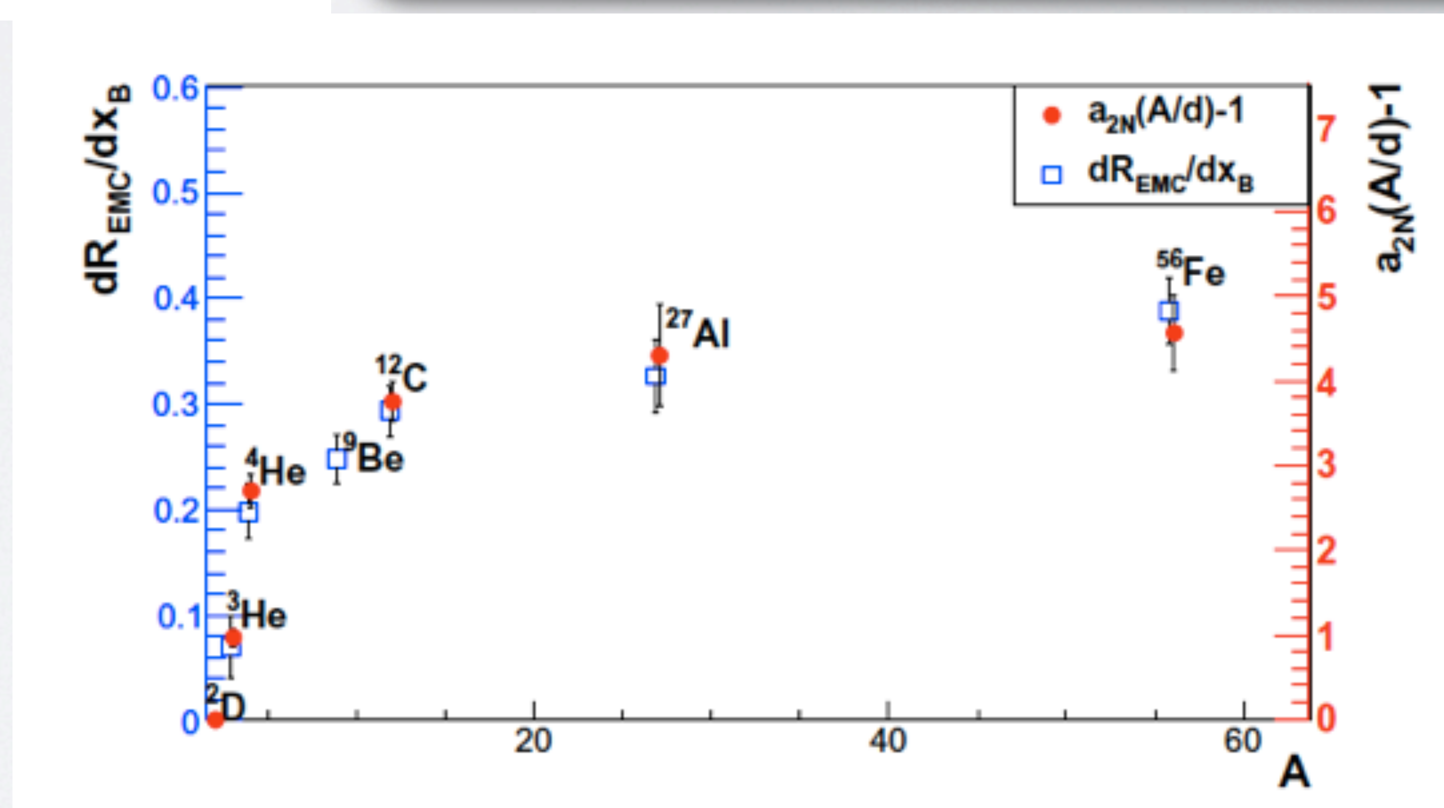
C. Ciofi degli Atti et al., Phys. Rev. C 76, 055206 (2007).
M. Paolone et al., Phys. Rev. Lett. 105, 072001 (2010).

Hints of correlation to SRC?



Are medium modifications related to Short Range Correlations?





E. Piasetzky et al., Nuclear Physics A 855, 245 (2011)

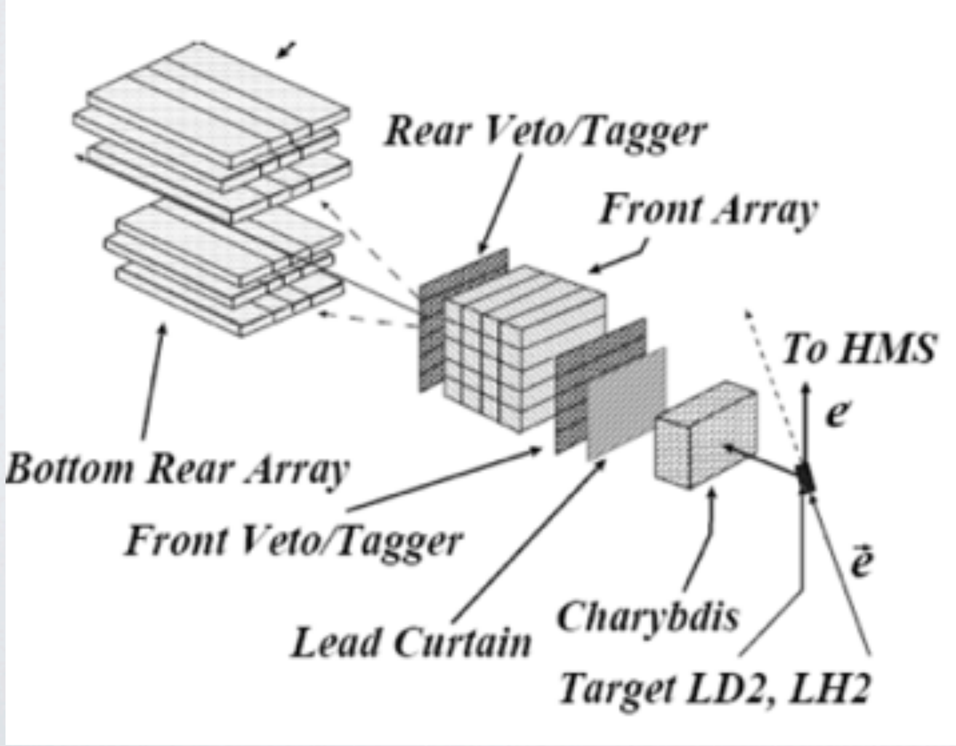
A New Proposal

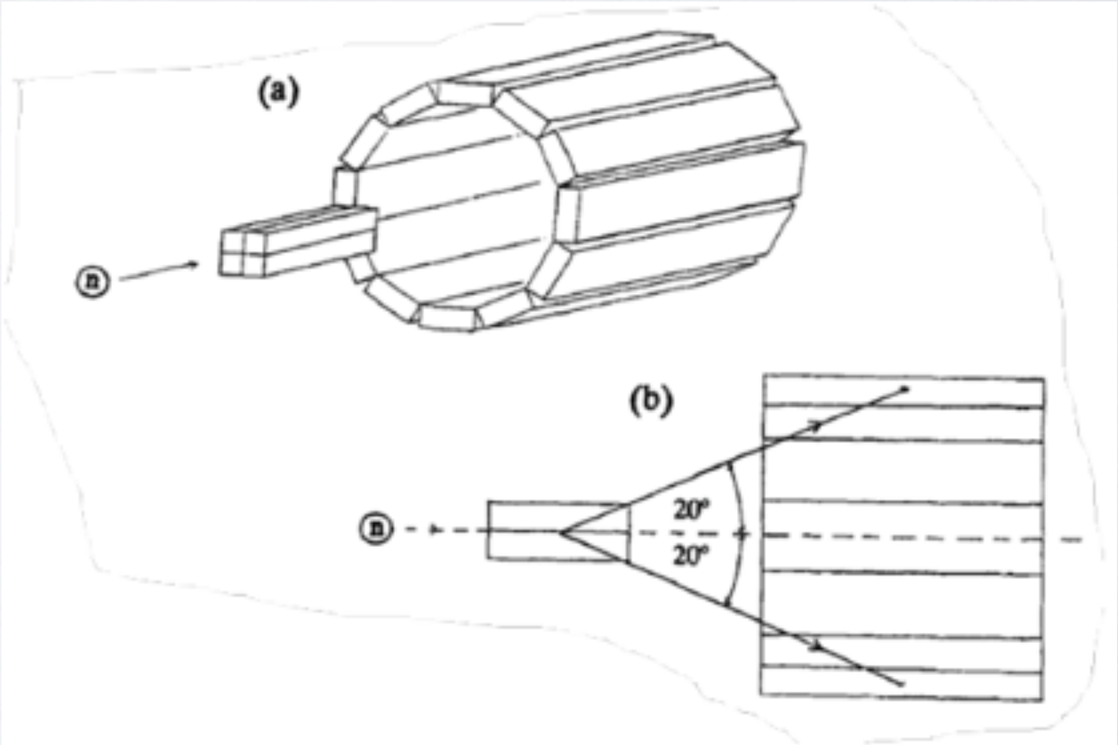
(G. Ron, D. Higinbotham, R. Gilman, S. Strauch, J. Lichtenstadt)

