Ernest Orlando Lawrence Berkeley National Laboratory

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Nucleon Form Factors and their *Modification in the Nuclear Medium*

Guy Ron
Lawrence Berkeley National Lab

University of New Hampshire
Apr 9, 2010

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The JLab Program @ Low Q^2

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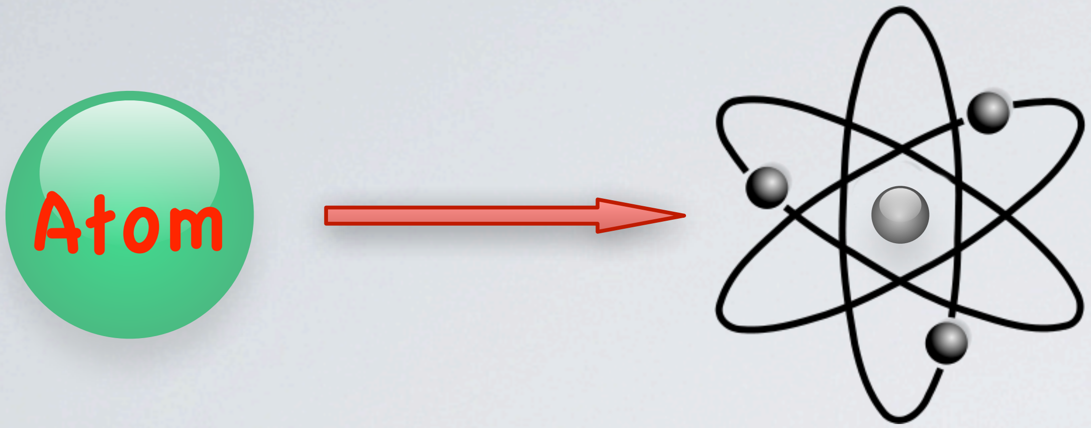
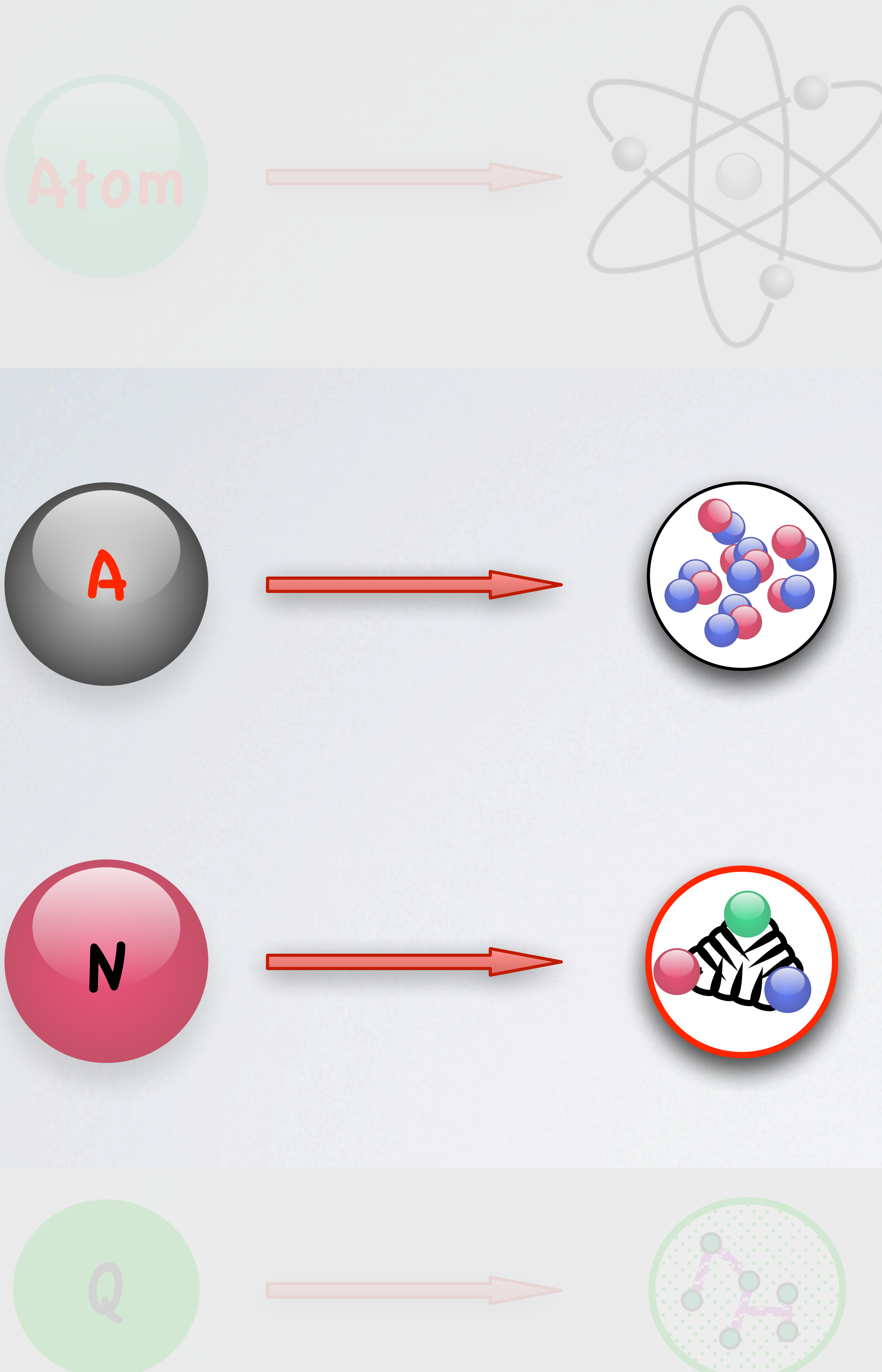


Atoms = Electrons + Nuclei + EM Interactions

Nucleus = Protons + Neutrons + Strong Interaction of Hadrons

Nucleon = Constituent Quarks+Strong Interaction of quarks

Constituent Quarks = Quarks + gluons + Strong Interaction



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Nucleus = Protons +
Neutrons + Strong
Interaction of Hadrons

Nucleon = Constituent
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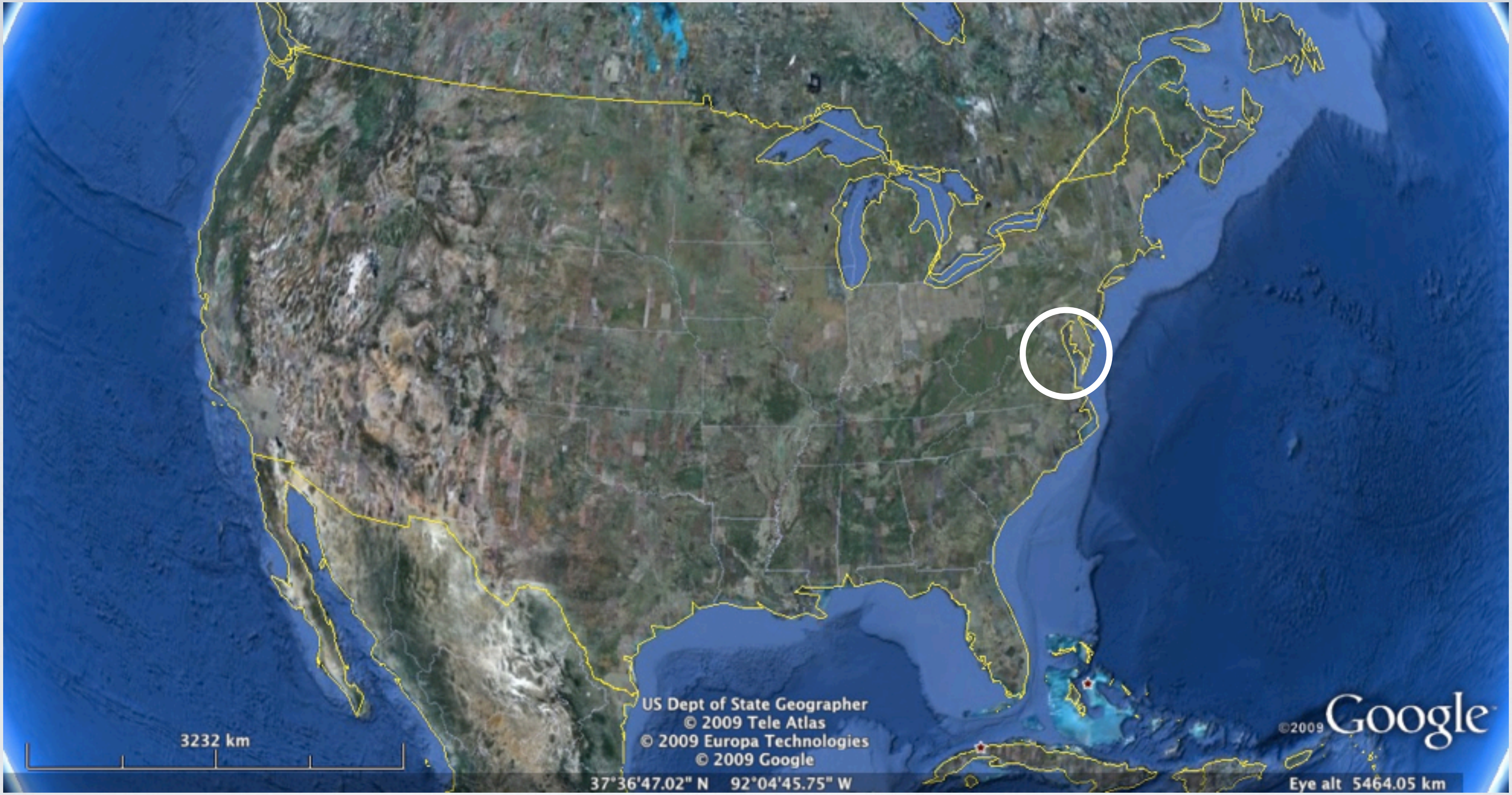
of quarks

Constituent Quarks =
Quarks + gluons + Strong
Interaction

OUTLINE

- Nucleon Structure 101.
- Measuring the nucleon Form Factors.
- Experimental Results.
- Impacts.
- Nucleons in the Medium - Some Examples of Modification.
- Probing Modifications with Polarization Observables.
- A New Prediction.
- Leads to... A New Proposal.

JLab



US Dept of State Geographer
© 2009 Tele Atlas
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3232 km
37°36'47.02" N 92°04'45.75" W
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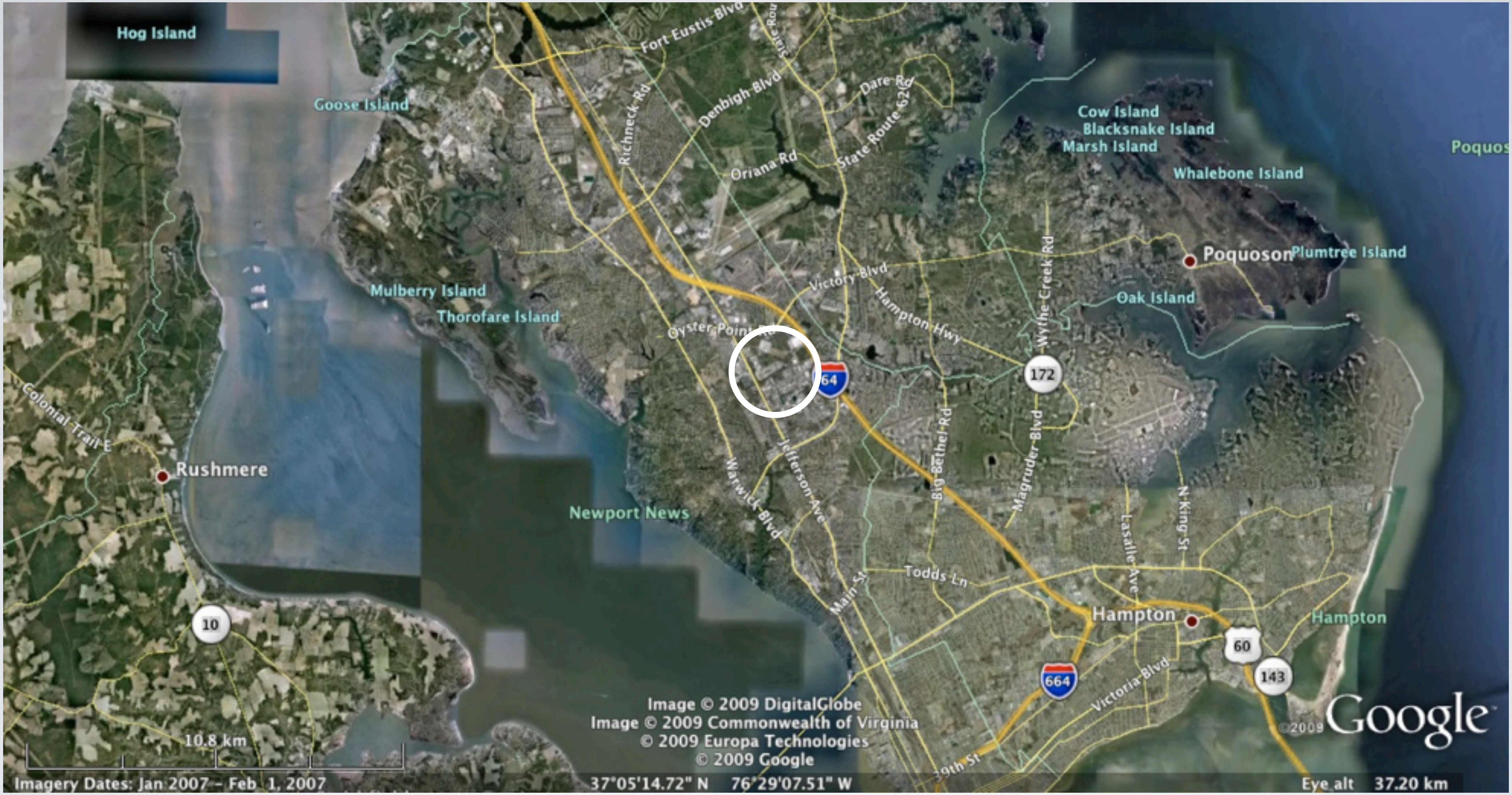
Eye alt 5464.05 km