A New Proposed Experiment for ????

$$^{4}\text{He}(\vec{e},e'\vec{n})^{3}\text{He}\,/\,^{2}\text{H}(\vec{e},e'\vec{n})p$$

- Quasi-Free scattering off the neutron in ^{4}He.
- Deuteron used for “free” neutrons.
- Recoil neutron polarization measured with (new) neutron polarimeter.





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A New Proposed Experiment for ????

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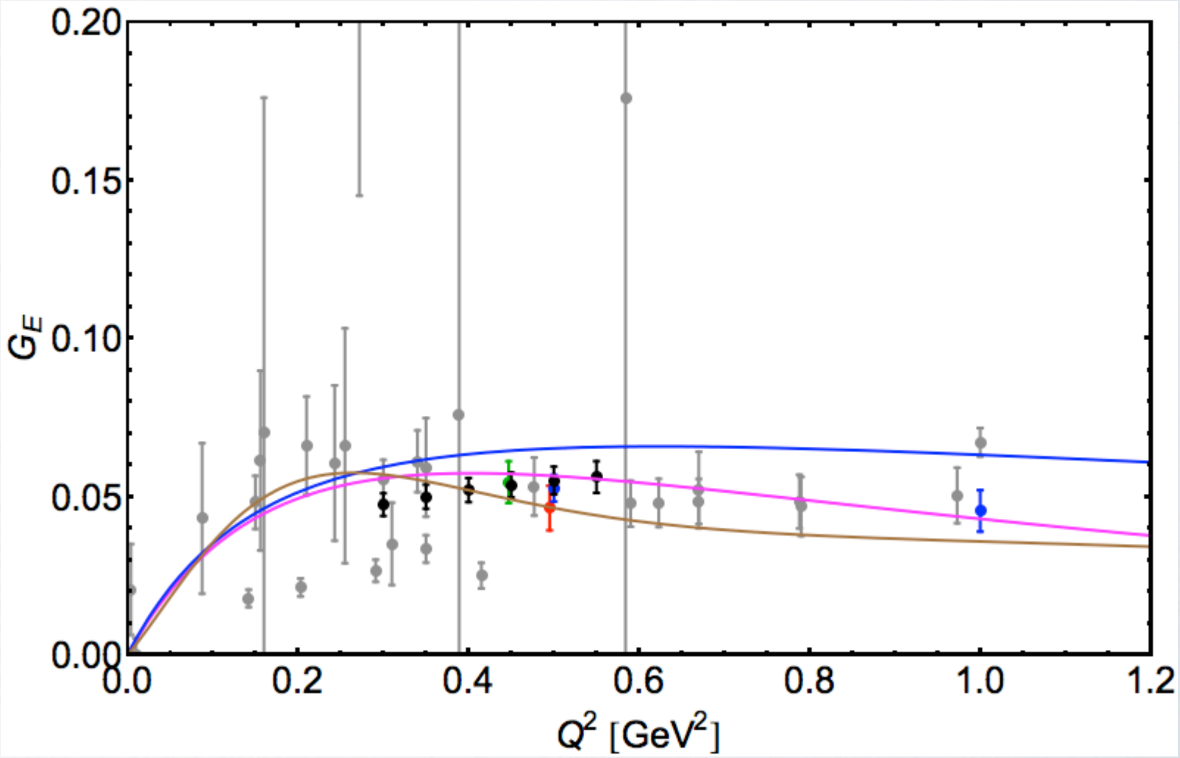
$$^4\mathrm{He}(\vec{e}, e'\vec{n})^3\mathrm{He} \,/\, ^2\mathrm{H}(\vec{e}, e'\vec{n})p$$

$$\left.\frac{dG_E^n(Q^2)}{dQ^2}\right|_{Q^2=0.4} = 0$$

- Quasi-Free scattering off the neutron in ^{4}He.
- Deuteron used for "free" neutrons.
- Recoil neutron polarization measured with (r
- $Q^2 = 0.1$ GeV^2 - Theory calculation best at low energy.
- $Q^2 = 0.4$ GeV^2 - Highest sensitivity to changes in magnetic FF.