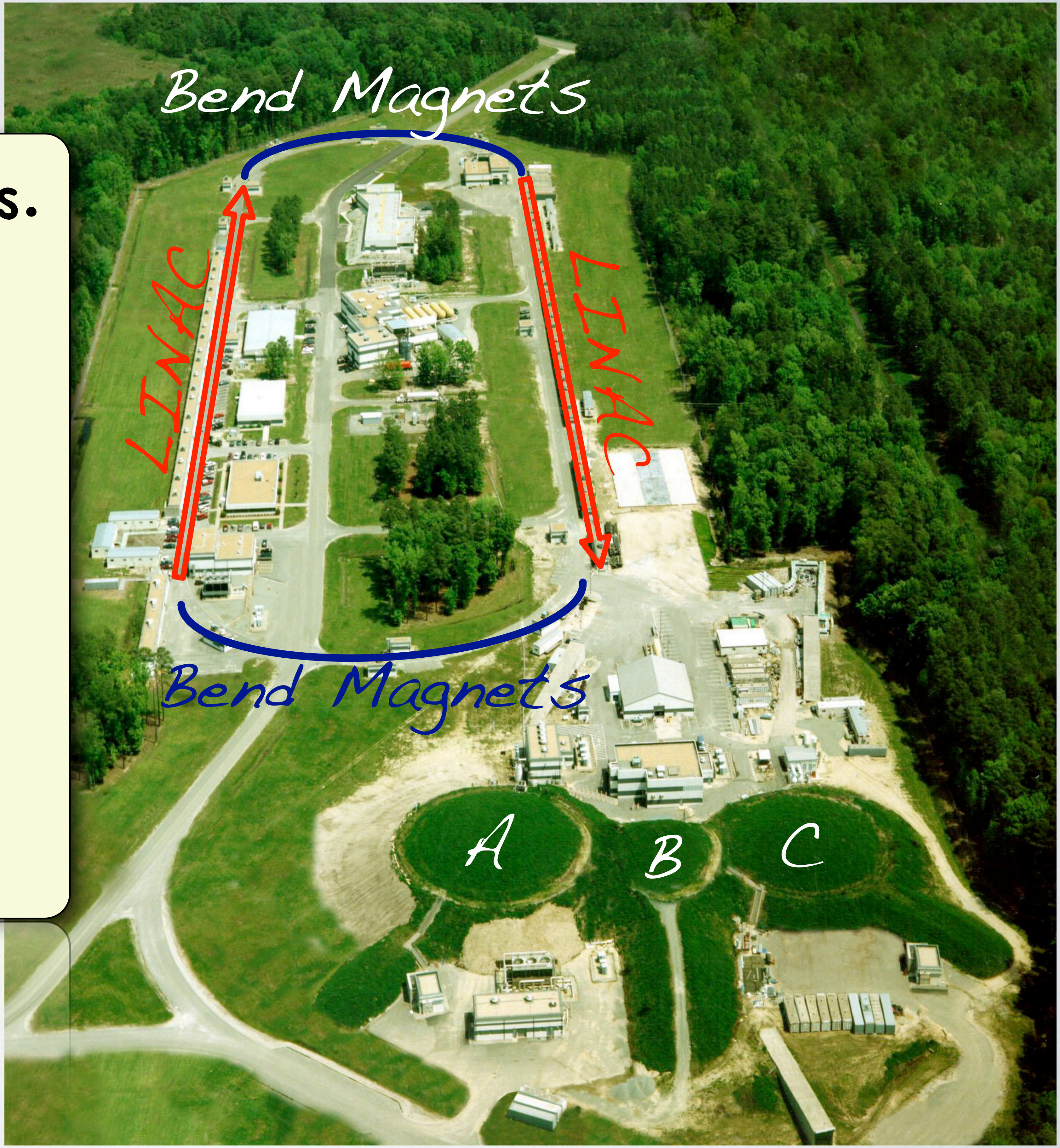
JLab



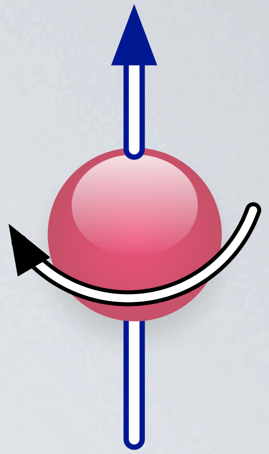
Hog Island
Goose Island
Fort Eustis Blvd
Denbigh Blvd
Richneck Rd
Dare Rd
State Route 621
Oriana Rd
Cow Island
Blacksnake Island
Marsh Island
Whalebone Island
Poquoson
Plumtree Island
Oak Island
Victory Blvd
Hampton Hwy
Wythe Creek Rd
Mulberry Island
Thorofare Island
Oyster Point Rd
64
172
Colonial Trail E
Rushmere
Newport News
Warwick Blvd
Jefferson Ave
Big Bethel Rd
Magruder Blvd
Lasalle Ave
N King St
Todds Ln
Main St
Hampton
10
60
143
664
Victoria Blvd
10.8 km
Image © 2009 DigitalGlobe
Image © 2009 Commonwealth of Virginia
© 2009 Europa Technologies
© 2009 Google
©2009 Google
Imagery Dates: Jan 2007 – Feb 1, 2007
37°05'14.72" N 76°29'07.51" W
Eye alt 37.20 km

JLab

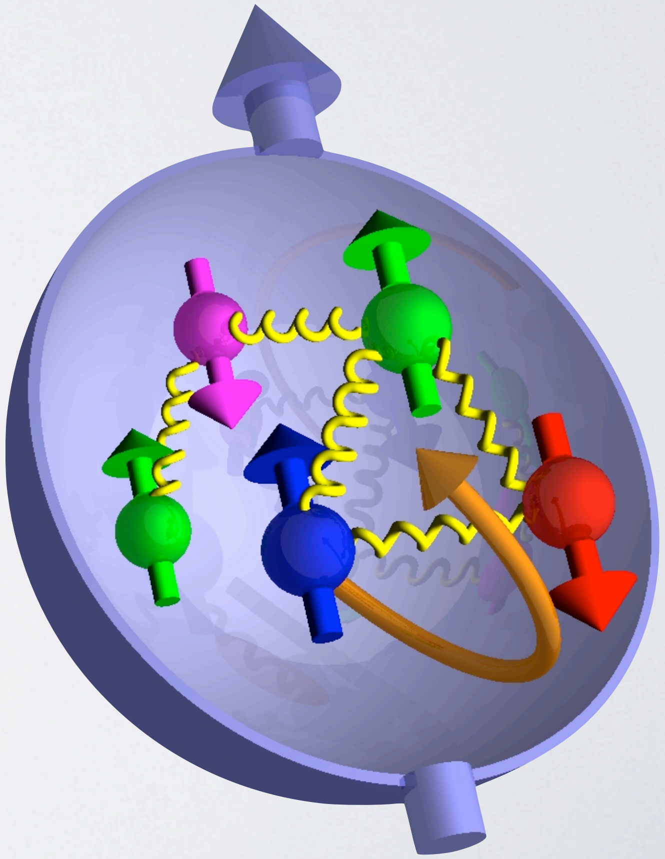
- 3 Experimental Halls.
- Up to 6GeV Beam Energy (upgrade to 12GeV by 2014).
- ~85% beam polarization.
- Up to 200μA beam (usually limited by target).
- 100% Duty factor.



Nucleon Structure



- Nucleons are spin-1/2 particles.
- But measured magnetic moment is $\mu_p \sim 2.793\mu_N$
  (should be 1 for proton and 0 for neutron) $\mu_n \sim -1.91\mu_N$
- Nucleons are not pointlike (also known from Deep Inelastic Scattering).
- Complex internal structure generated by interactions between pointlike (dressed?) constituents (quarks/partons).



- Even more complex behavior comes from virtual constituents ("sea" quarks, gluons).

The Differential Cross Section

The probability to scatter a particle in a given state per solid angle.

$$\frac{d\sigma}{d\Omega} = \frac{N_s}{N_b \cdot \rho_t \cdot l_t \cdot \Delta\Omega \cdot \varepsilon_d} [L^2]$$

Removes all the trivial variables - only depends on the physics.

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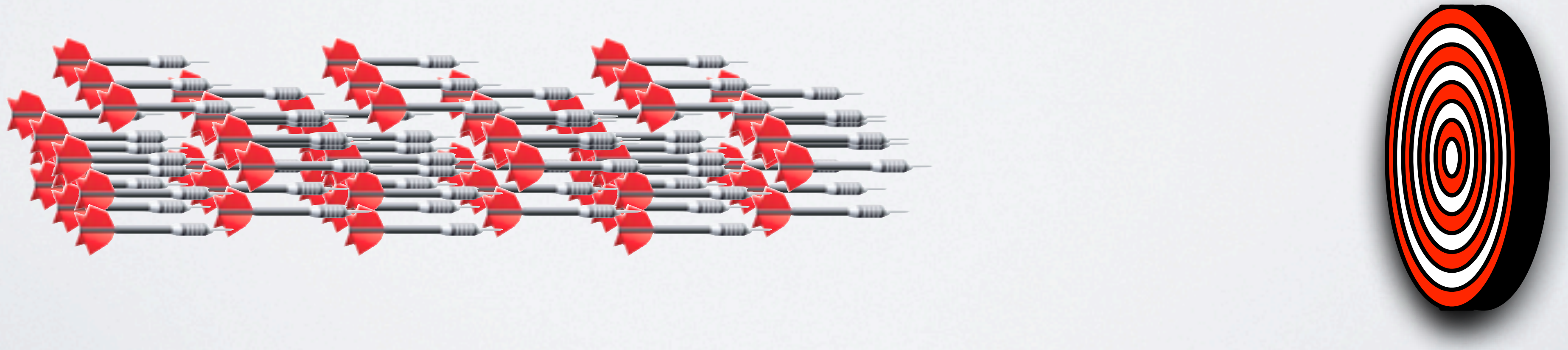

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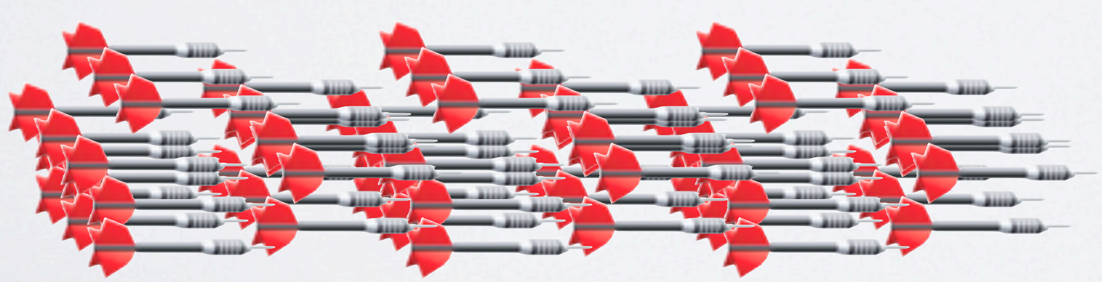

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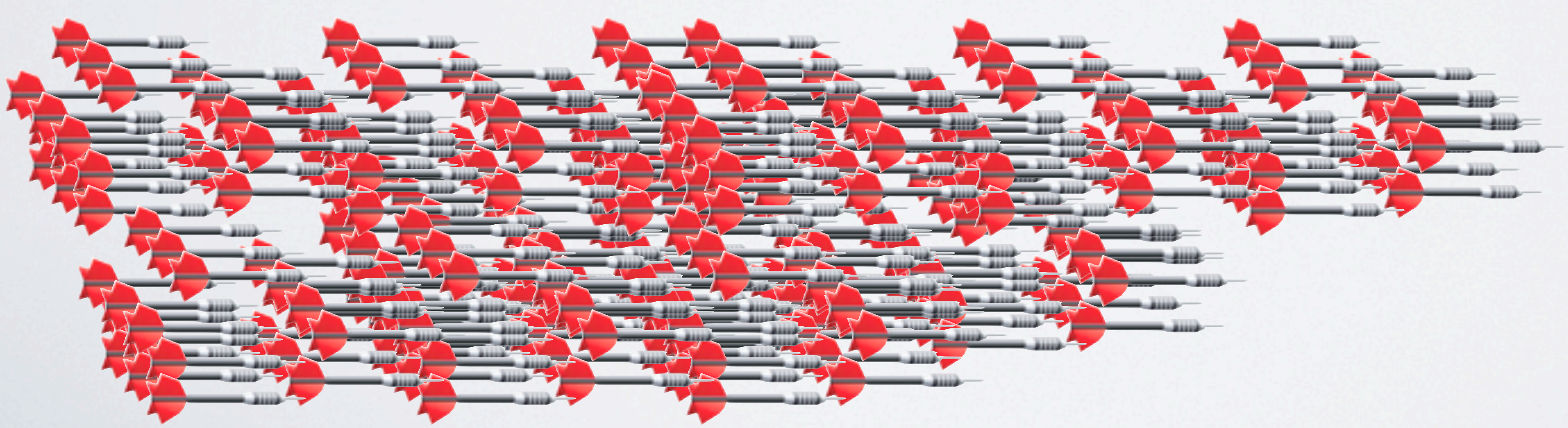

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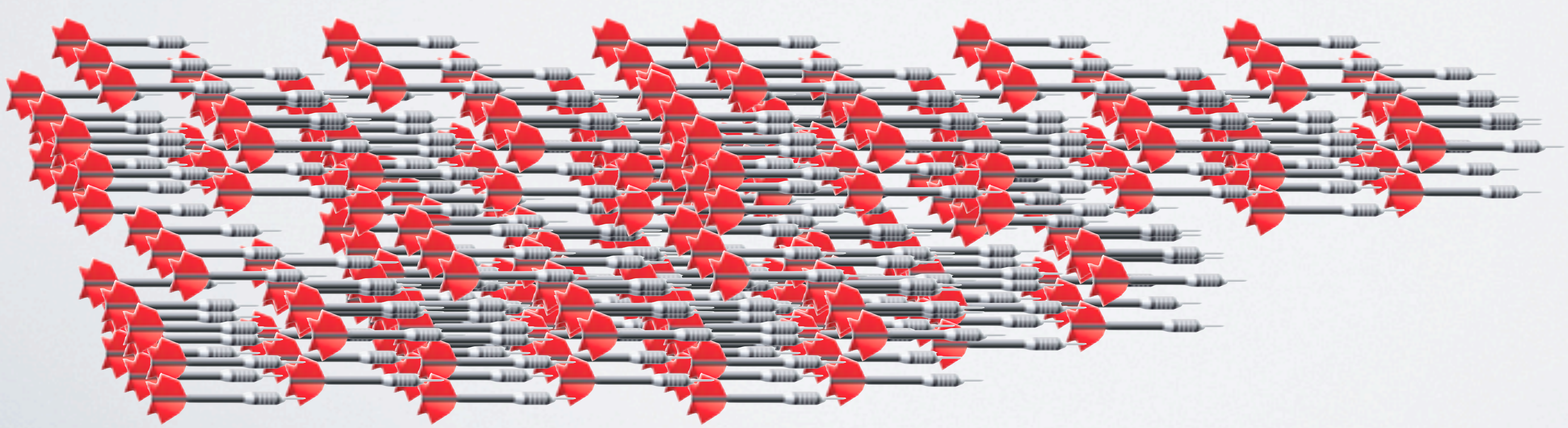

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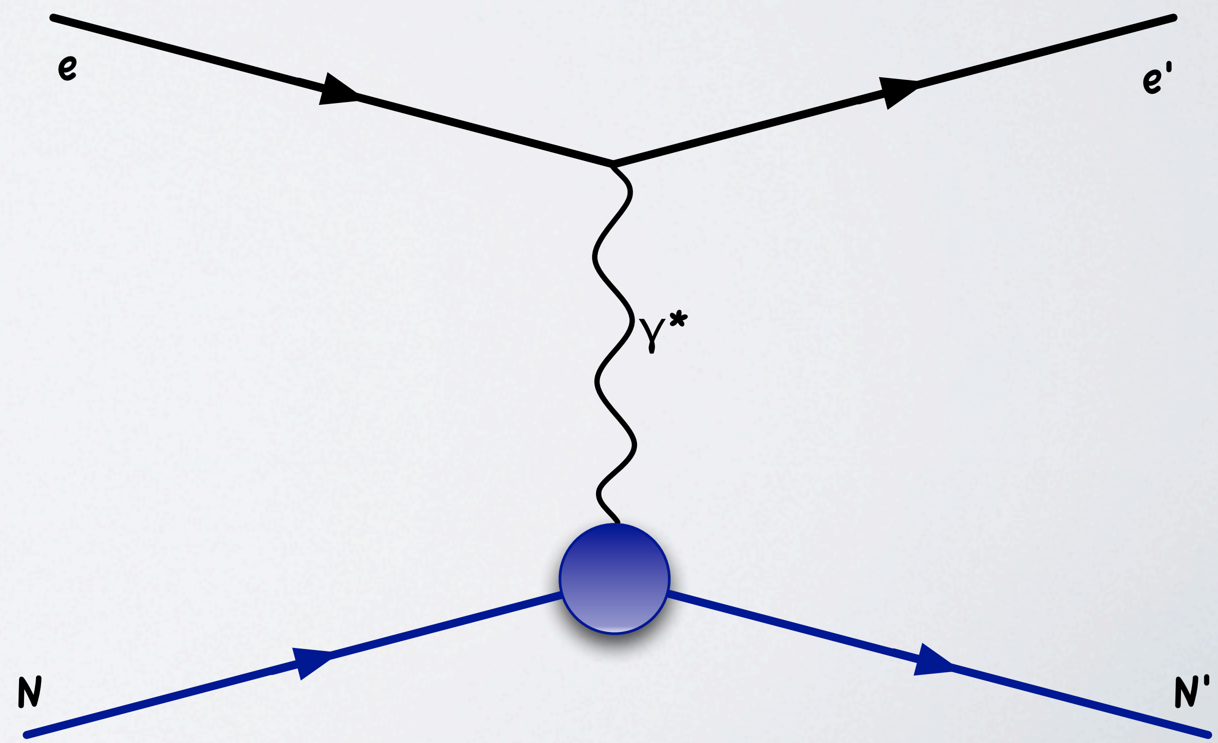
Removes all the trivial variables - only depends on the physics.