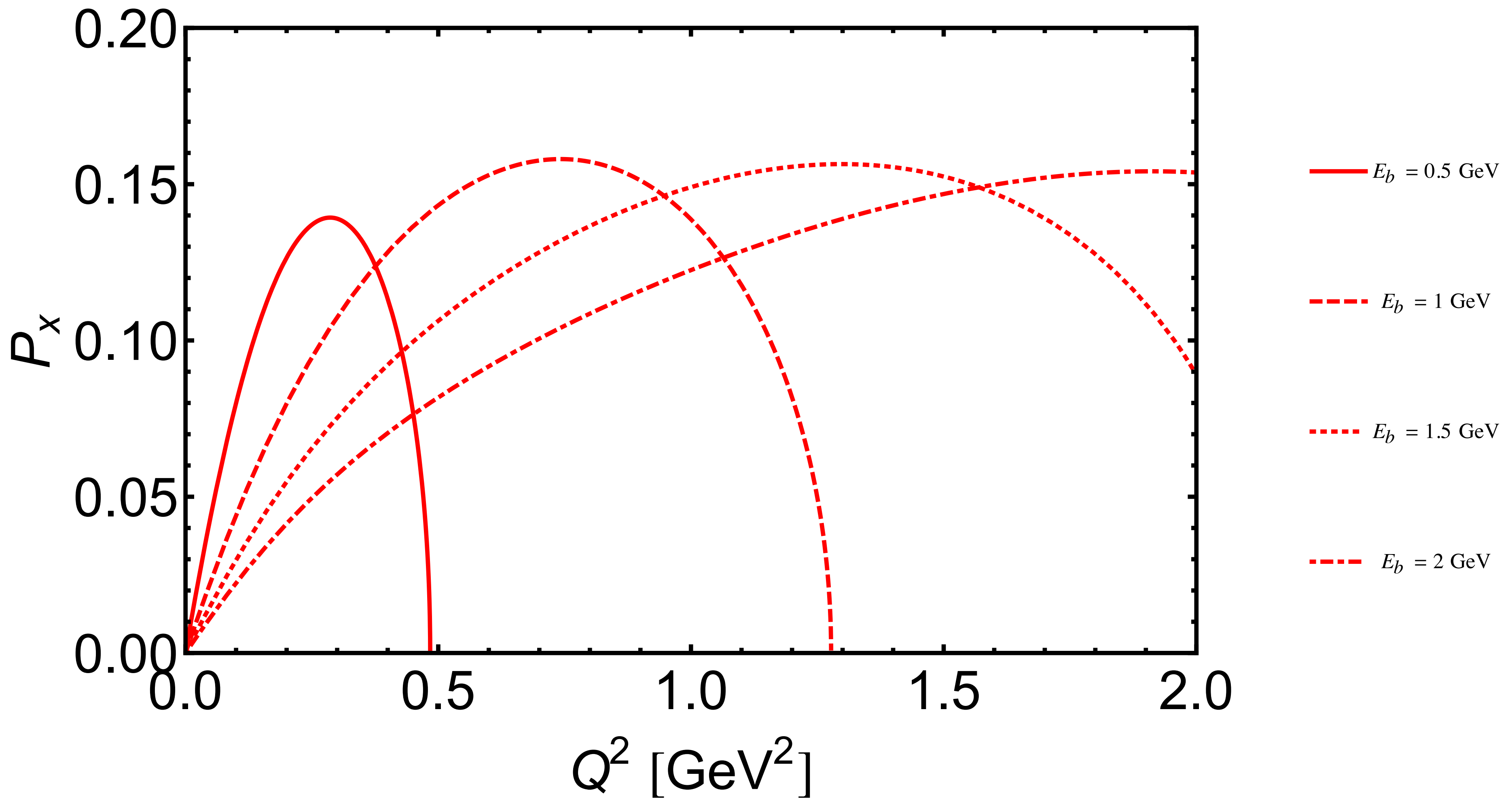
A New Proposal

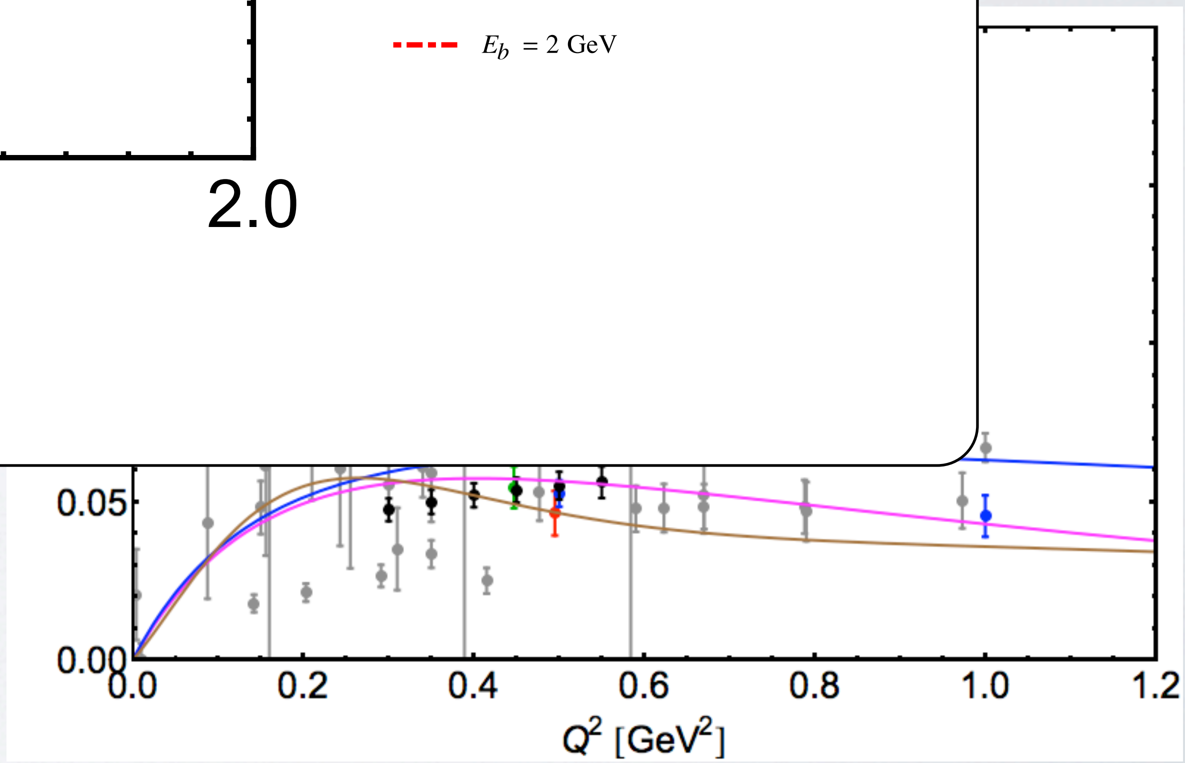
(G. Ron, D. Higinbotham, R. Gilman, S. Strauch, J. Lichtenstadt)

A New Proposed Experiment for ????

$= 0$

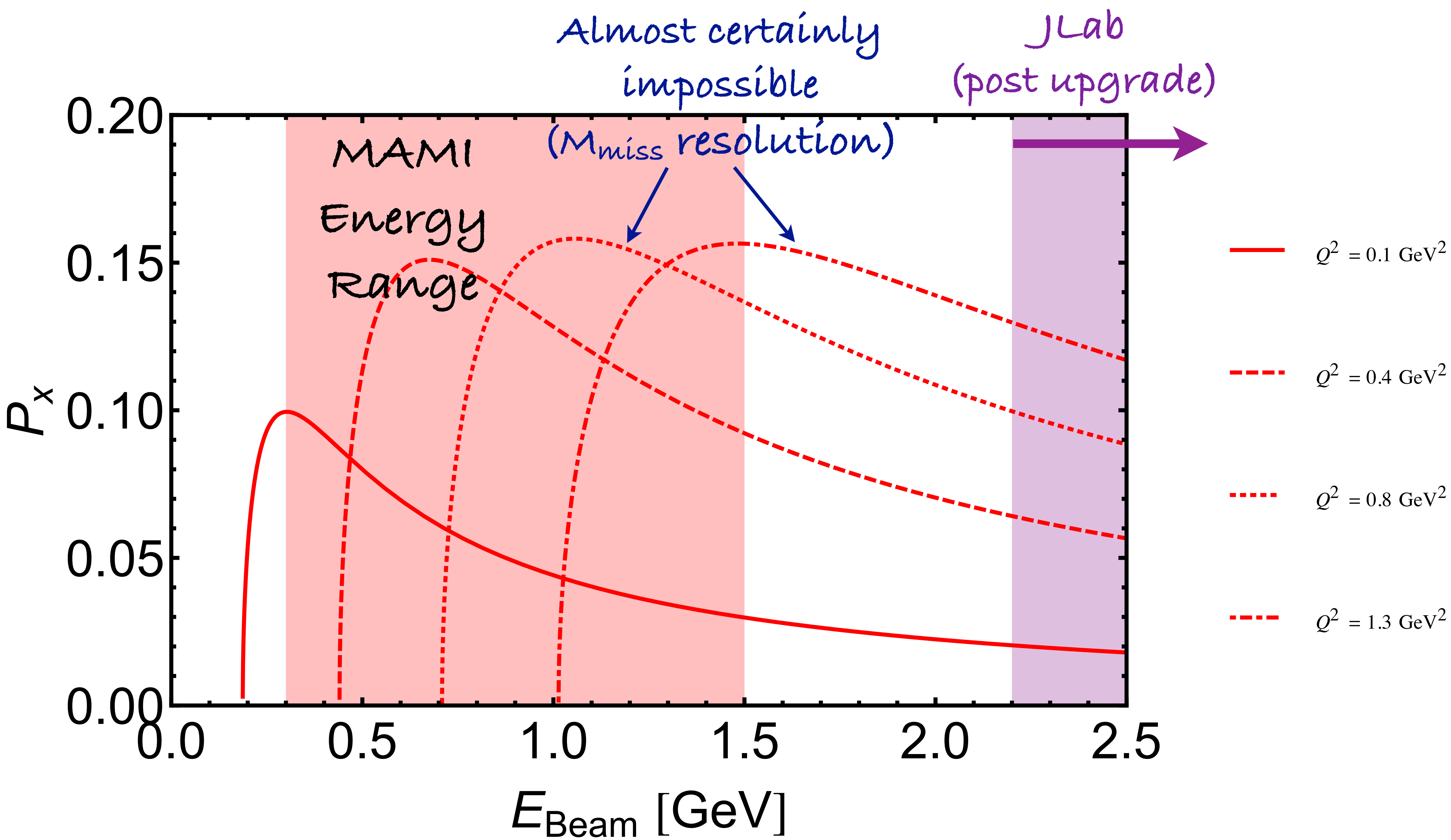
- Q
- D
- R
- Q c
- Q sensitivity to changes in magnetic FF.





A New Proposal

Run @ MAMI!