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)

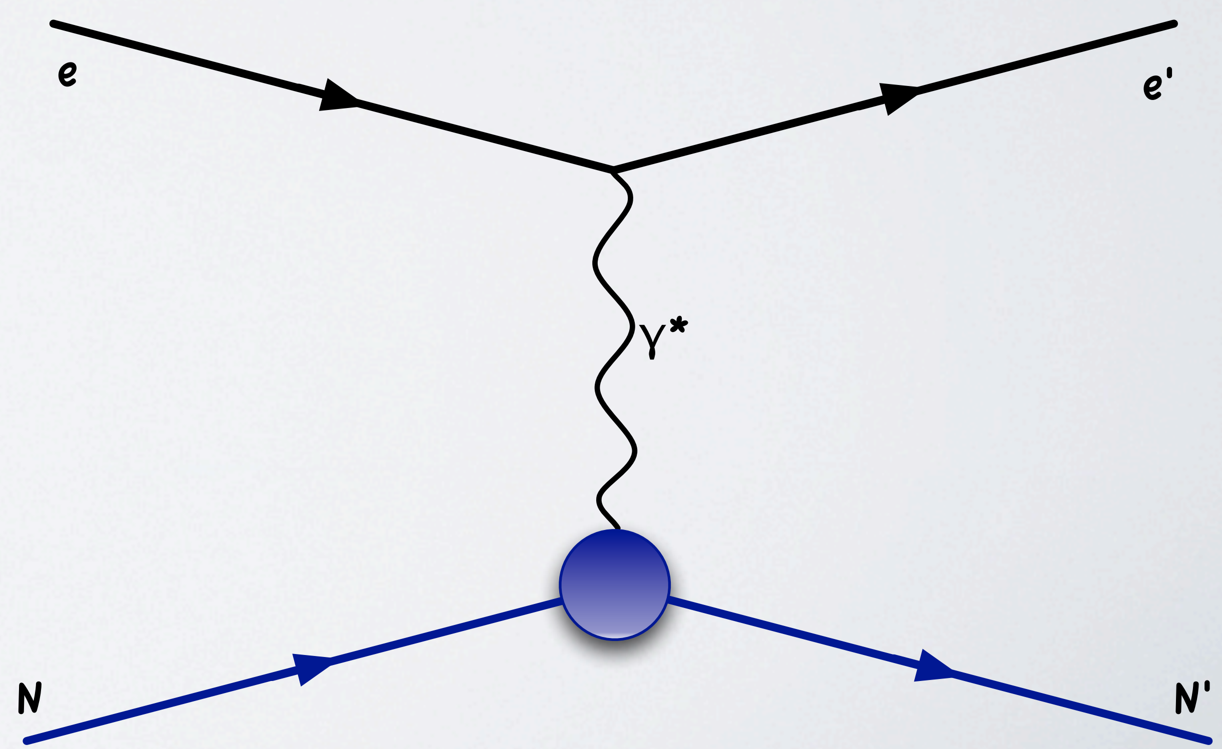
$$\frac{d\sigma_R}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 \frac{\cot^2\frac{\theta_e}{2}}{1+\tau}$$

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

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

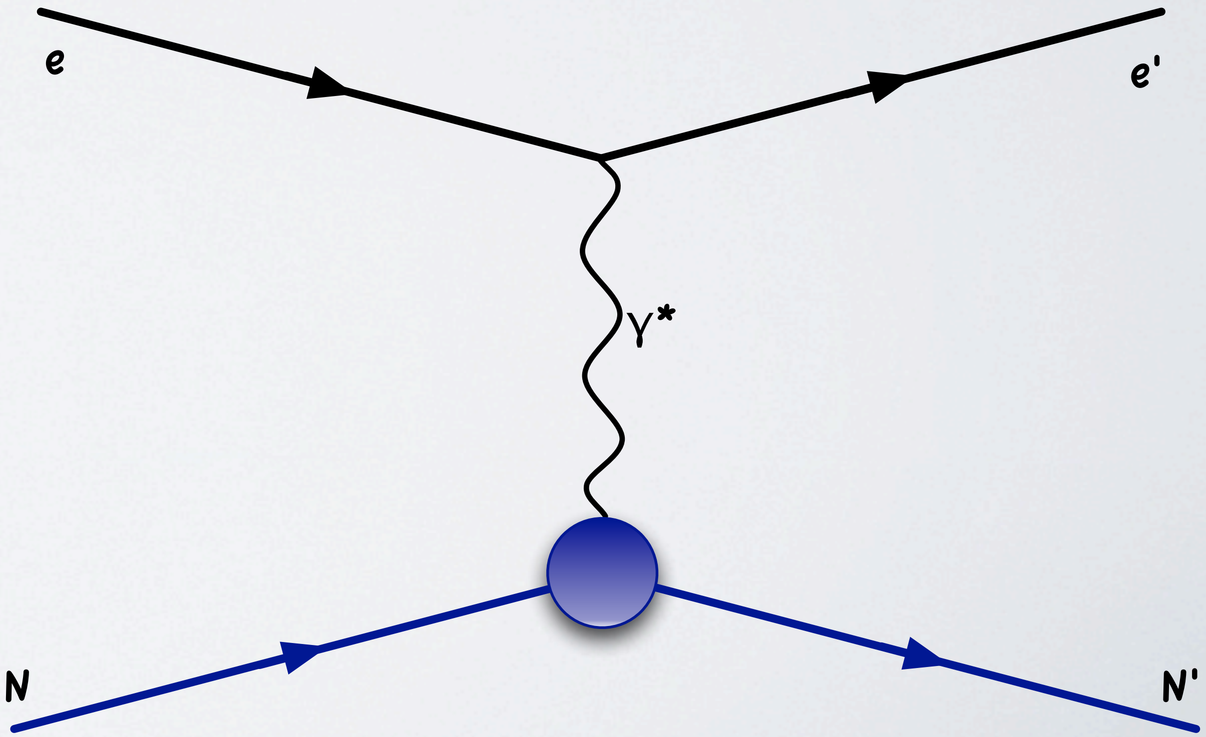
$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

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

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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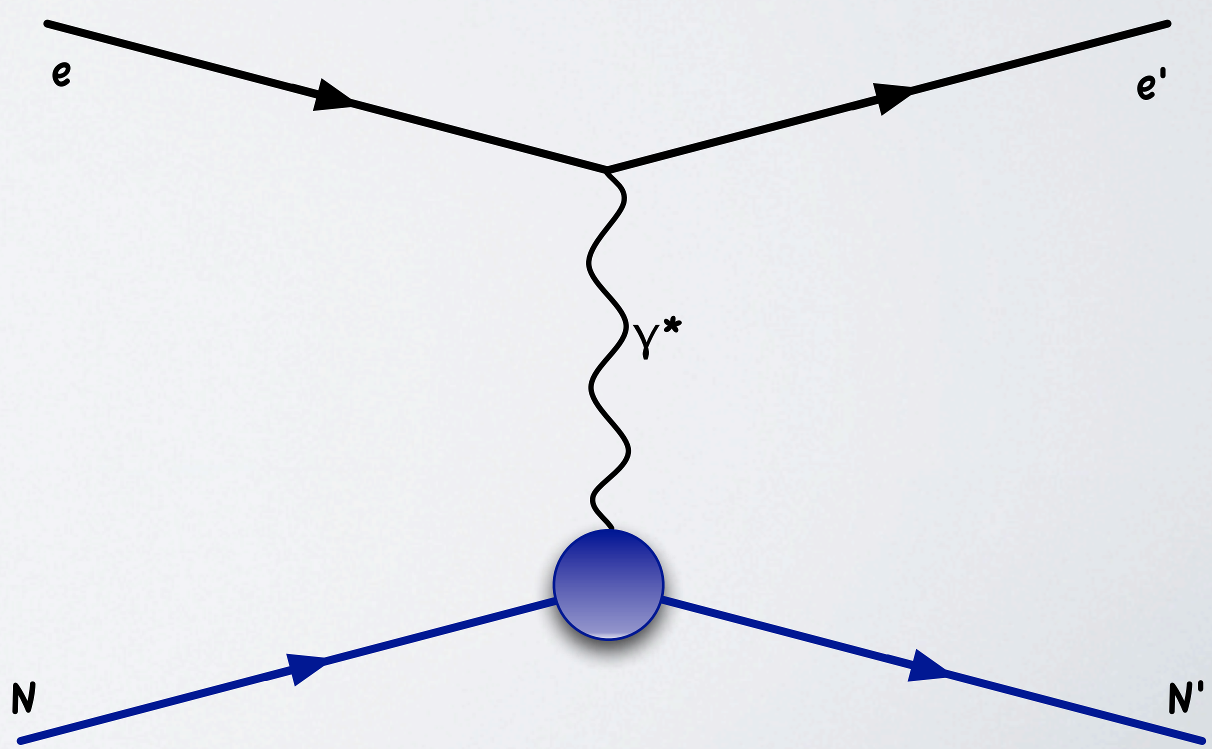


Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$

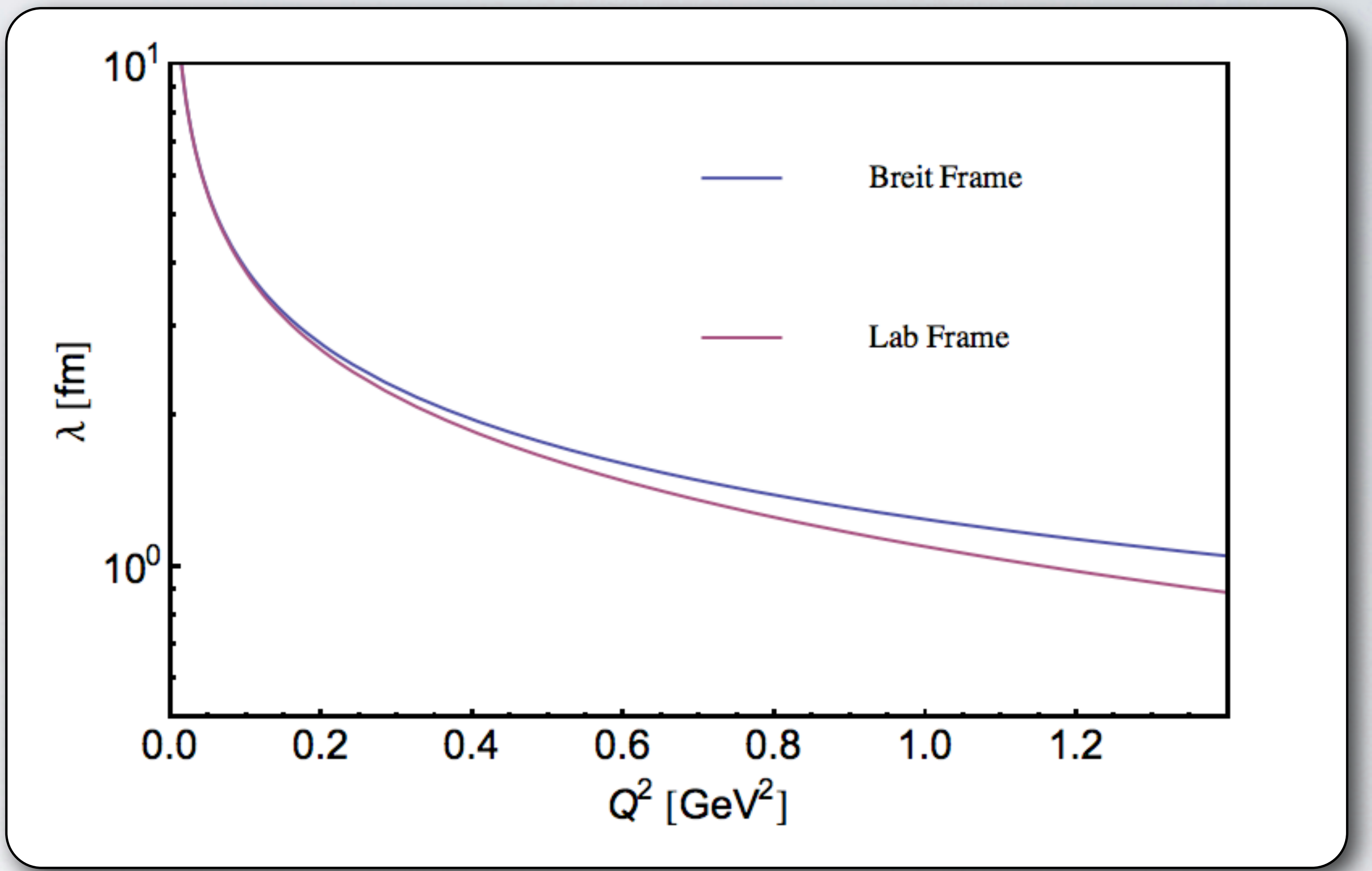
THE NAIVE INTERPRETATION

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

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

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.



What we know

- Experimentally found to approximately follow (to about 10%) the dipole form:

$$\mathbf{F_D(Q^2) = \left(1 + Q^2/0.71\right)^{-2}}$$

- Dipole form in Q space → exponential in r space.
- We know the limiting values at Q^2=0.
- But... We know that there are deviations from dipole (very pronounced at high Q^2).

Why We Care

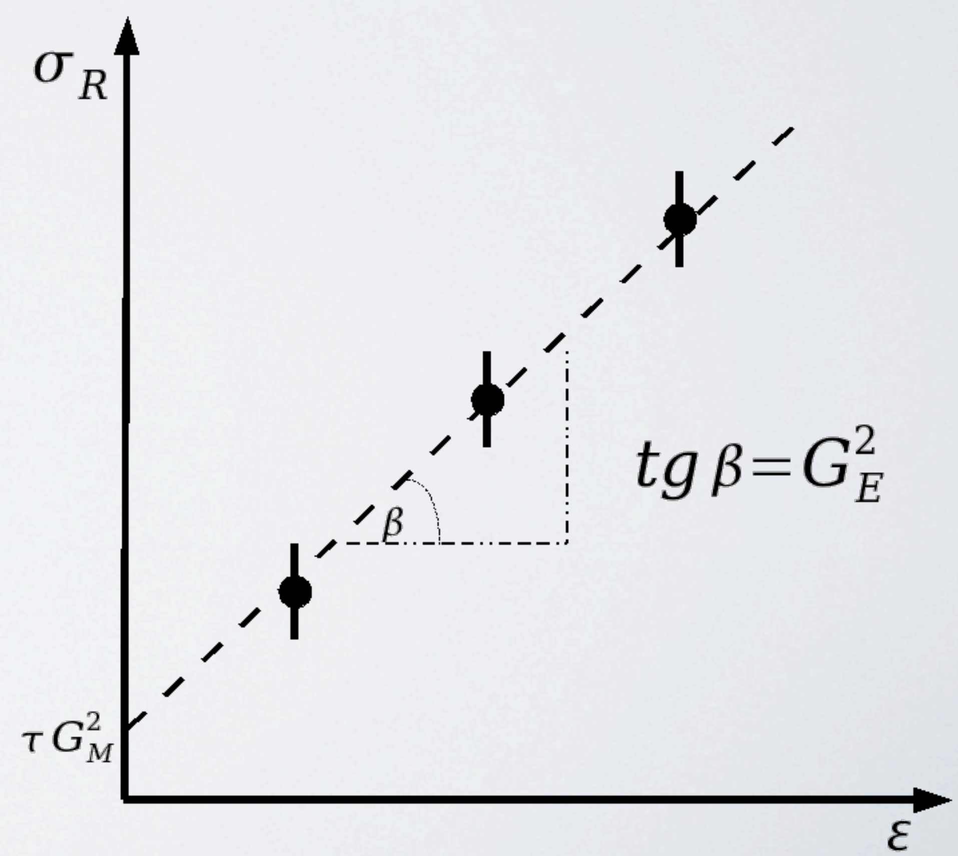
- FF are a basic property of the nucleon, related to the complex internal structure.
- Completely describe the EM structure of the nucleon ground state.
- Comparing G_E and G_M → difference between spatial distributions of charge and magnetization.
- Input to other calculations (more later).
- Different theories constrained by different Q^2 regions.
- An important place to look for quark/gluon → hadron/meson p picture transition.
- EM structure expected to change in the nuclear medium.