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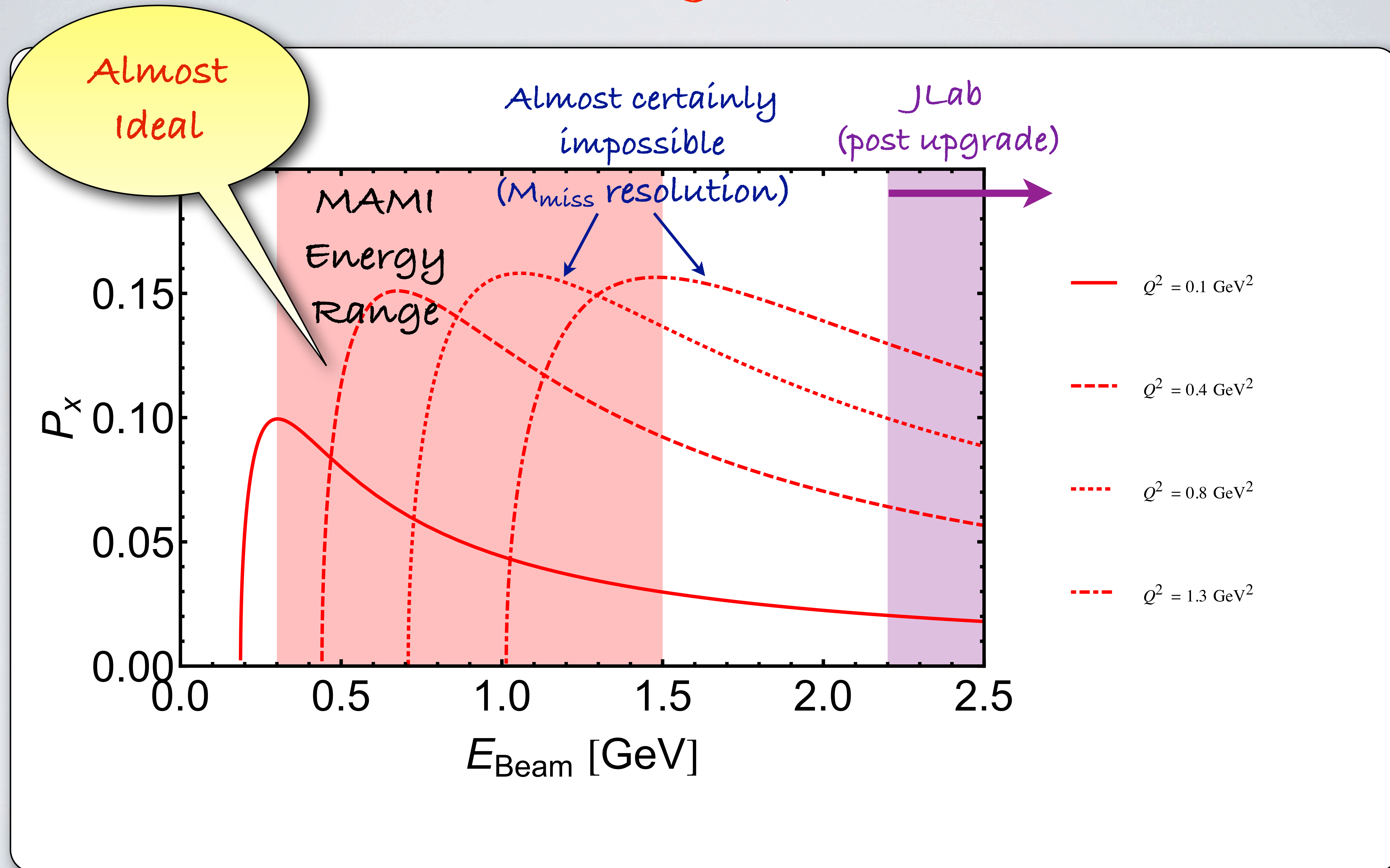

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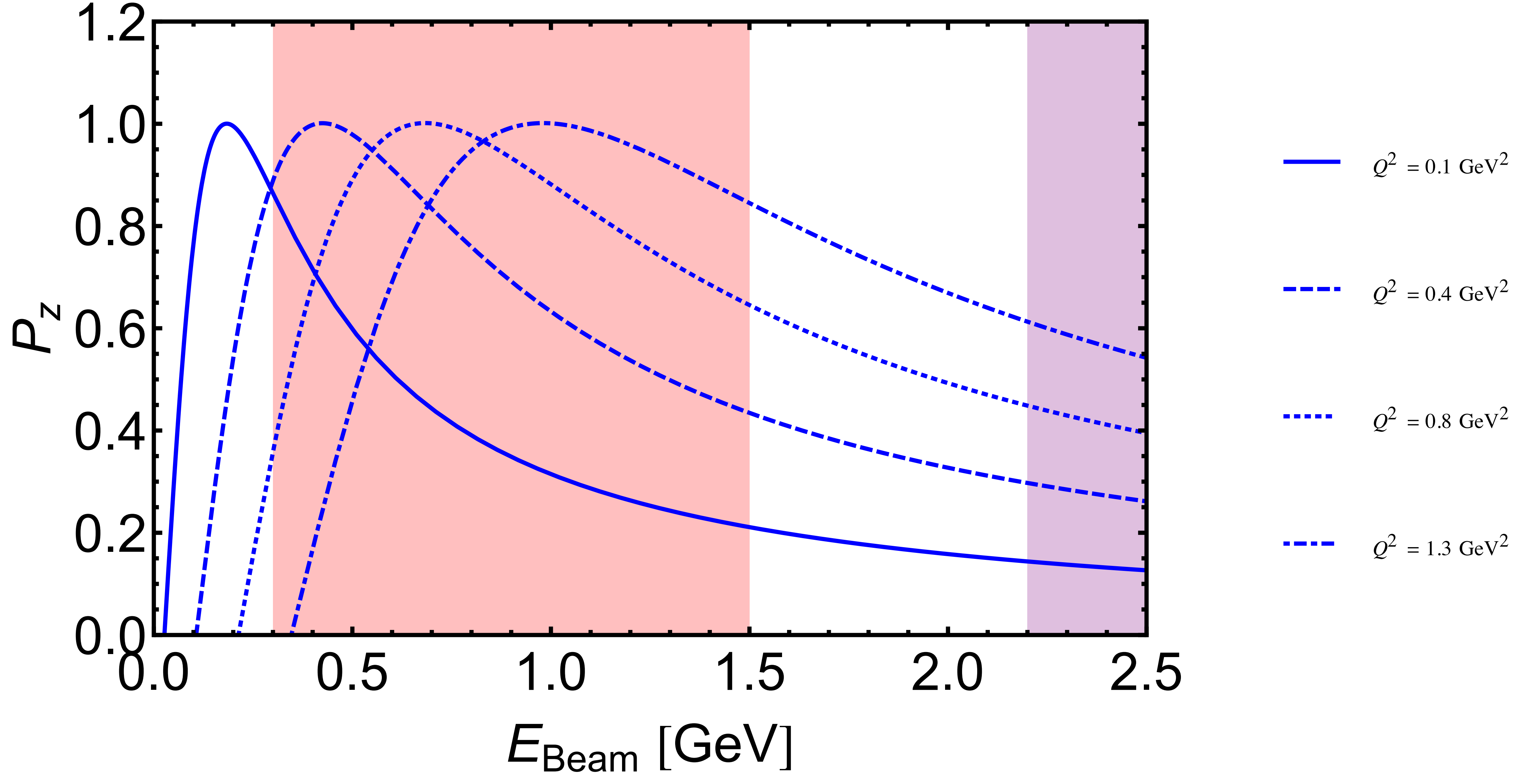
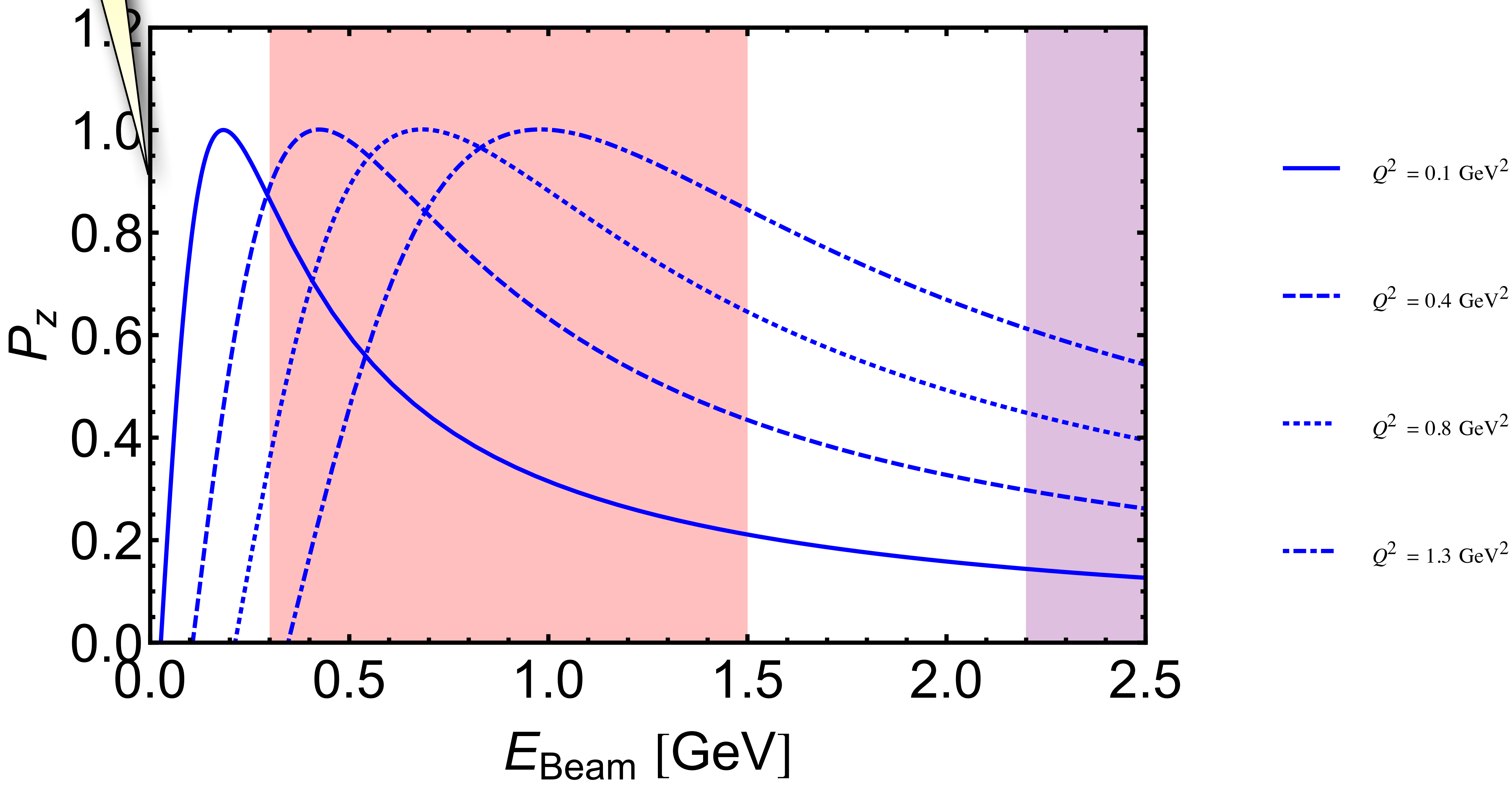