Measurement Techniques

Rosenbluth Separation

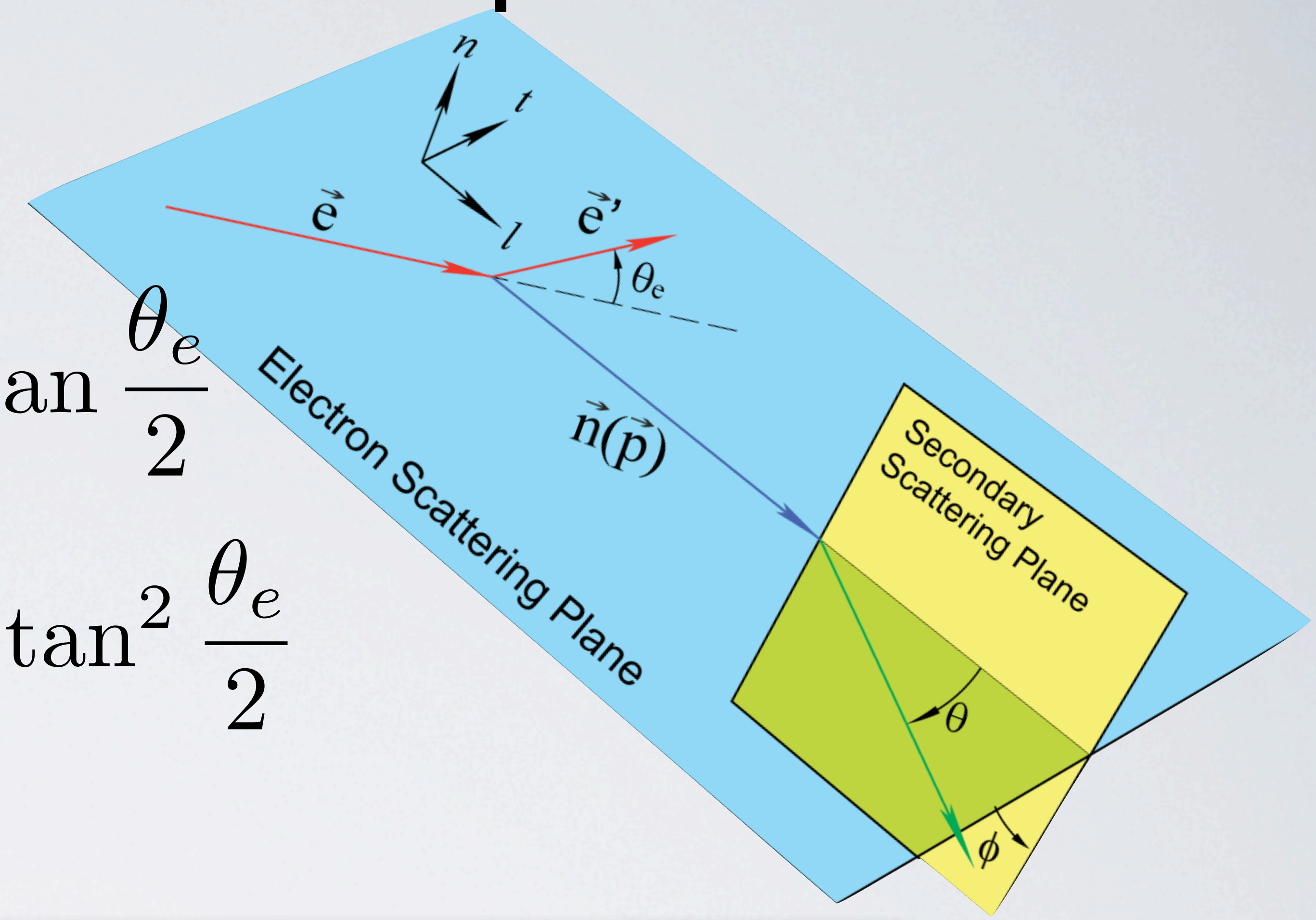
$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\text{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

- Measure the reduced cross section at several values of ε (angle/beam energy combination) while keeping Q^2 fixed.
- Linear fit to get intercept and slope.
- But... G_M suppressed for low Q^2 (and G_E for high) - $\tau = Q^2/4M^2$.
- Also normalization issues/acceptance issues/etc. make it hard to get high precision.



Measurement Techniques

Recoil Polarization



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

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

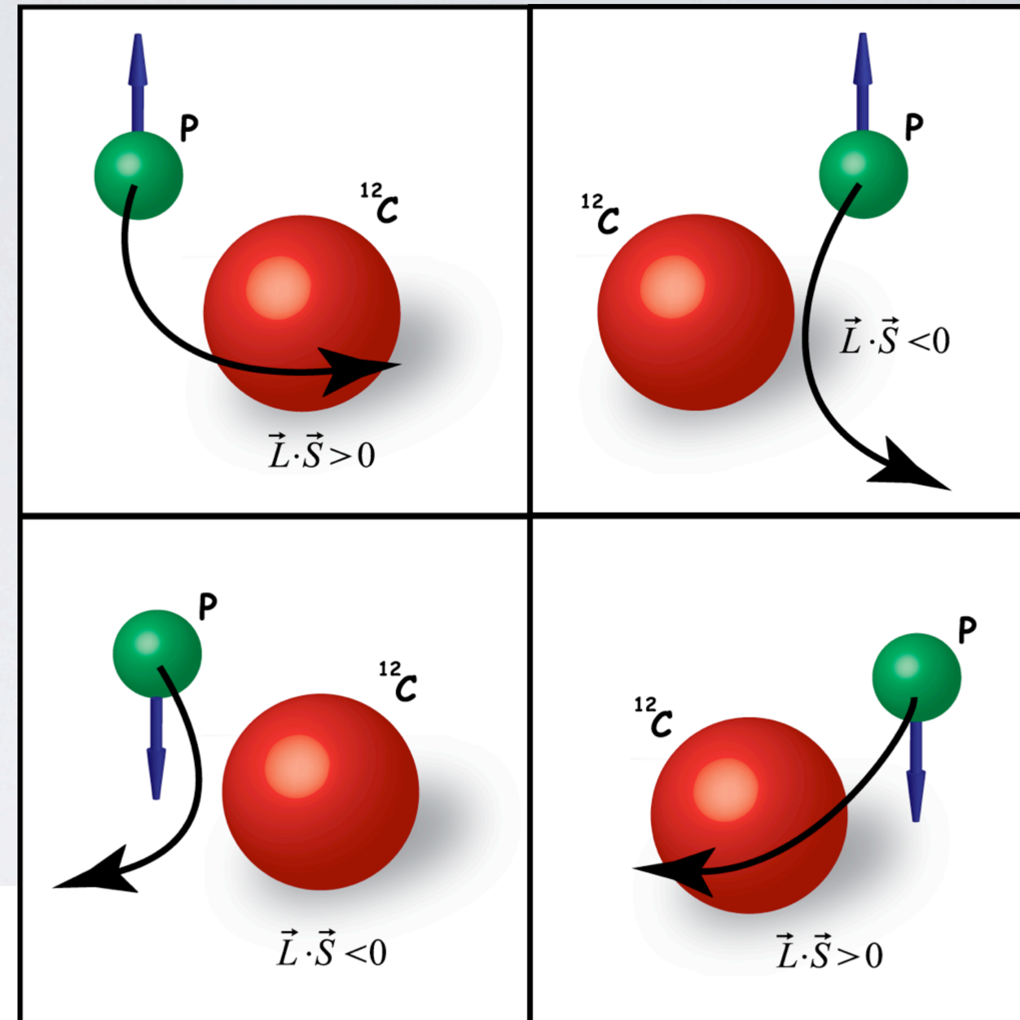
$$P_n = 0 \ (1\gamma)$$

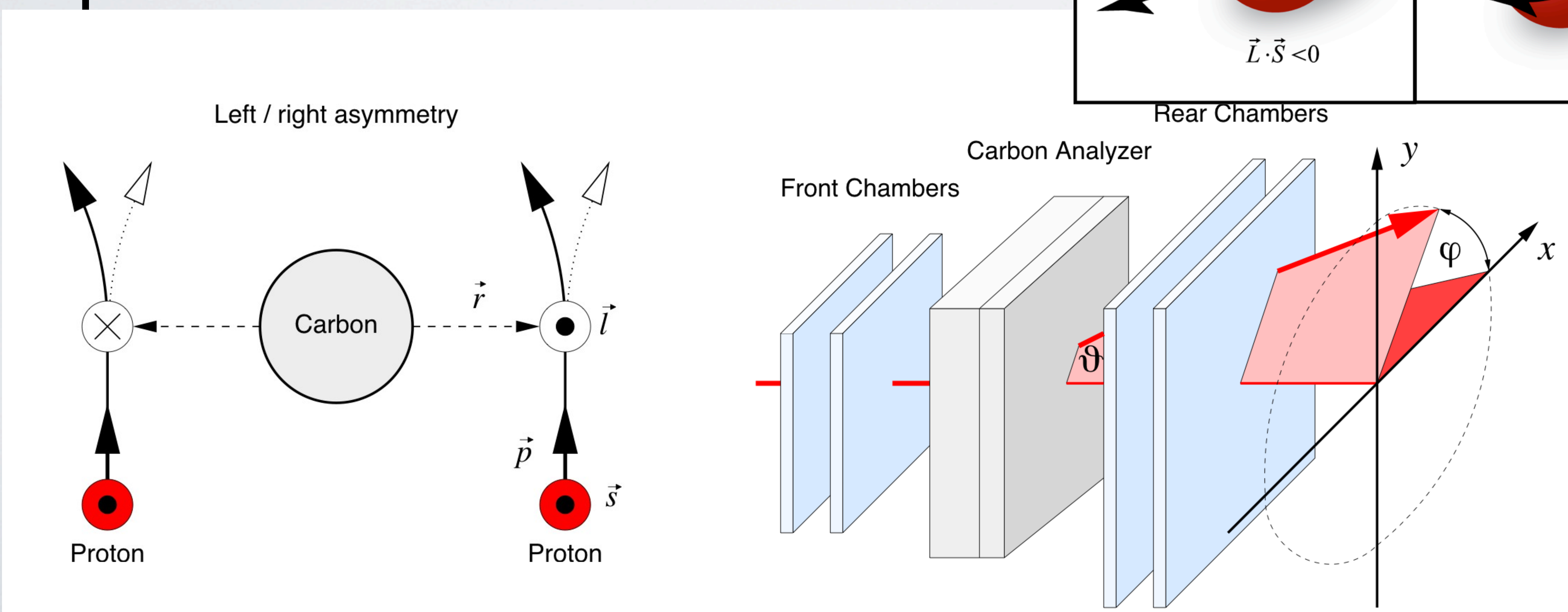
$$\mathcal{R} \equiv \mu_p \frac{G_E}{G_M} = -\mu_p \frac{P_t}{P_l} \frac{E_e + E_{e'}}{2M} \tan\frac{\theta_e}{2}$$

- A single measurement gives ratio of form factors.
- Interference of "small" and "large" terms allow measurement at practically all values of Q^2.

How to measure the polarization

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



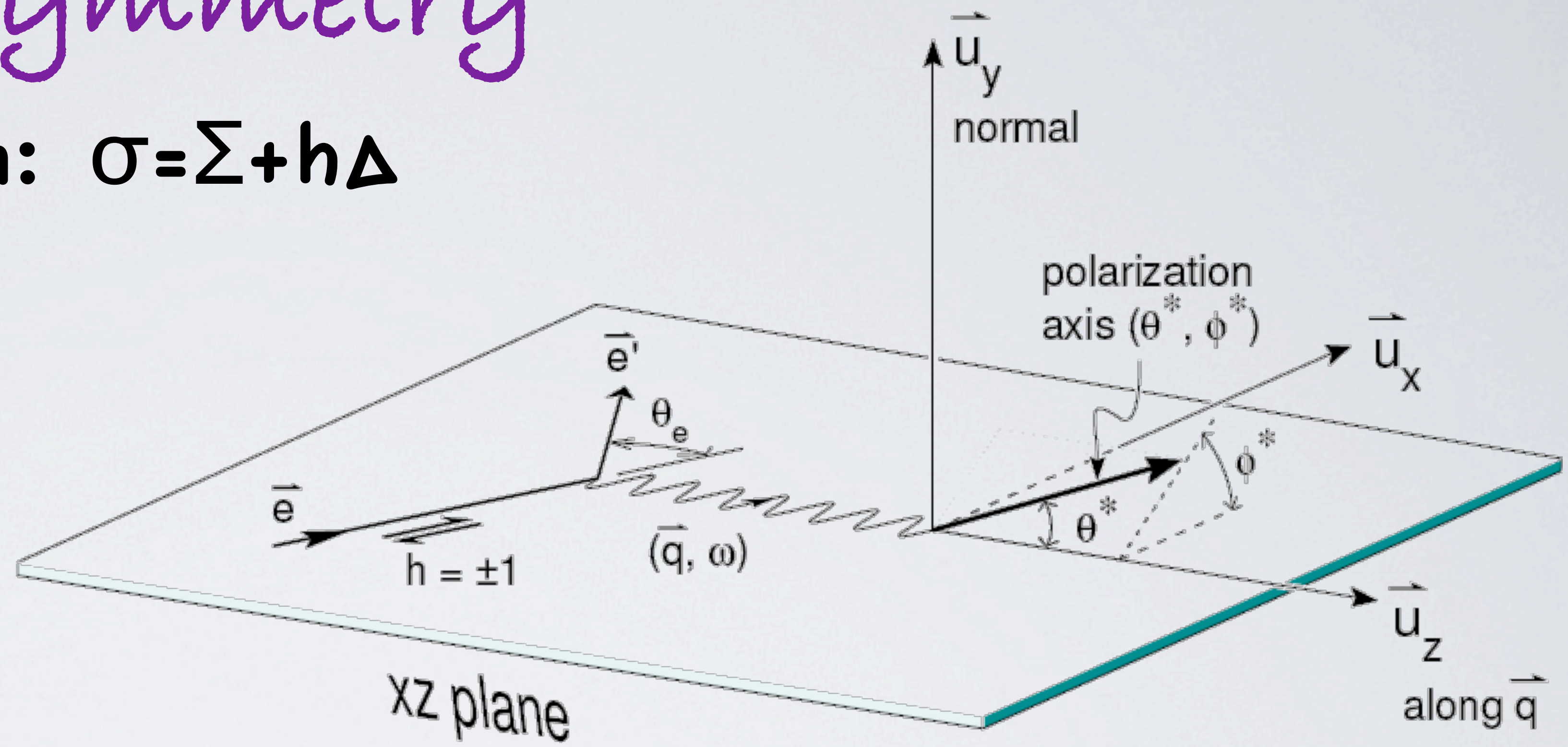


Measurement Techniques

Beam-Target Asymmetry

Polarized Cross Section: σ=Σ+hΔ

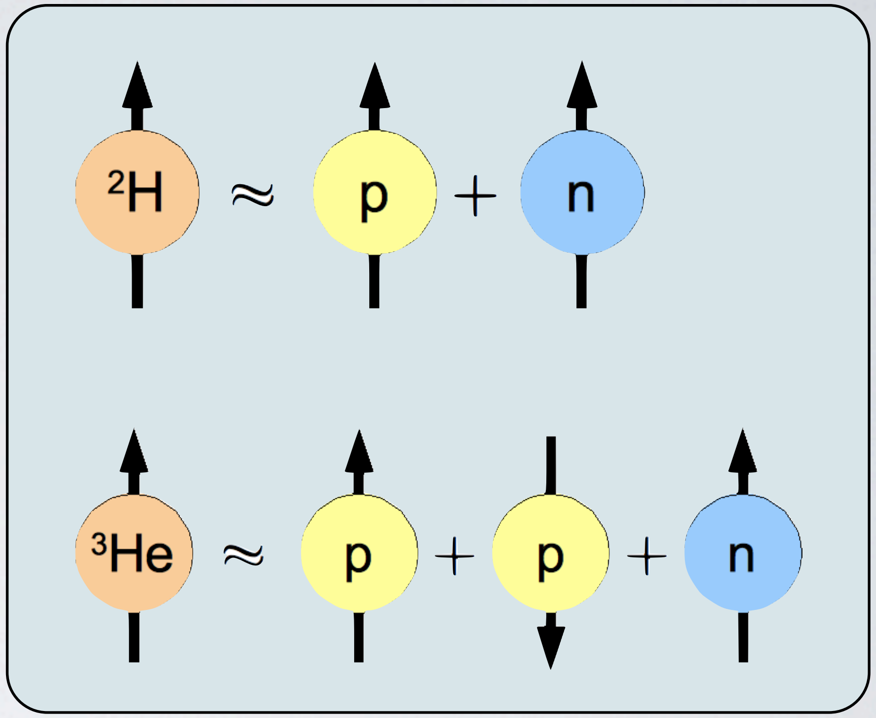
$$\mathcal{A} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$



$$\mathcal{A} = f P_b P_t \frac{\overbrace{a\,cos\theta^* G_M^2}^{A_T} + \overbrace{b\,sin\theta^*\,cos\phi^* G_E G_M}^{A_{LT}}}{c G_M^2 + d G_E^2}$$

Measure asymmetry at two different target settings, say θ*=0, 90.
Ratio of asymmetries gives ratio of form factors.
Functionally identical to recoil polarimetry measurements.

The curious case of the neutron



- No free neutron targets.
- Must use light nuclei to measure neutron form factors.
- Ratio method (JLab Hall B):

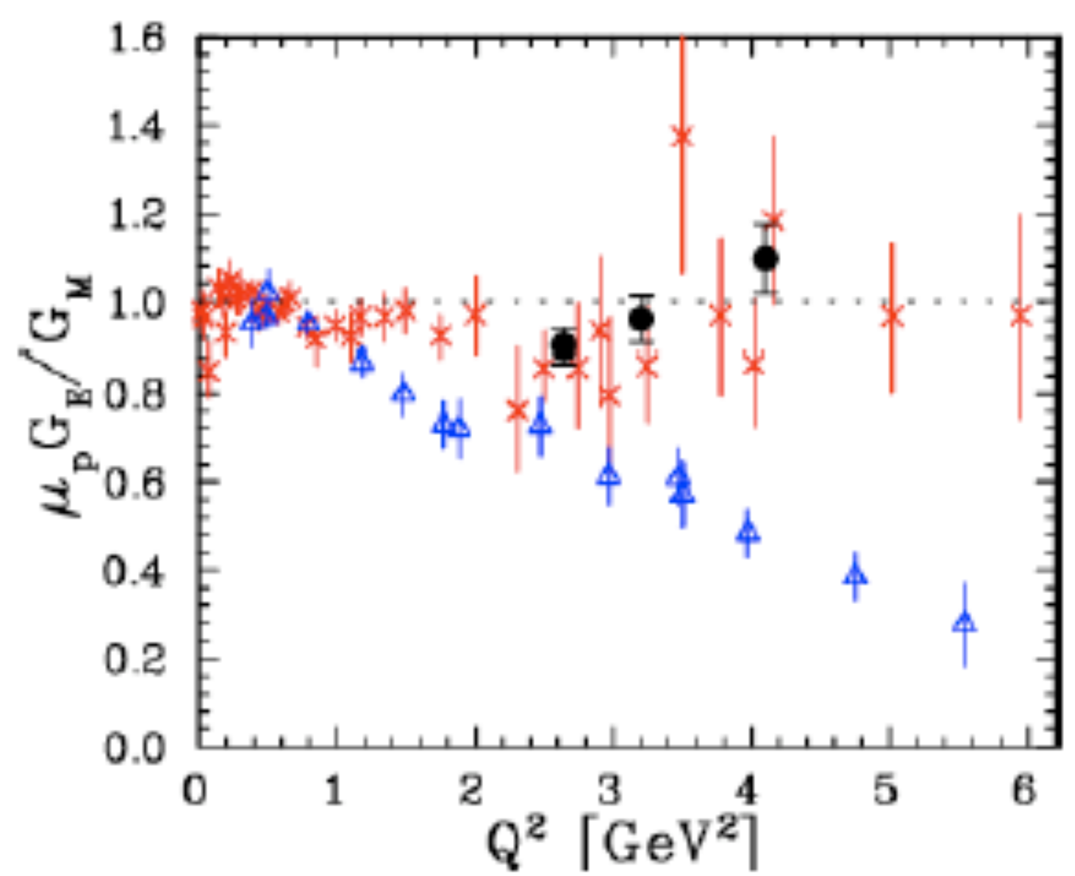
$$R \equiv \frac{d\sigma}{d\Omega}\left[{}^2H(e,e'n)_{QE}\right] / \frac{d\sigma}{d\Omega}\left[{}^2H(e,e'p)_{QE}\right]$$

$$R = a\left(E, Q^2, \theta_{pq}^{max}, W_{max}^2\right) \frac{\sigma_{\text{Mott}}\left(\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau} + 2\tau\tan^2\frac{\theta_e}{2}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}\left[{}^1H(e,e')p\right]}$$

- Polarization:
  - Recoil polarization from ^{2}H (Bates, Mainz, JLab Hall C).
  - Beam target asymmetry on polarized ND_3 (NIKHEF, JLab Hall C).
  - Beam target asymmetry on polarized ^{3}He (Bates, NIKHEF, Mainz, JLab Hall A).

The high Q^2 discrepancy

- At high Q^2 Rosenbluth and polarization measurements for the proton are in violent disagreement.



I. Qattan *et al.*, Phys. Rev. Lett. **94**, 142301 (2005).

- Almost certainly explained by multi-γ effects.
- *But what about low Q^2?*

Why Low Q^2?

- Deviations from dipole form evident.
- Probe static properties ($Q^2 \rightarrow 0$) and peripheral structure.
- Small Q^2 does not allow for pQCD, many competing EFTs.
- Hitting the π mass region.
- Potentially impacts many high precision measurements (nucleon GPDs, parity violation, Zemach radius,...).

Some Models

VMD

$$F(Q^2) = \Sigma \frac{C_{\gamma V_i}}{Q^2 + M_{V_i}^2} F_{V_i N}(Q^2)$$

Breaks down at high Q^2

Lattice QCD *(not really a model....)*

RCQM

Point Form

Light Front

di-Quark

CBM/LFCBM

pQCD

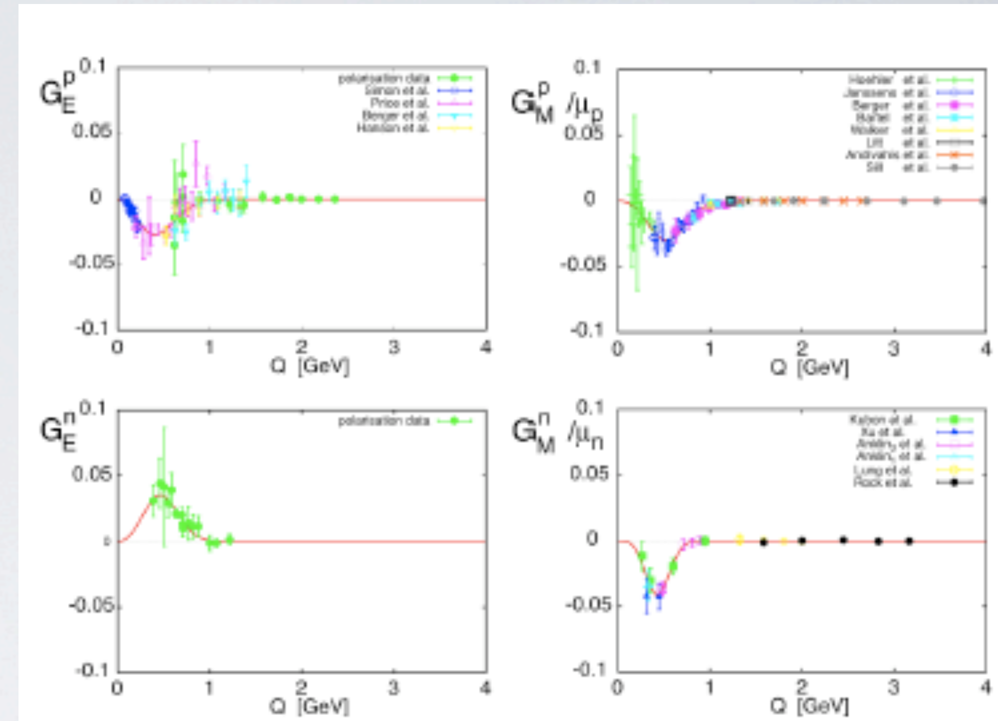
Helicity Conservation

Counting rules $\frac{Q^2 F_2}{F_1} \rightarrow \text{Constant}$

Low Q^2 Notable Results

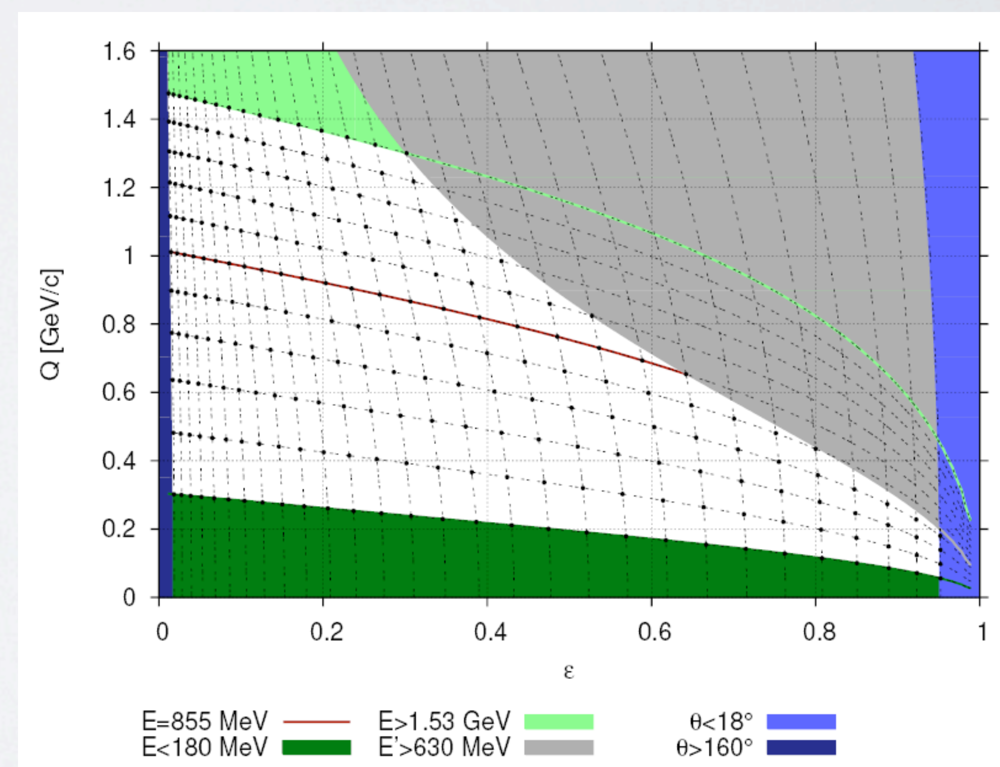
Friedrich & Walcher analysis

Eur. Phys. J. A17, 607 (2003)



- Bump/dip (+2 dipoles) structure in all 4 form factors.
- Possibly interpreted as effects of a virtual meson cloud.

Mainz A1 FF Experiment



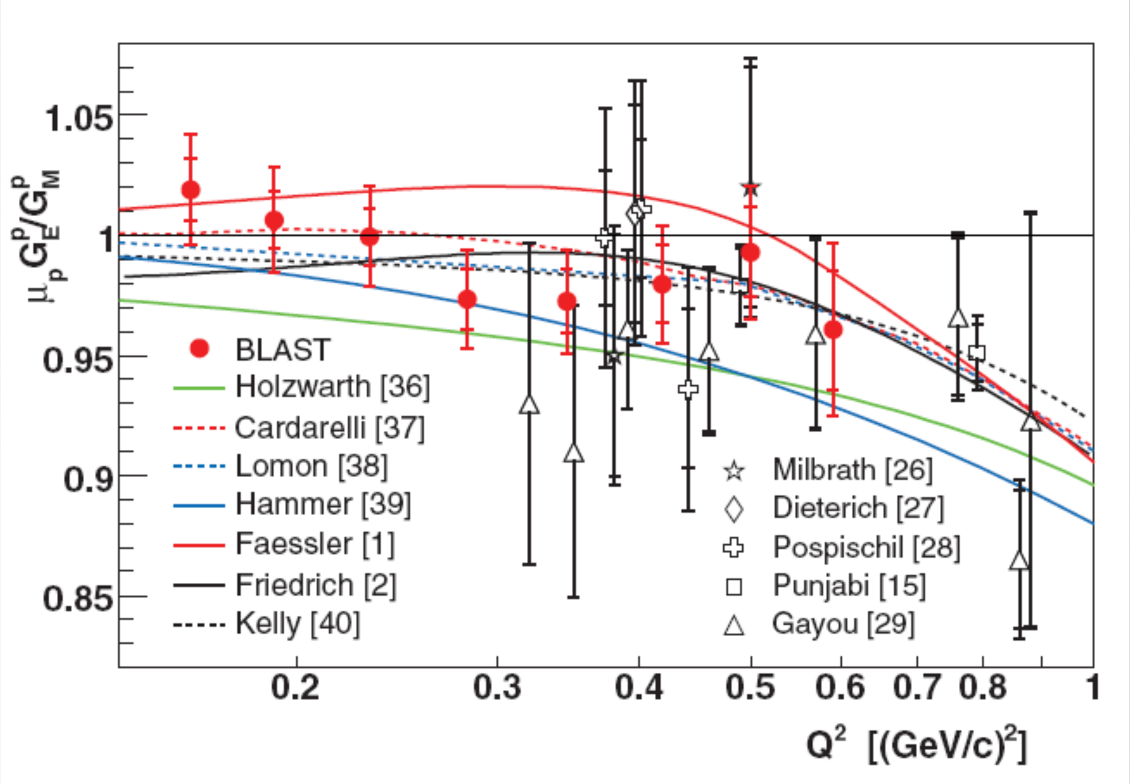
- High precision cross section survey down to $Q^2 \sim 0.01 GeV^2$.
- Preliminary results for XS vs. scattering angle already shown.
- F&W analysis not supported.

Low Q^2 Notable Results

BLAST @ MIT Bates - proton

C.B. Crawford et al., Phys. Rev. Lett. 98, 052301 (2007)

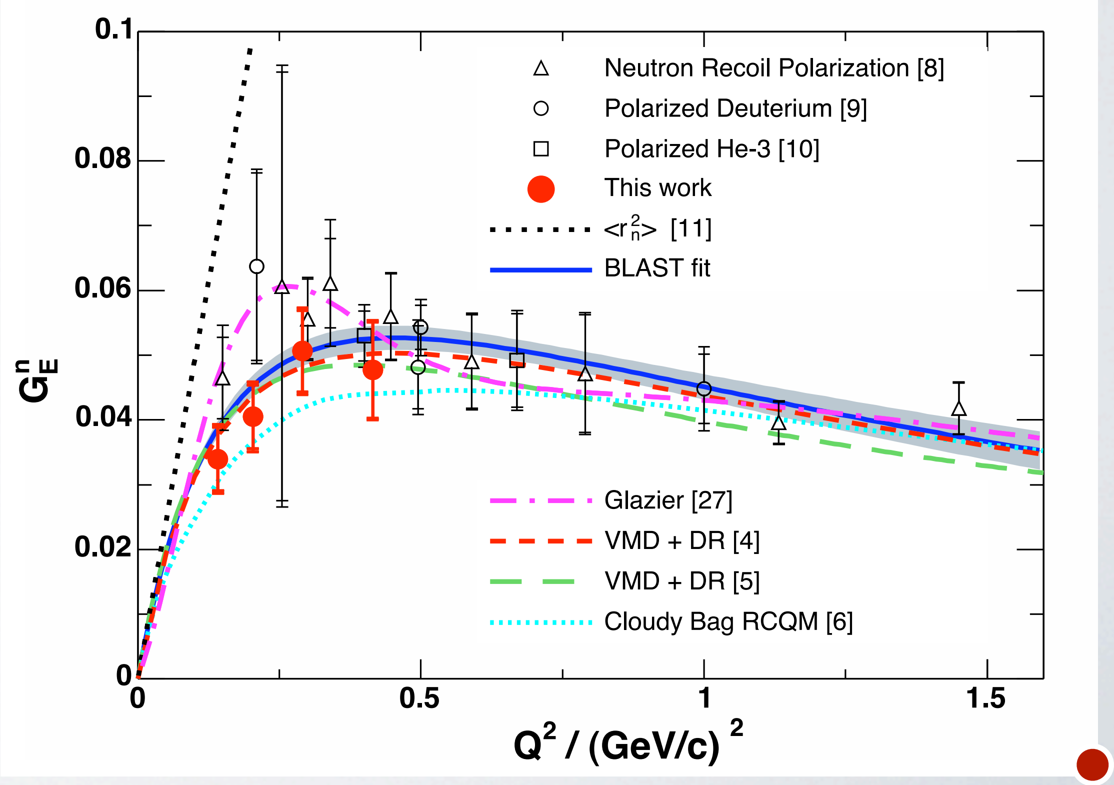
- Beam target asymmetry measurement using polarized H internal gas target.
- (Barely) consistent with unity and the F&W analysis.