A New Proposal

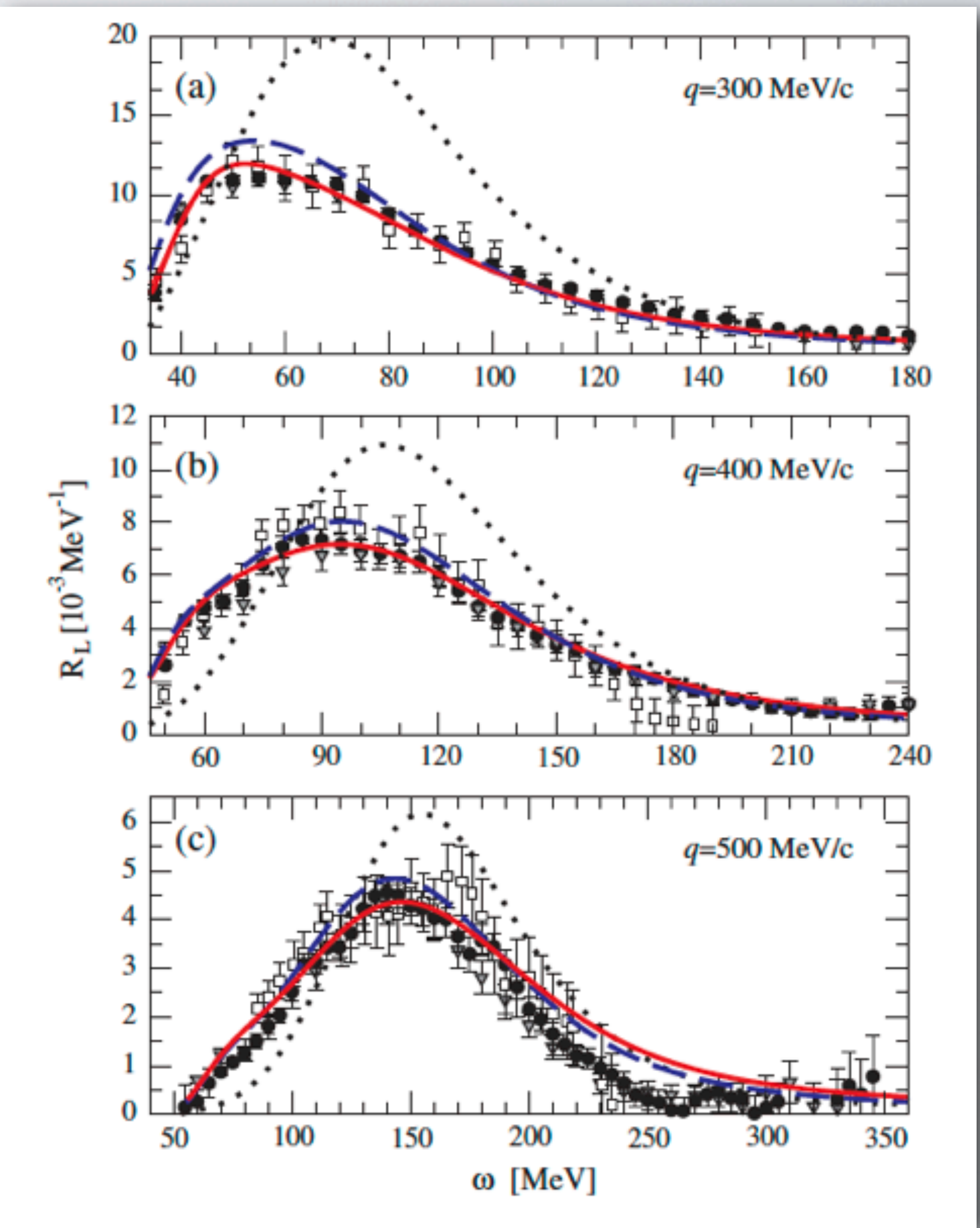
Run @ MAMI!

P_z not a problem!



How well can we do the theory?

- Calculation of longitudinal response function R_L for $^4He(e,e')$.
- AV18 + UIX.
- Low momentum transfer ➙ percent theoretical accuracy achievable (for A=4).
- Calculation of Medium Modified FFs (Miller / Cloet) calculation done for nuclear matter needs to be looked at for bound ➙free transition).
- Trento/HUJI group hard @ work on L/T response functions.



S. Bacca, N. Barnea, W. Leidman, and G. Orlandini, PRL 102, 162501 (2009)

How well can we do the theory?