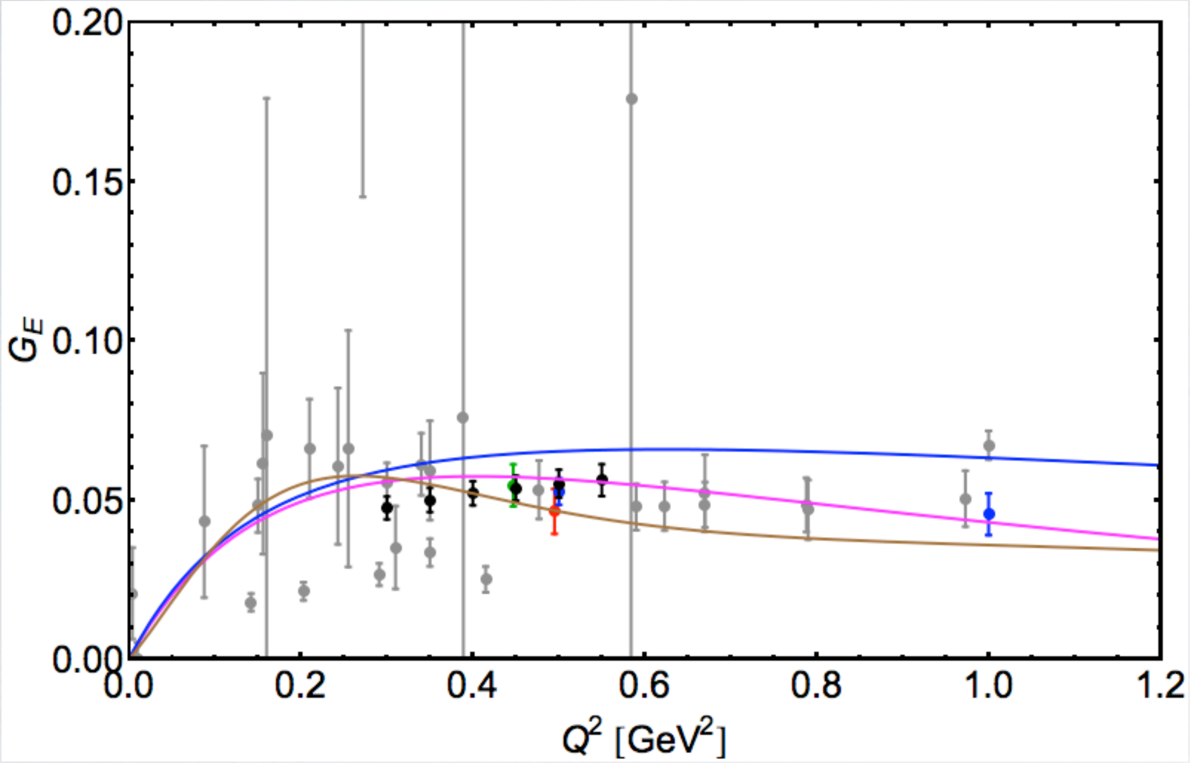
BLAST @ MIT Bates - neutron

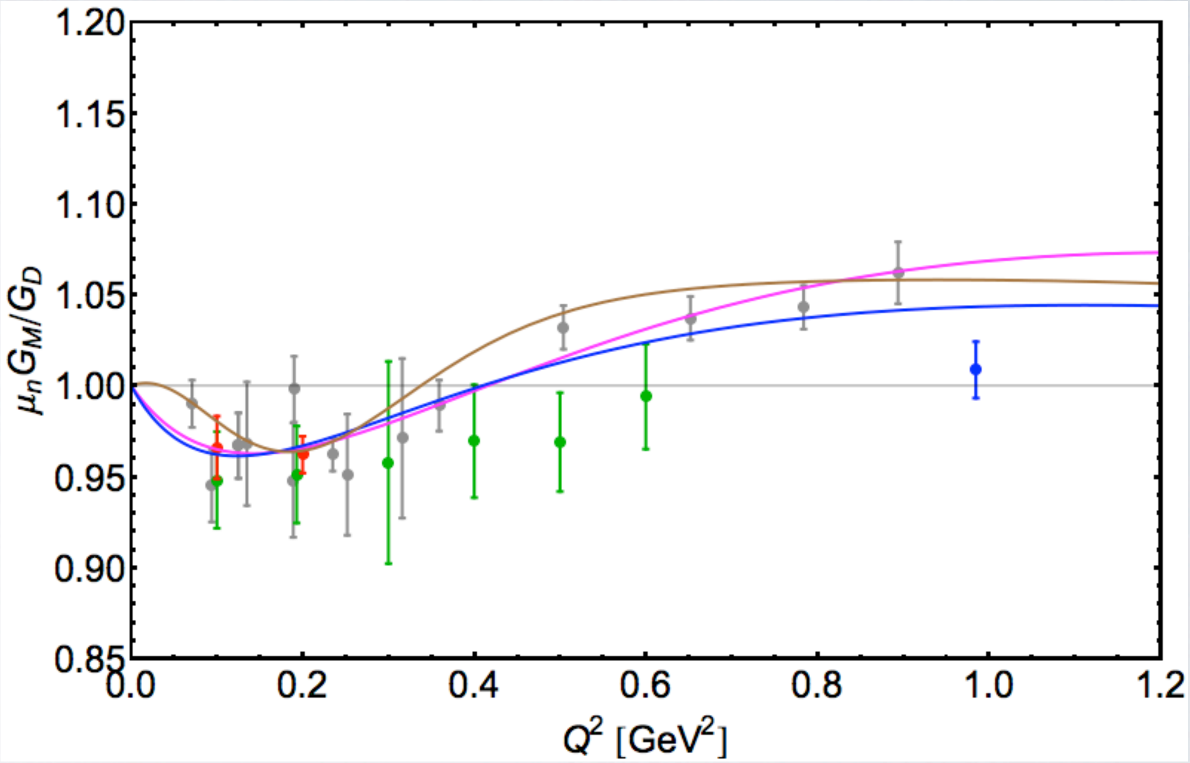
E. Geis et al., Phys. Rev. Lett. 101, 042501 (2008)

- Beam target asymmetry measurement using vector polarized ^{2}H internal gas target.
- Inconsistent with Bump/Dip structure.



The JLab low Q^2 program
Neutron FFs - What we've learned





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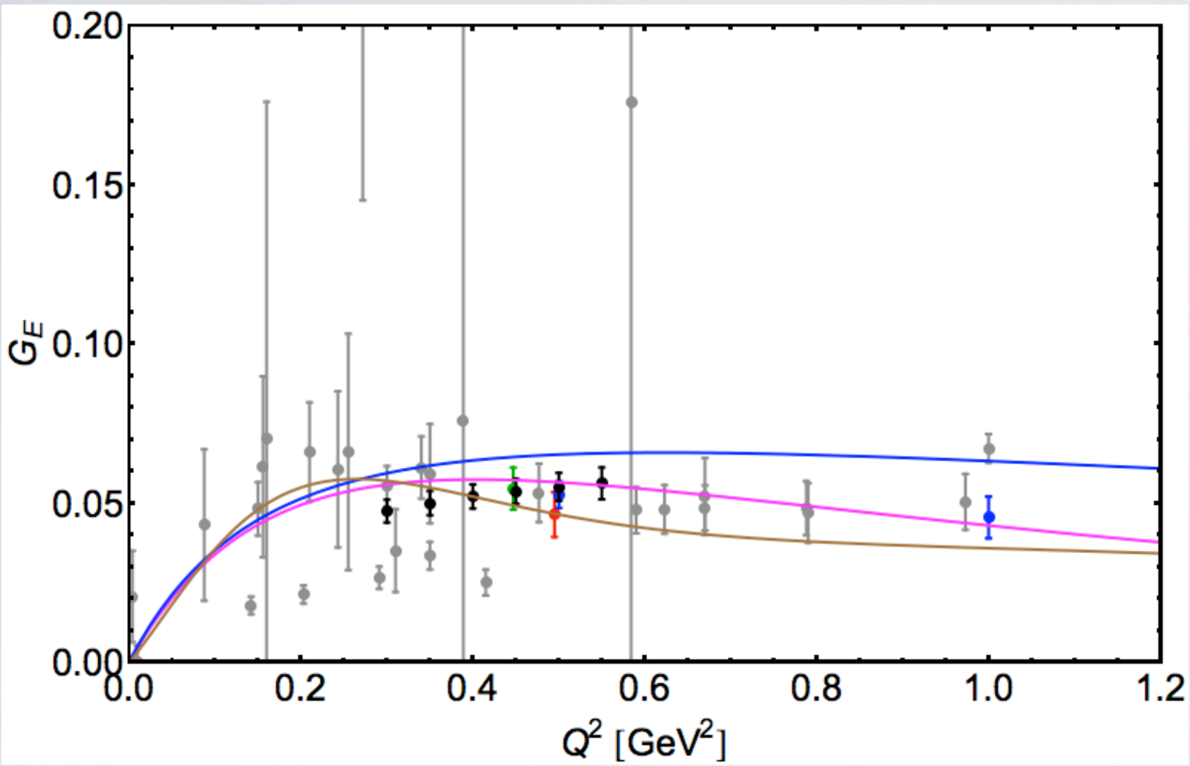
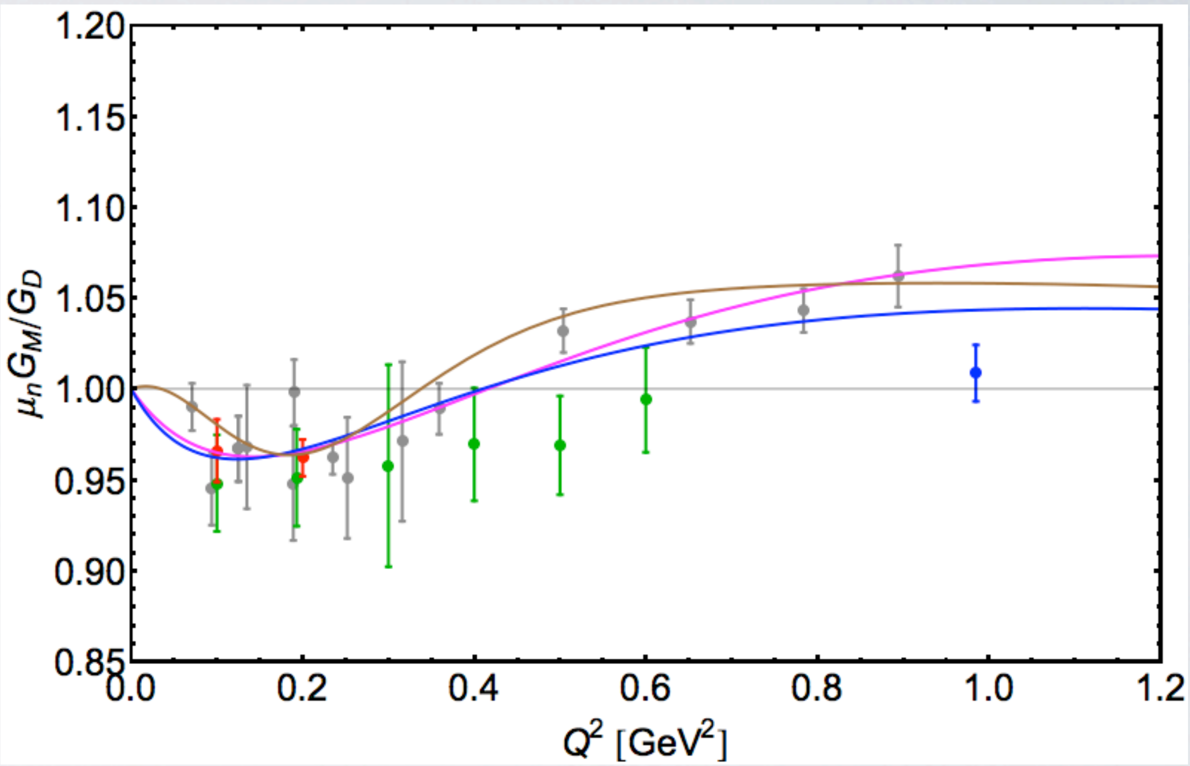




More data needed at low Q^2
(but currently no plans).
F&W parameterization seems not to fit data.

The JLab low Q^2 program
Proton FFs

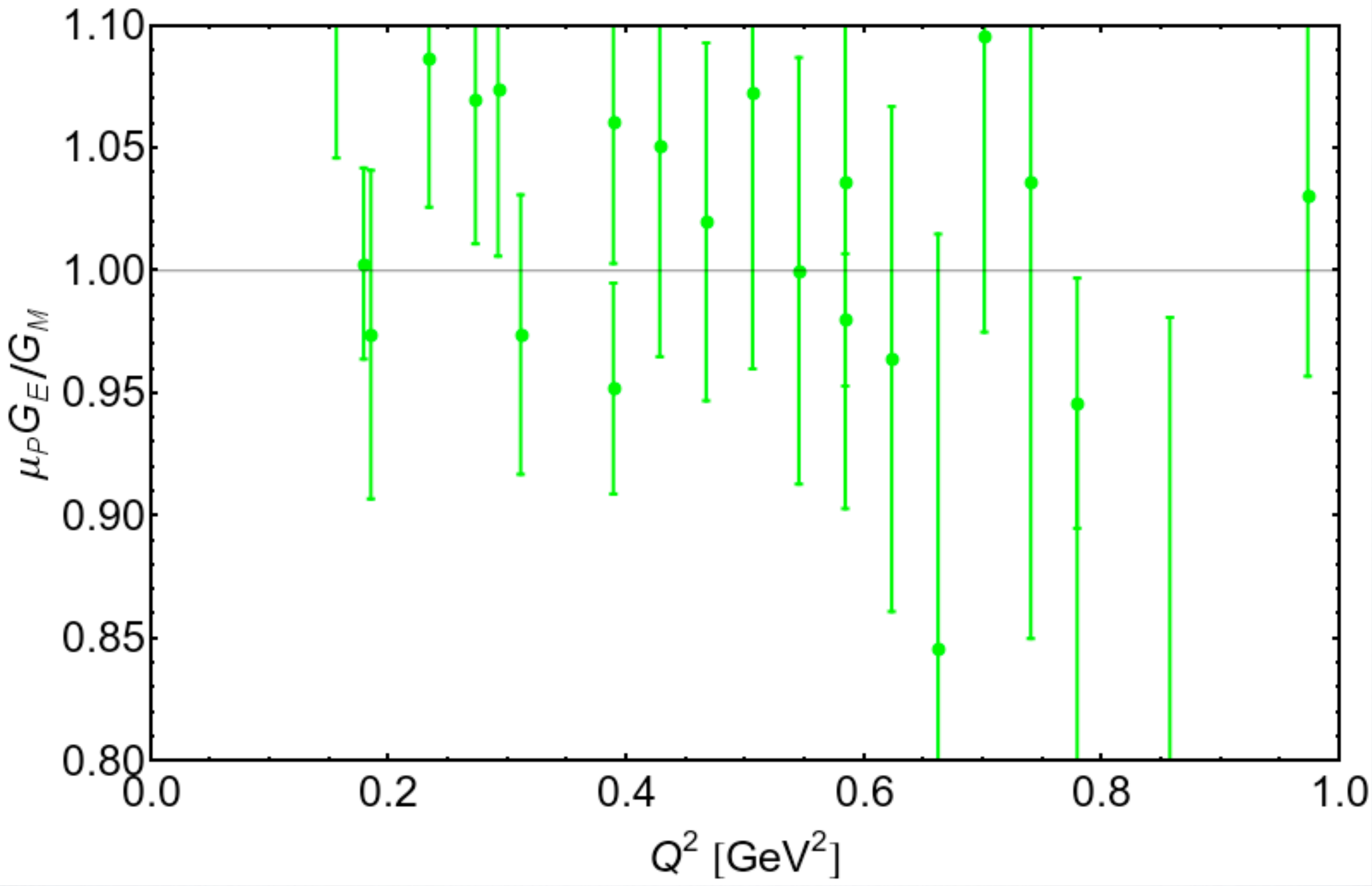
- LEDEX -
  - Recoil polarization measurement of the FF ratio.
  - Calibration run from γD measurement.
  - 8 Q^2 data points (0.25 - 0.5 GeV^2) with ~ 1.5% uncertainty on best data points.
  - Led to the proposal of:

The JLab low Q^2 program
Proton FFs

- LEDEX -
  - Recoil polarization measurement of the FF ratio.
  - Calibration run from γD measurement.
  - 8 Q^2 data points (0.25 - 0.5 GeV^2) with ~ 1.5% uncertainty on best data points.
  - Led to the proposal of:
- E08-007 -
  - A dedicated 2 part experiment to map the proton FF ratio at low Q^2.
  - First part used recoil polarization to achieve:
    - ~ 1% uncertainty (*best ever achieved*) at Q^2~ 0.3 - 0.7 GeV^2.
  - Second part will use beam target asymmetry (more later).