- Calculation of longitudinal response function R_L for $^4He(e,e')$.
- AV18 + UIX.
- Low momentum transfer ➞ percent theoretical accuracy achievable (for A=4).
- Calculation of Medium Modified FFs (Miller / Cloet) calculation done for nuclear matter needs to be looked at for bound ➞free transition).
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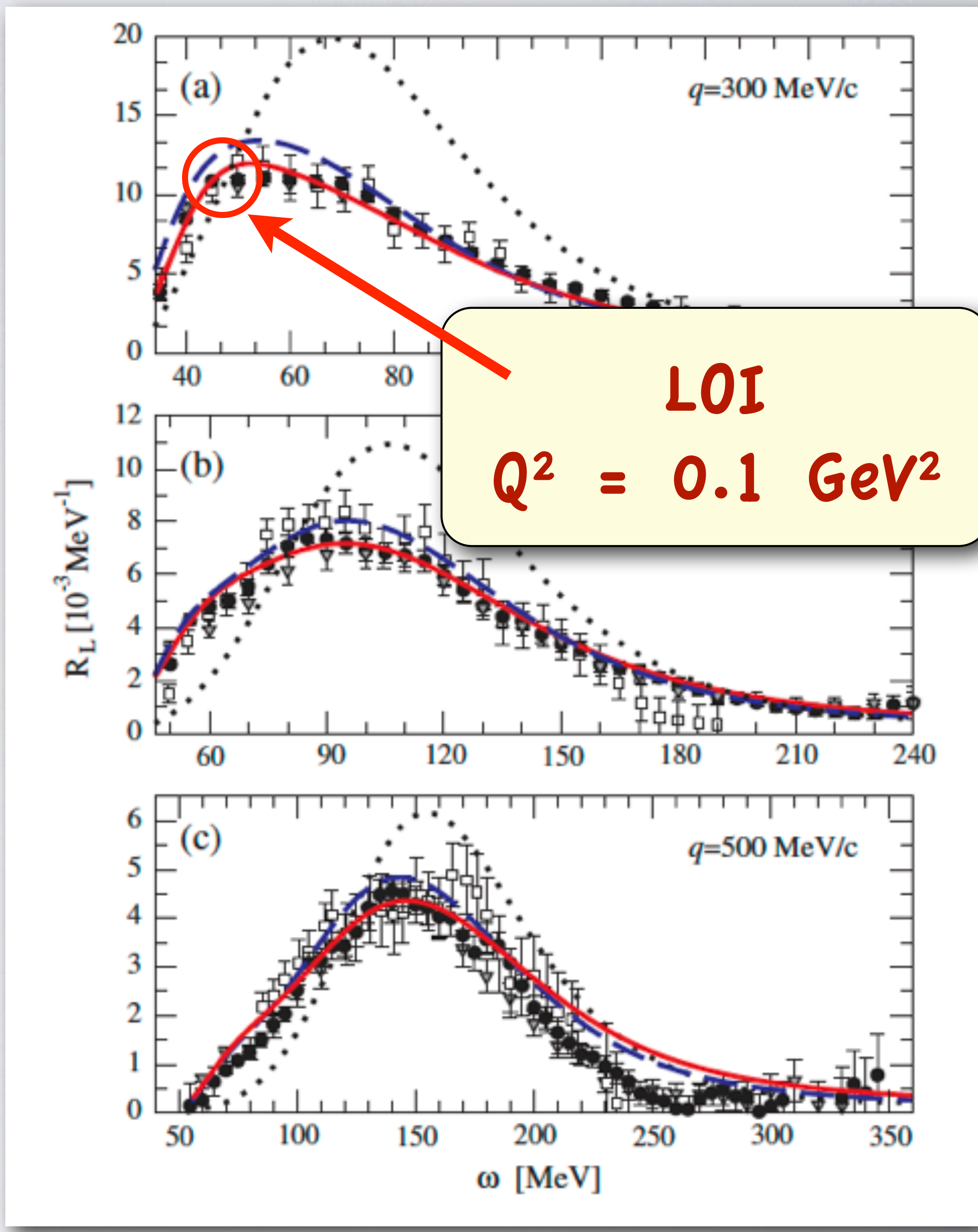

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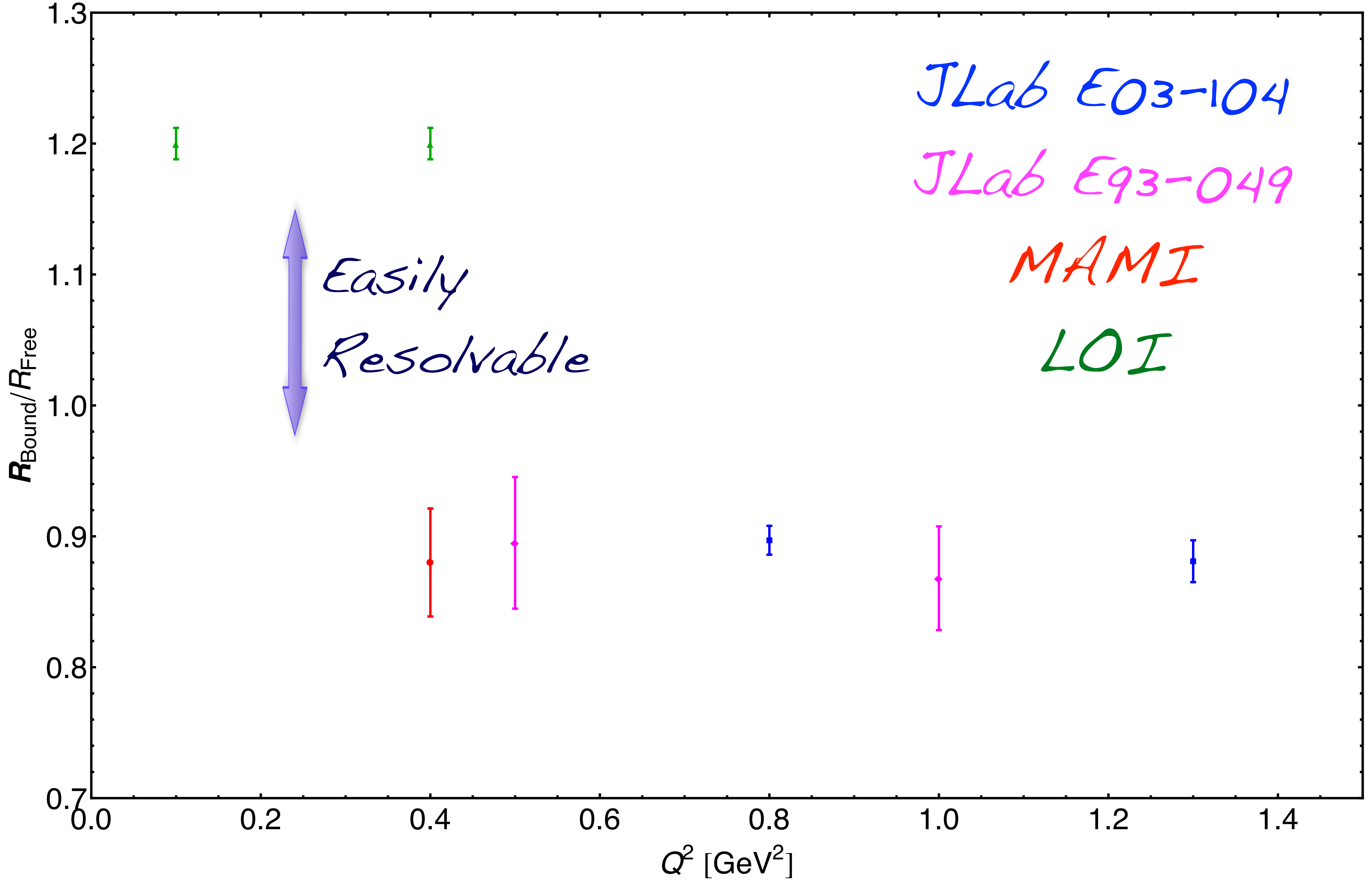
And the Experiment?