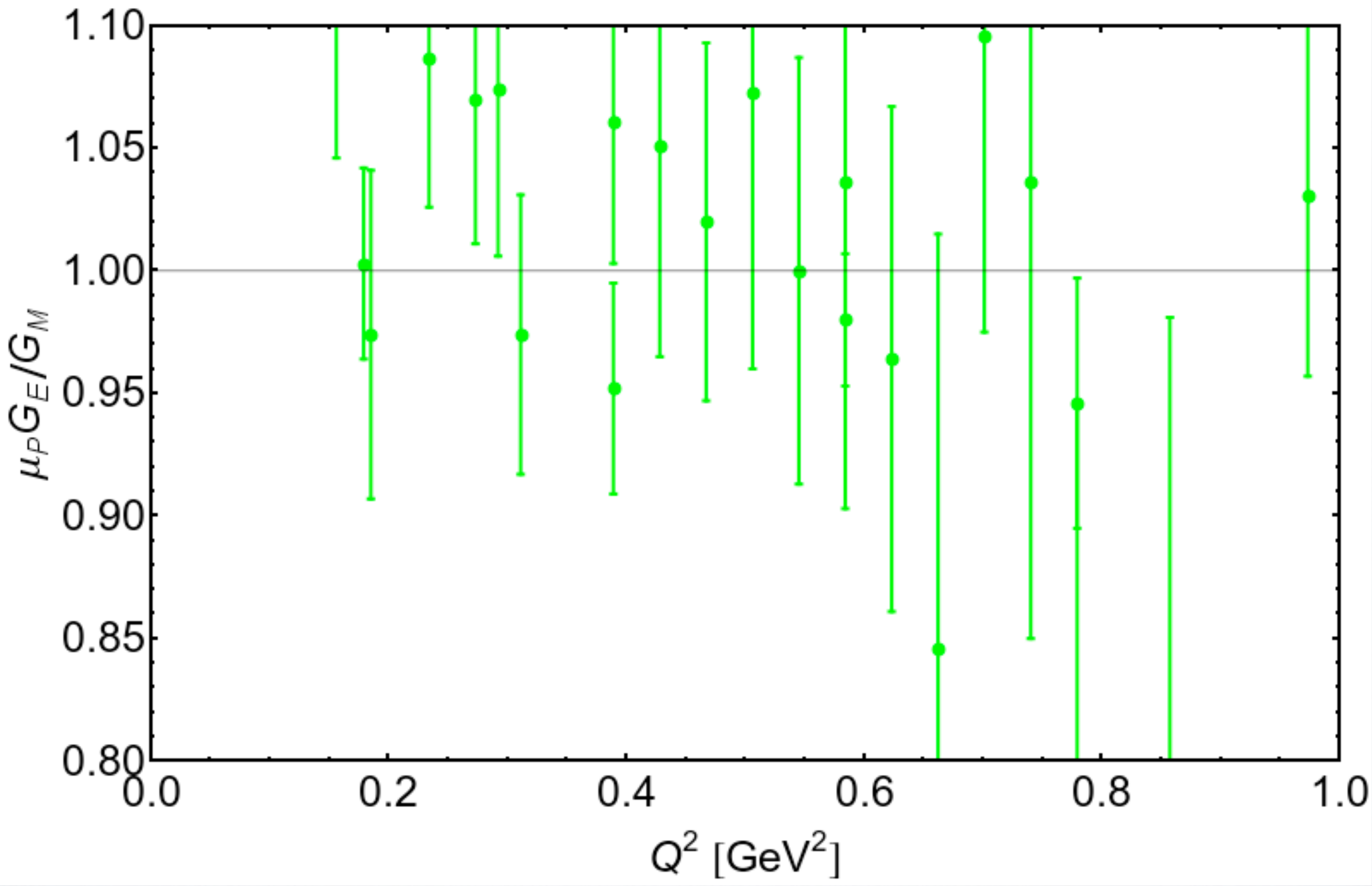
A Sense of Scale

Rosenbluth



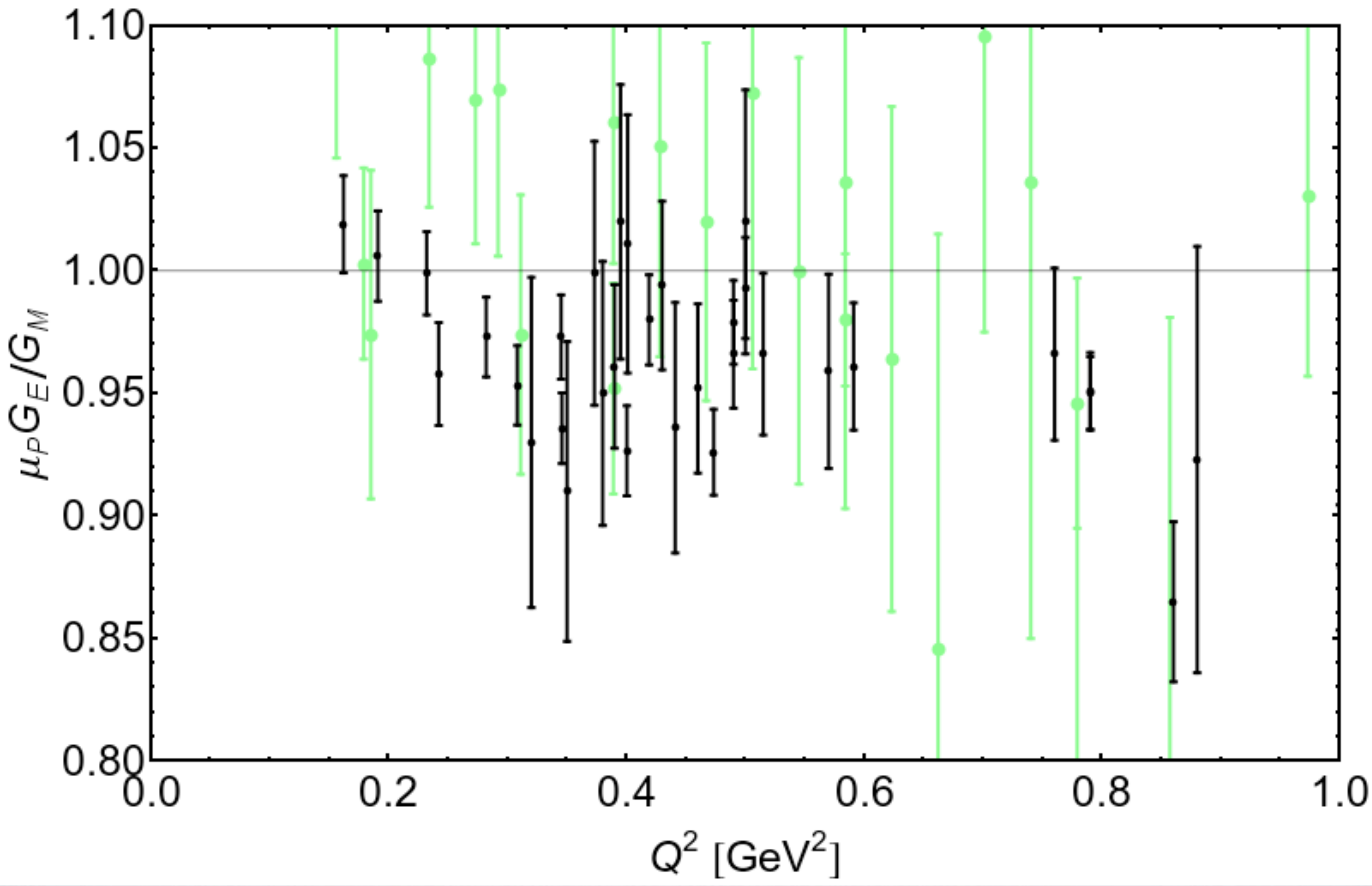
A Sense of Scale

Rosenbluth



A Sense of Scale

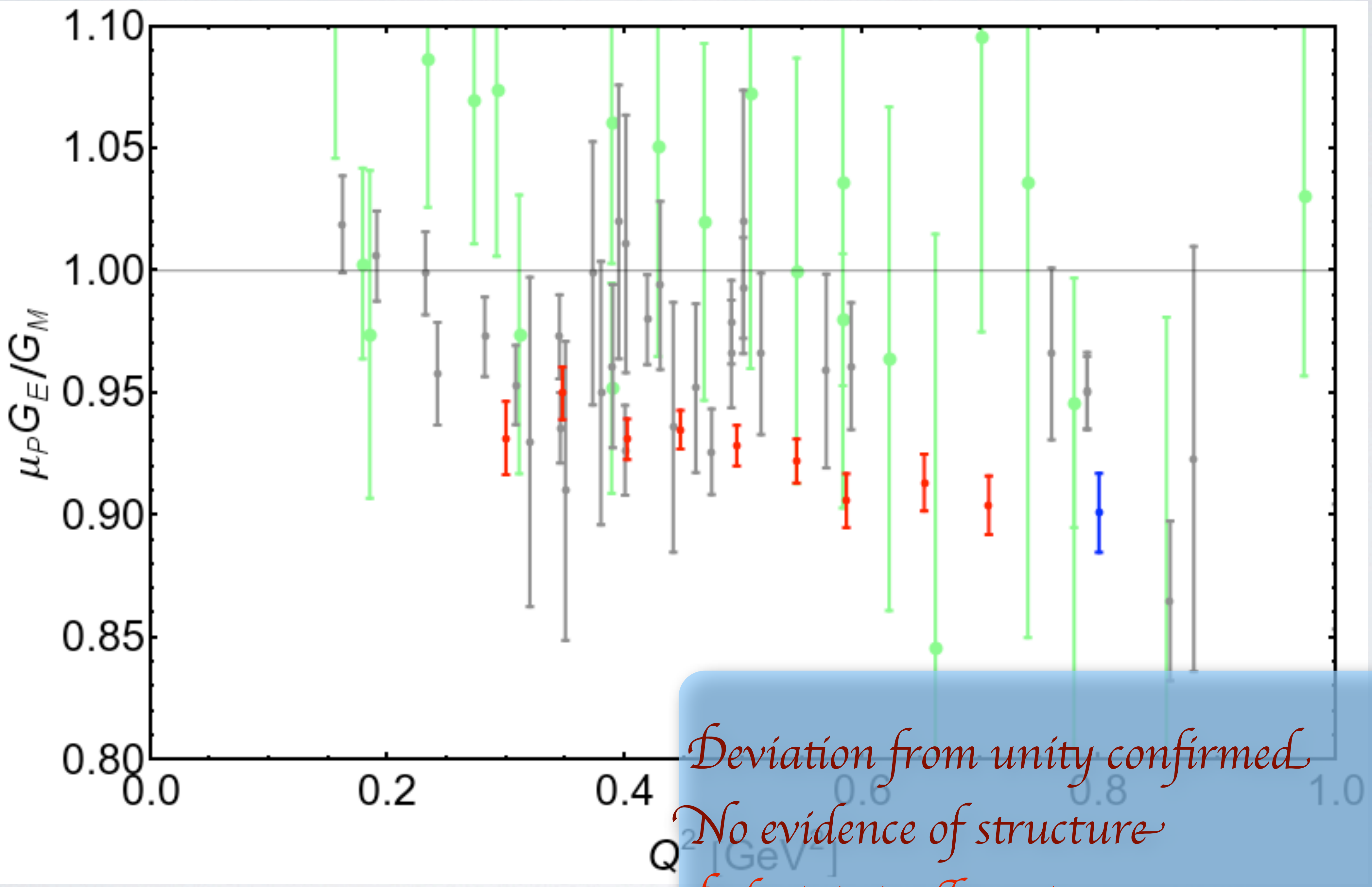
World Polarization Data



A Sense of Scale

E08007 - Part I

(and E03-104)



Deviation from unity confirmed

No evidence of structure

Relativistic effects important even at low Q^2

A Sense of Scale
E08007 - Part I
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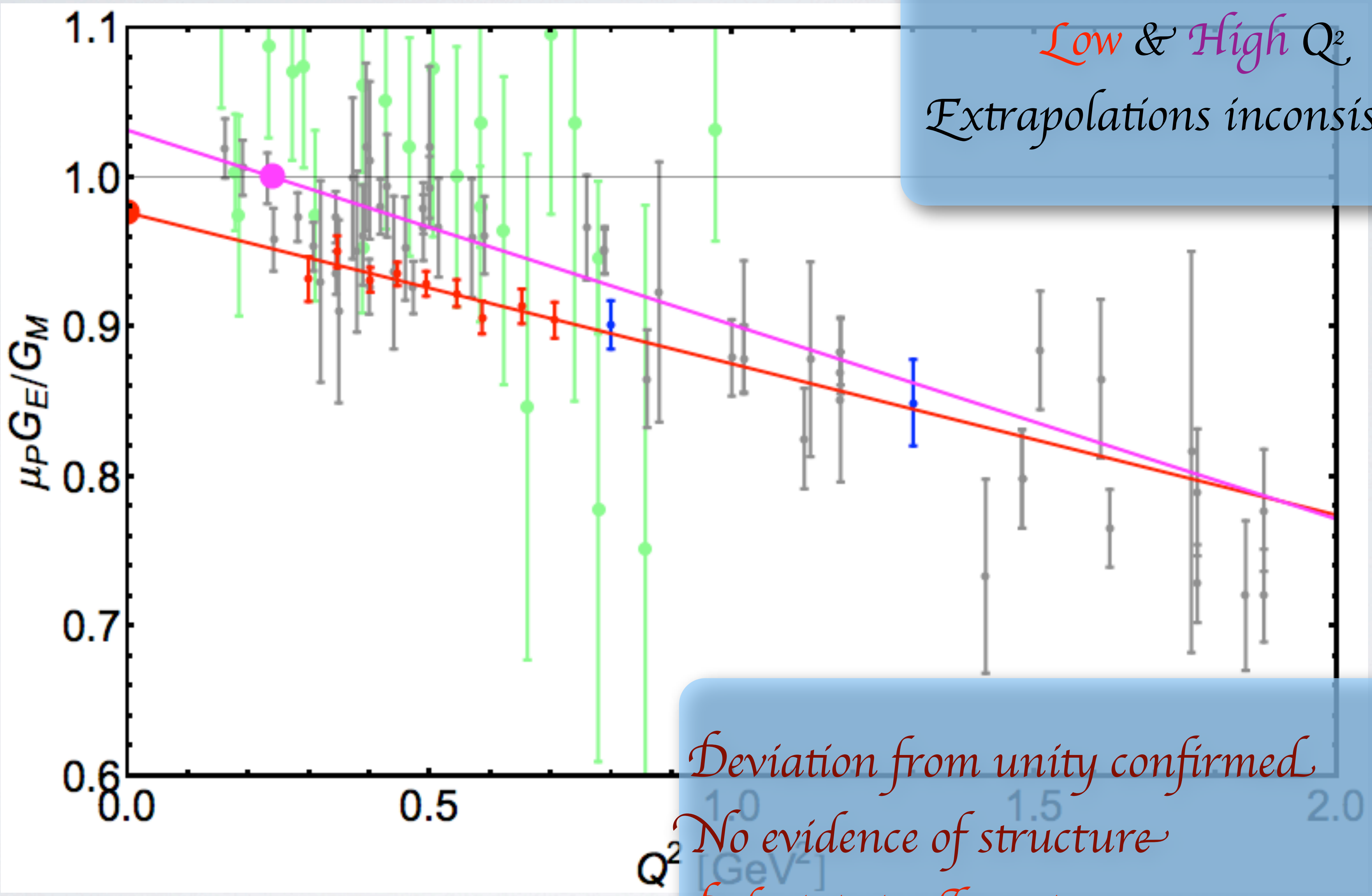

Low & High Q^2 Extrapolations inconsistent.

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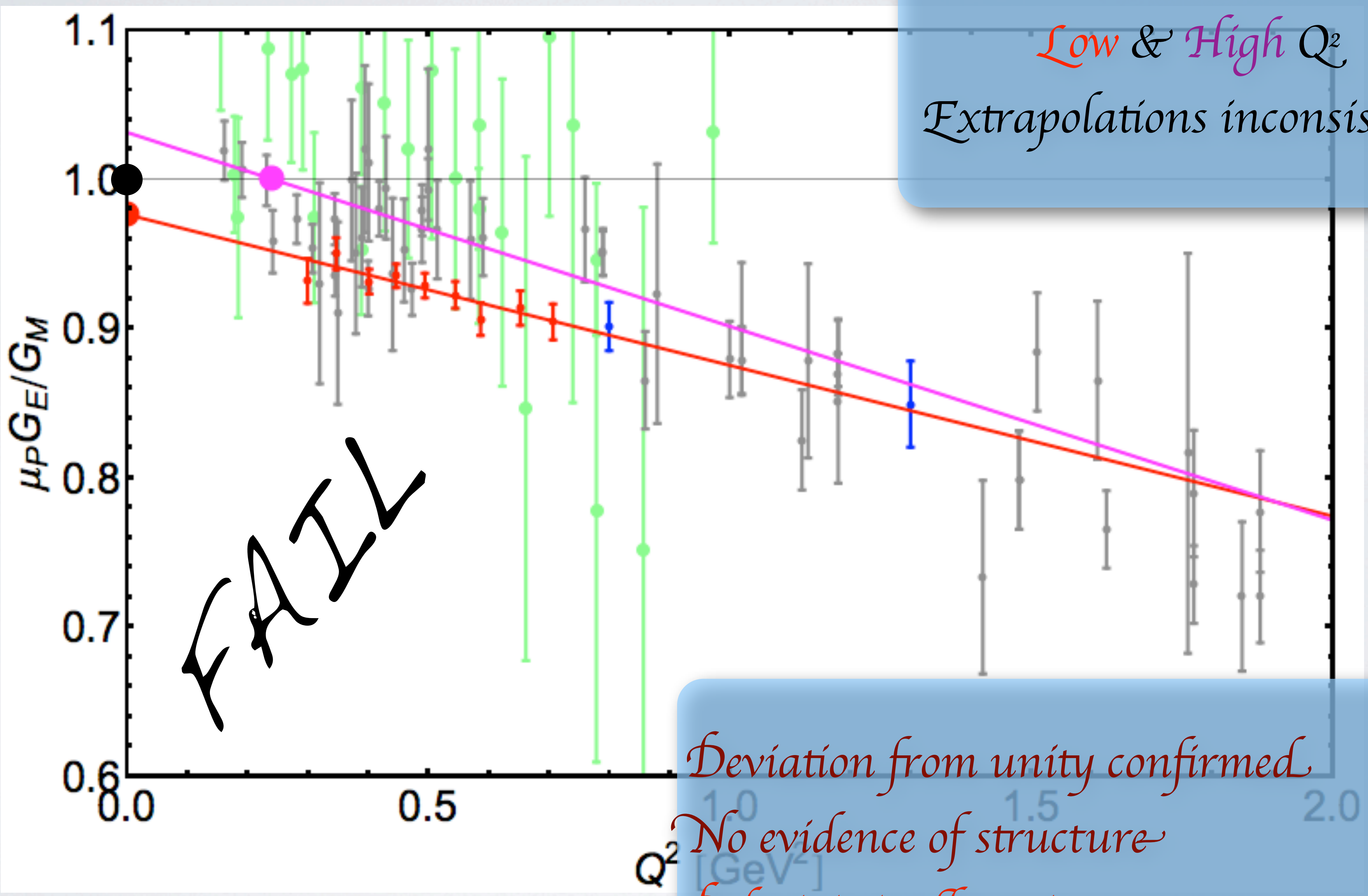
E08007 - Part I