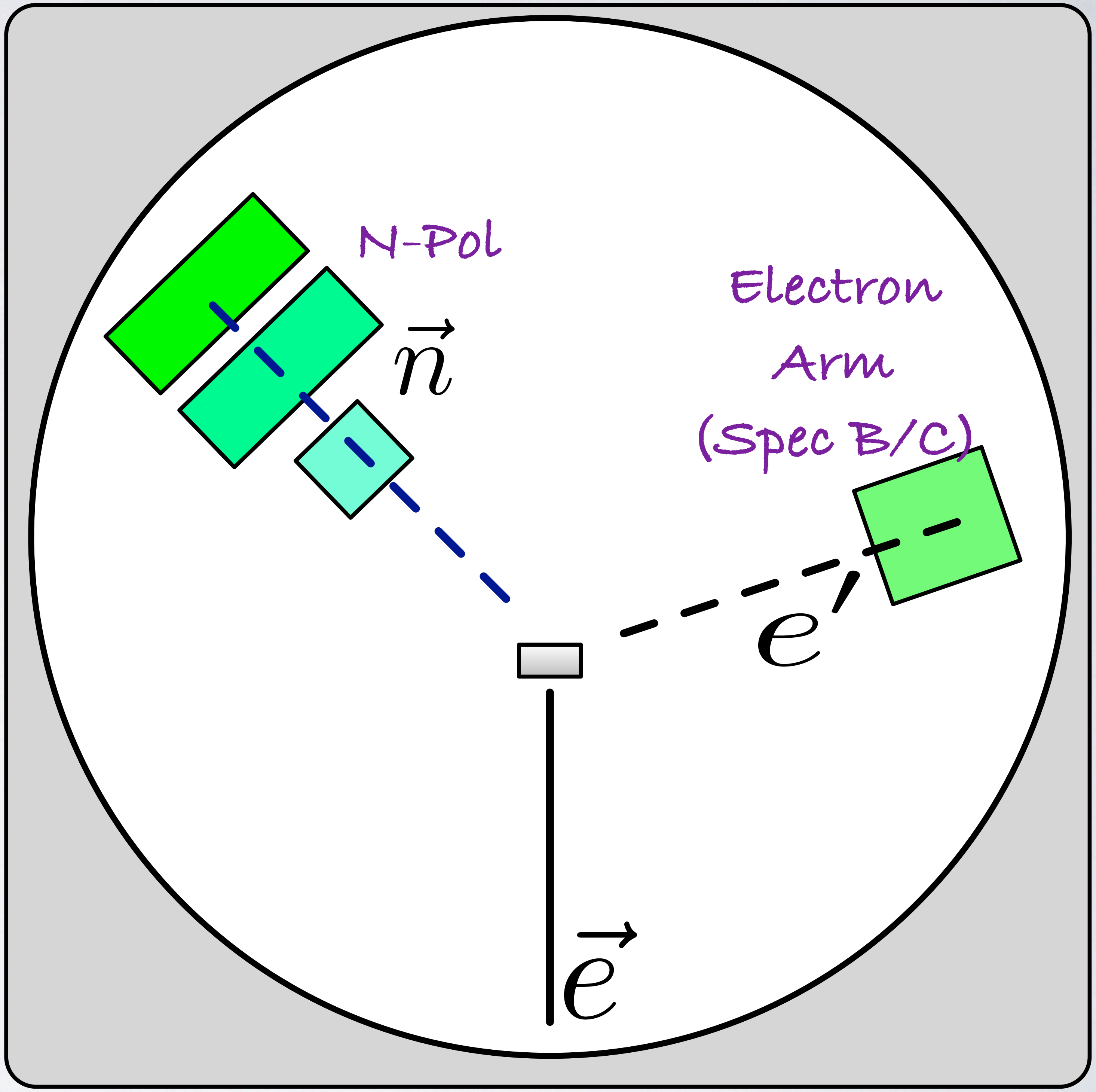
Projected Uncertainties



A New Proposal - Parts 2+3

(not in the original LOI)

- Measure neutron/proton polarizations in deuteron electro-disintegration a a function of virtuality.
- Low Q^2 for better statistics and theory.
- Anti-parallel kinematics for FSI reduction.
- Very simple system.



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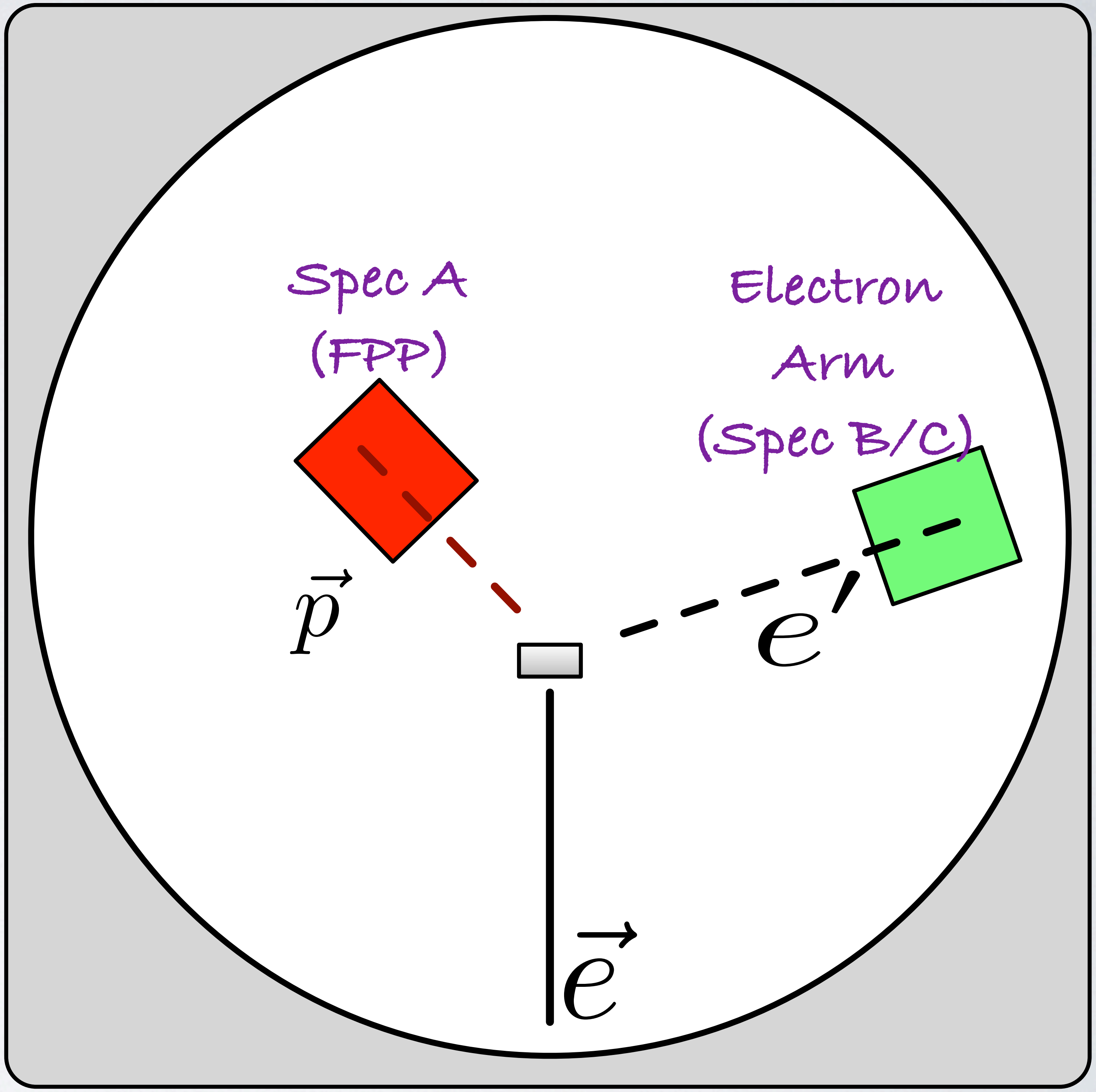

Summary - I

Neutron modifications predicted to be different than proton modifications ➝ strong experimental prediction/handle and a piece of the EMC puzzle.

What if the effect is generated by FSI?

"If one says that the proton experiment sees no medium modification, the neutron experiment becomes more interesting simply because medium modifications must be present somewhere." - Miller

Need a prediction using the Schiavilla model for the neutron.

LOI-10-007 Approved by JLab PAC (But want to run @ MAMI)

Much work still ahead in the coming year (polarimeter design + prototype, in collaboration with A1)

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Neutron modifications predicted to be different than proton modifications ➛ strong experimental prediction/handle and a piece of the EMC puzzle.

What if the

“If one says
modificatio ... eresting
simply beca
somewhere.

The surprise **is not** that the nucleons are modified.
The surprise **is** that they are so little modified.

Need a predi ... tron.

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Much work still ahead in the coming year (polarimeter design + prototype, in collaboration with A1)

An Experimentalist's Take on Things

- The definition of medium effects is irrelevant from an experimental point of view.
- Experiments are just a testing ground for theories.
- But theory should point us towards relevant measurements.

Take-Home Messages

Take-Home Messages

Nucleons are modified in the nuclear medium -
But how?
We don't yet know.

Take-Home Messages

Nucleon... *medium* -

- Is the nuclear medium effect from modification of the wavefunction?
- Or from nuclear effects? FSI?
- Or maybe just a bad question?

Take-Home Messages

Nucleons are modified in the nuclear medium - But how? We don't yet know.

We have the capability to measure at the sub percent level. necessary for the ~10% effects.

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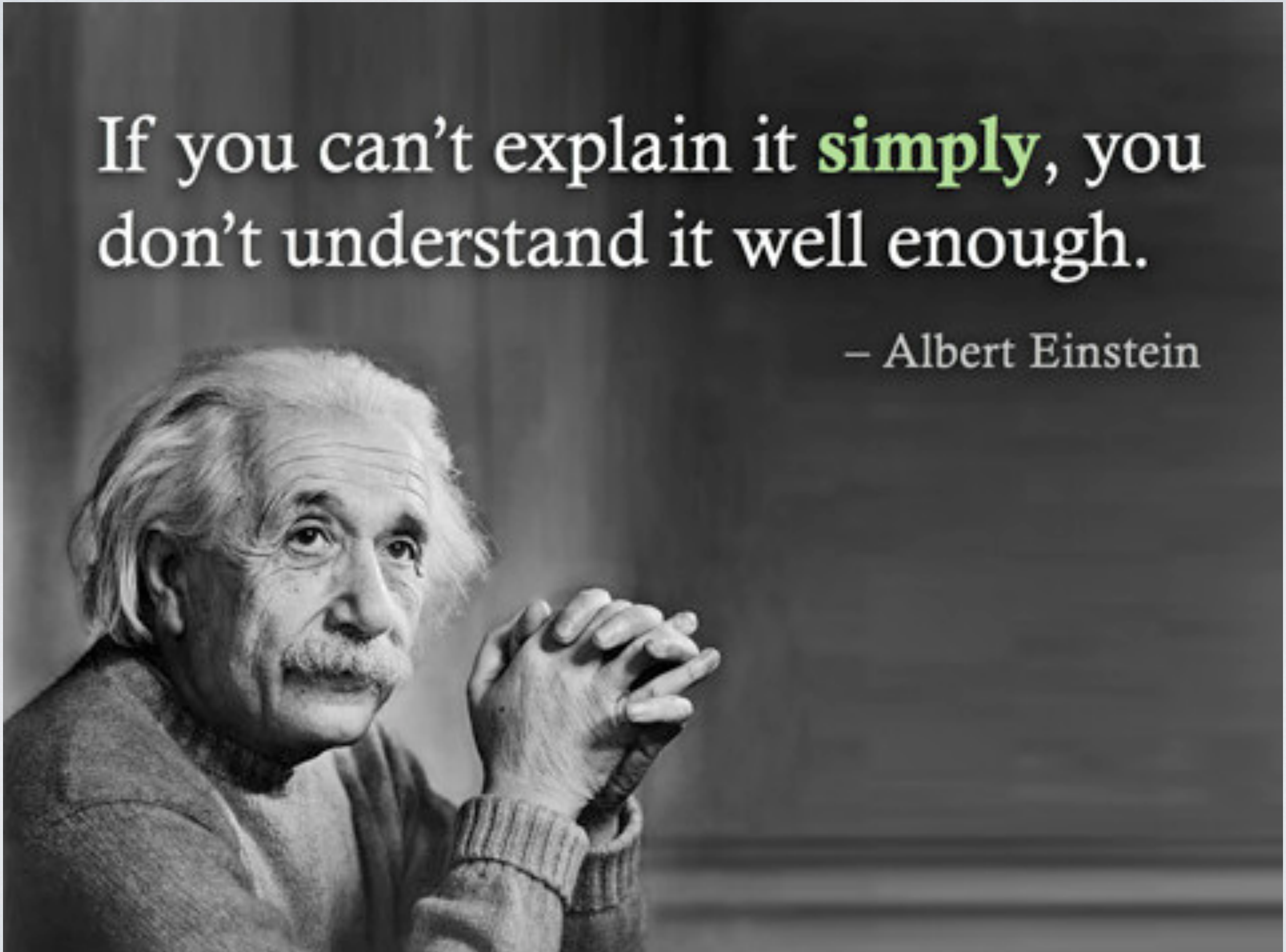
Nucleons are modified in the nuclear medium -
But how?
We don't yet know.

We have the capability to measure at the sub percent level.
necessary for the ~10% effects.

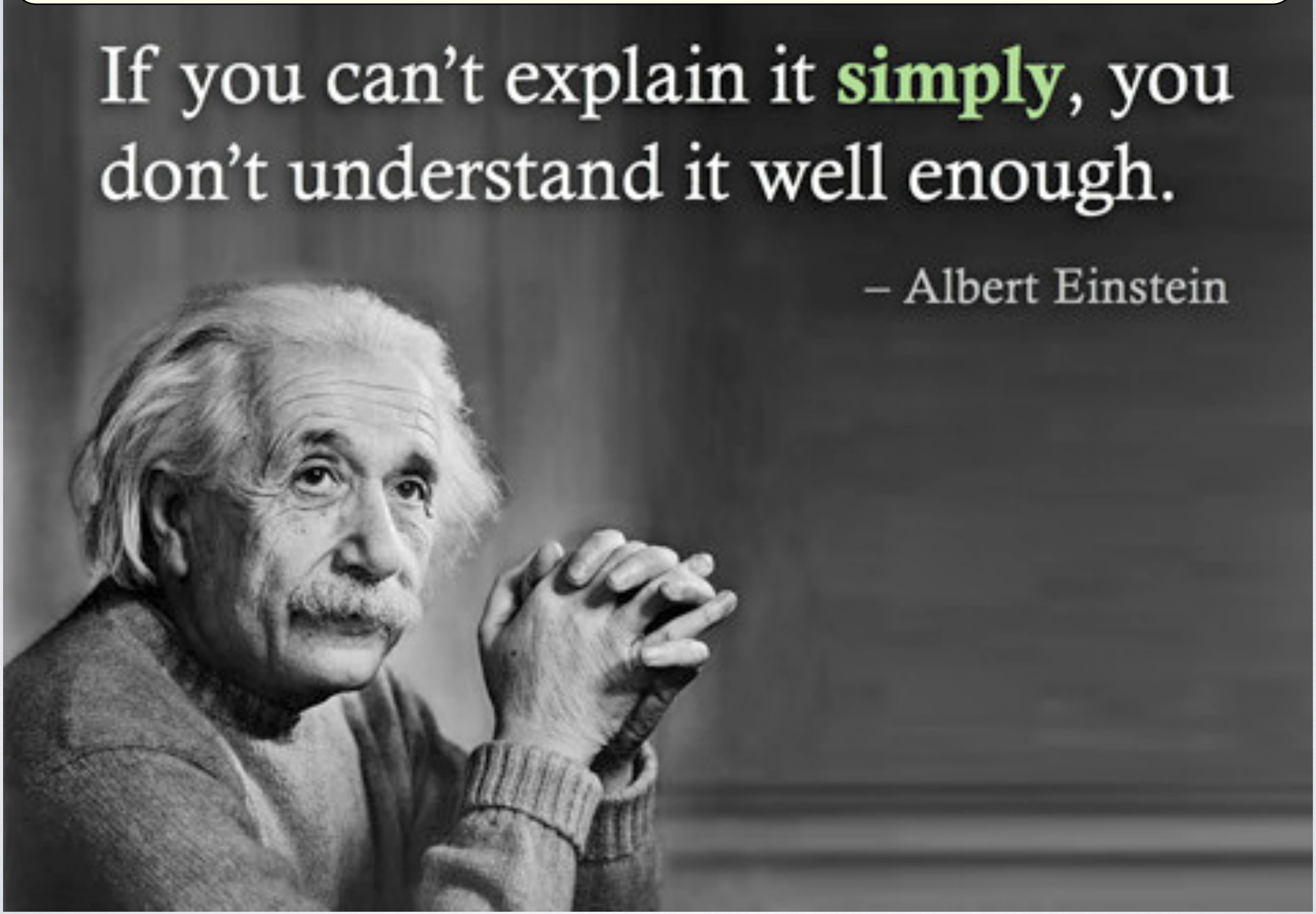
We are in (fairly) good shape experimentally,
theory input always welcome
(especially if we want to get more experiments approved).


If you can't explain it simply, you don't understand it well enough.
– Albert Einstein

WANTED

2011.07.19: nucl-ex Postdoc (Hebrew U.) **[Deadline: Open until filled]**

Nucleon Structure Postoctoral Research Assistant



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