(and E03-104)



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Extracting the individual FFs

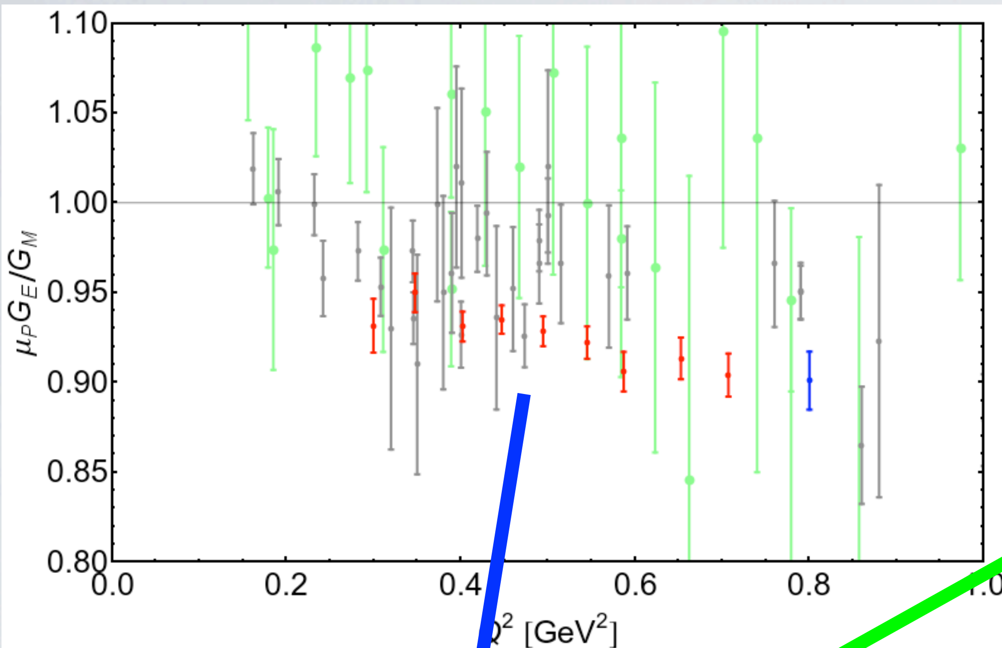
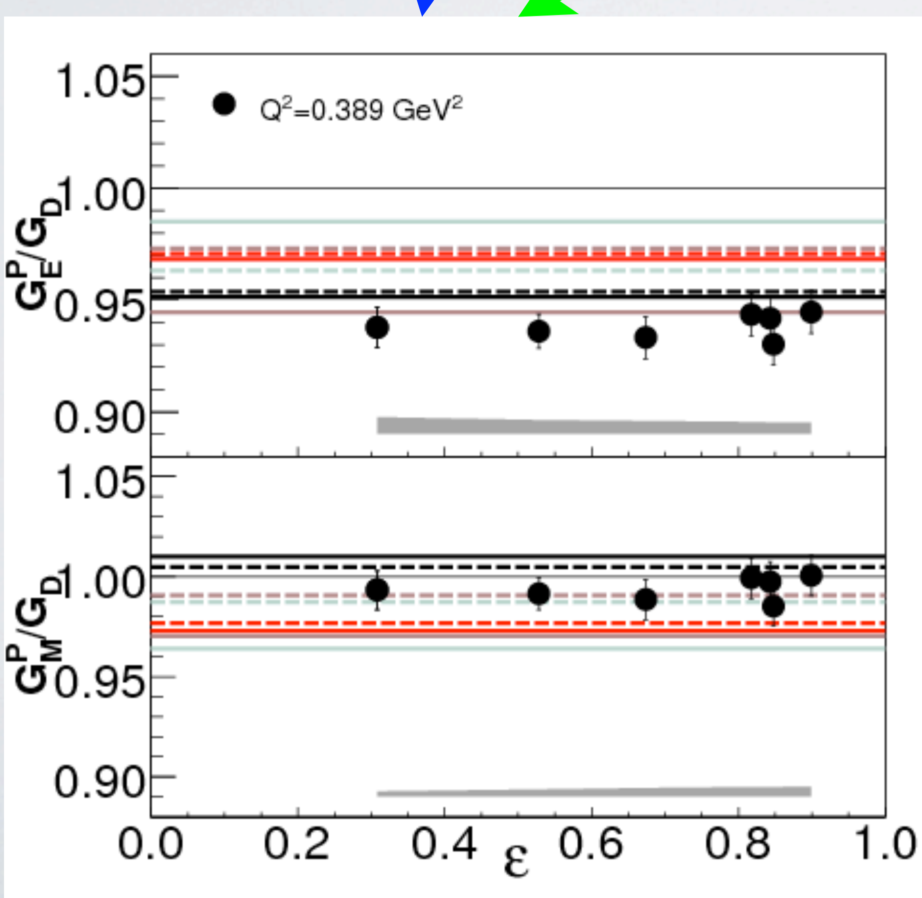


Table 1.
Differential cross sections: The quoted errors are only random errors. A normalization error of ± 4% has to be added.

$q^2 (f^{-2})$	θ (°)	s_0 (GeV)	$\frac{d\sigma}{d\Omega}$ [10^{-34} $\frac{cm^2}{ster}$]	
2	25.25	0.660	32800	± 990
3	25.25	0.815	18570	± 550
3.065	35.15	0.605	8630	± 260
5	25.25	1.064	8410	± 260
	35.15	0.784	4000	± 120
8	25.25	1.364	3610	± 90
10	25.25	1.537	2285	± 46
	31.74	1.249	1328	± 26
	32.27	1.231	1310	± 26
	35.15	1.142	1080	± 22
	50.06	0.848	460.3	± 9.4
	64.72	0.696	252.9	± 4.1
	90.27	0.556	117.8	± 2.3



High precision cross section and FFR combined → High precision individual form factors.

Deviation from unity (at least for Q^2 ~ 0.39 GeV^2) caused by G_E.

Will eventually combine with high precision Mainz XS database.

G. Ron et al., Phys. Rev. Lett. 99, 202002 (2007)

What we've learned

Charge Densities

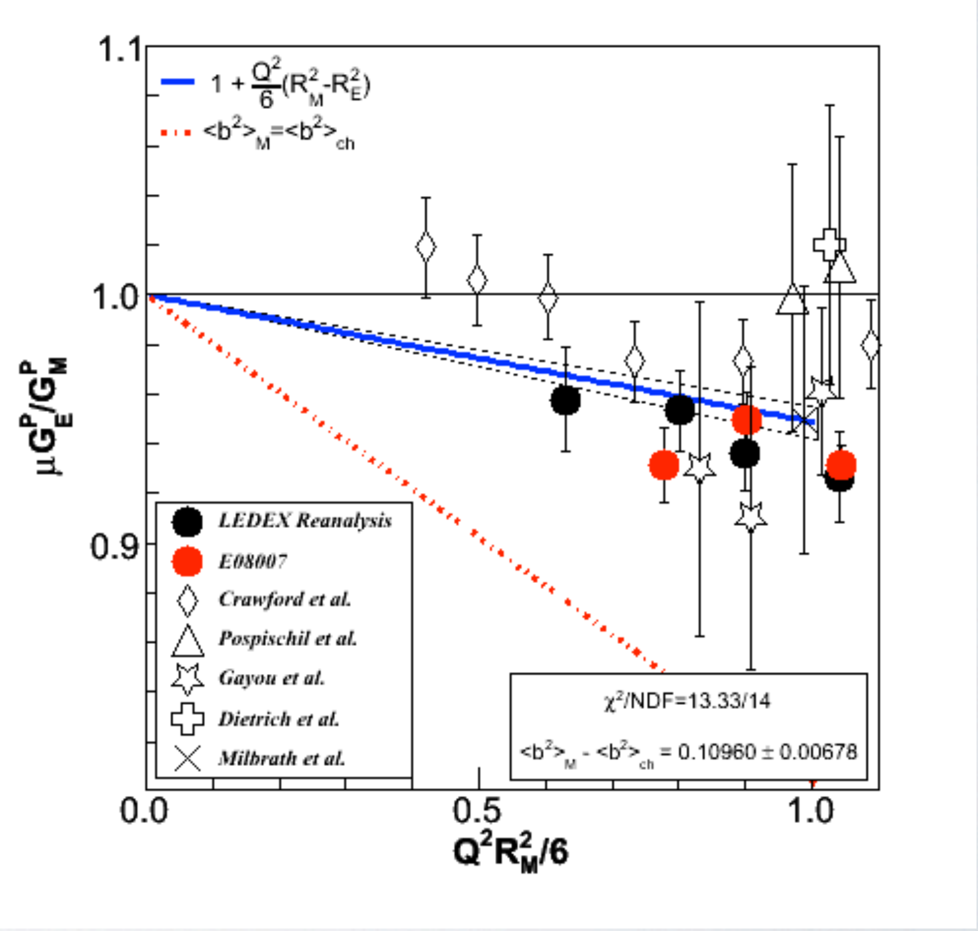
- Sachs FFs cannot be related to charge/ magnetization densities:
- Relativistic effects (Lorentz contraction).
- Initial/Final states not identical (cannot be interpreted as density).
- Can be shown that F_1 & F_2 are 2D transforms of charge and magnetization densities.
- Low Q^2 expansion gives:

$$\langle b^2\rangle_M - \langle b^2\rangle_{Ch} = \frac{\mu}{\kappa}\frac{2}{3}(R_M^{*2} - R_E^{*2}) + \frac{\mu}{M^2}$$

- And fit to data gives:

$$\left\langle b^2\right\rangle_M - \left\langle b^2\right\rangle_{ch} = 0.0909 \pm 0.0039\ \mathrm{fm}^2$$

$$\rho_{Ch}(\vec{b}) = \mathcal{F}^{-1}\left[F_1(Q^2)\right]$$
$$\rho_M(\vec{b}) = \mathcal{F}^{-1}\left[F_2(Q^2)\right]$$



G. Miller, Phys. Rev. Lett. 99, 112001 (2007)

G. Miller, E. Piasetzky & G. Ron, Phys. Rev. Lett. 101, 082002 (2008)

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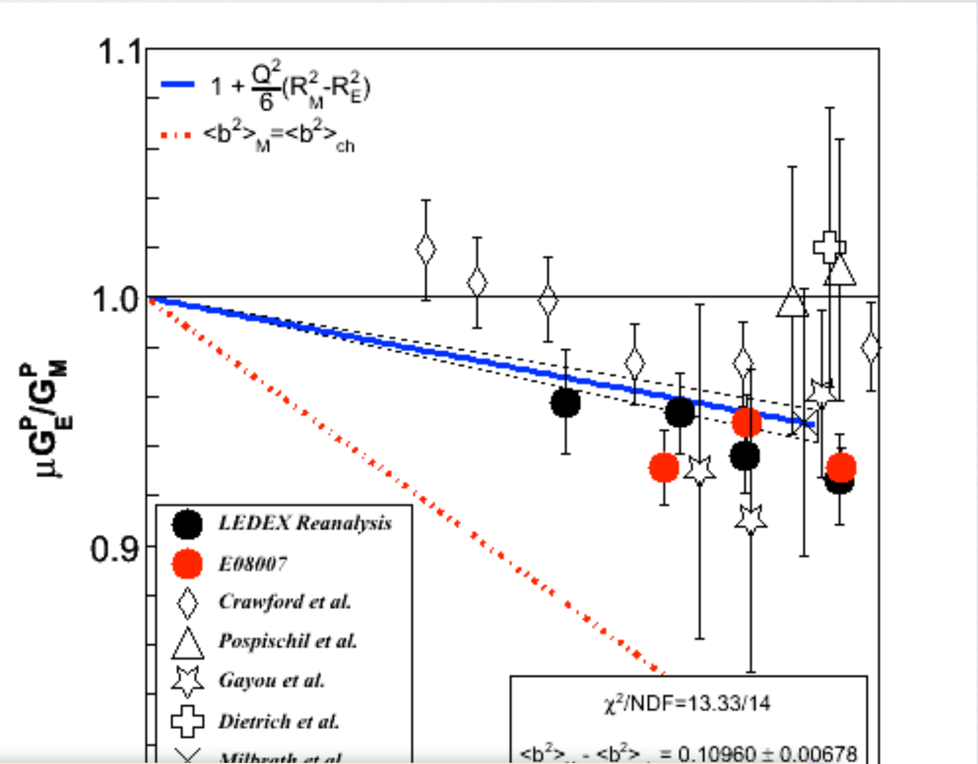

Counter intuitive?

G. Miller, Phys. Rev. Lett. 99, 112001 (2007)

G. Miller, E. Piasetzky & G. Ron, Phys. Rev. Lett. 101, 082002 (2008)

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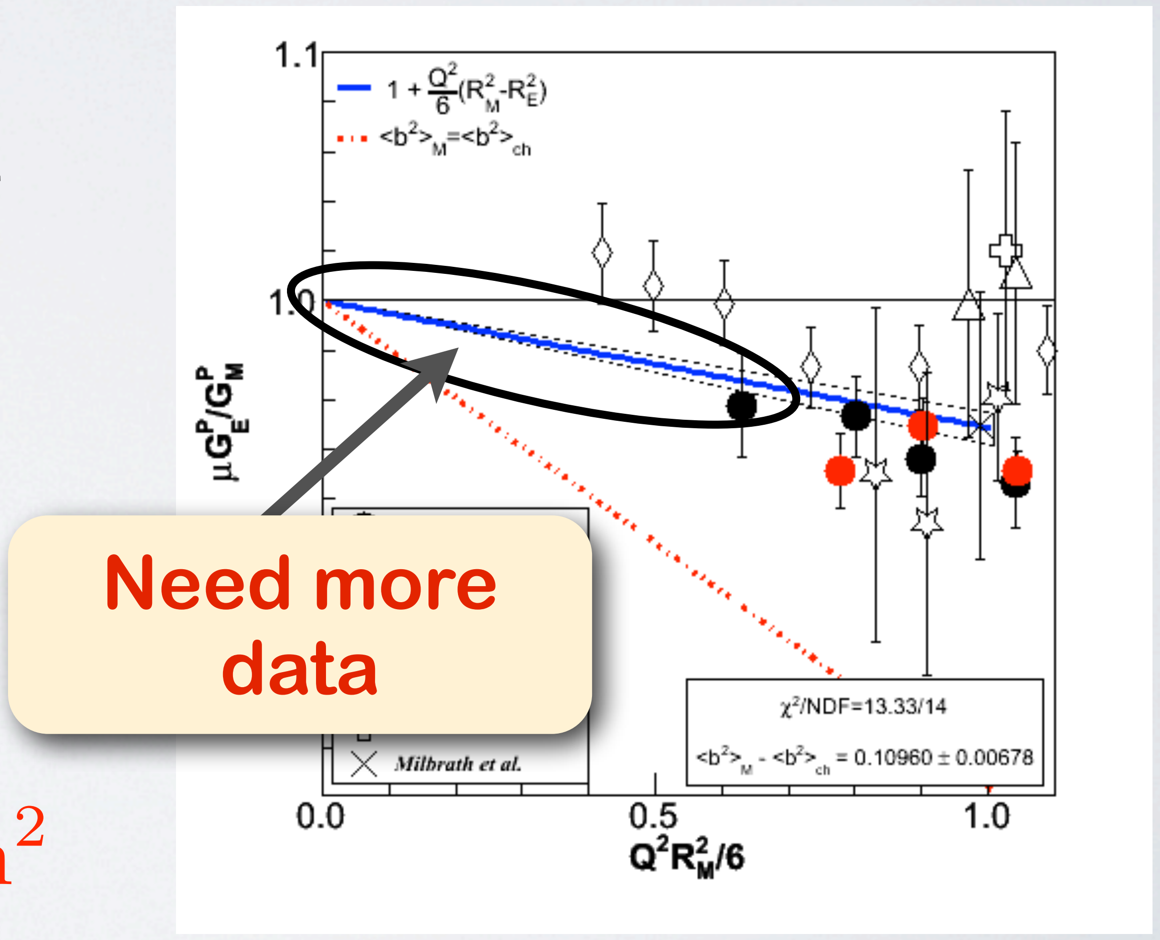


G. Miller, Phys. Rev. Lett. 99, 112001 (2007)

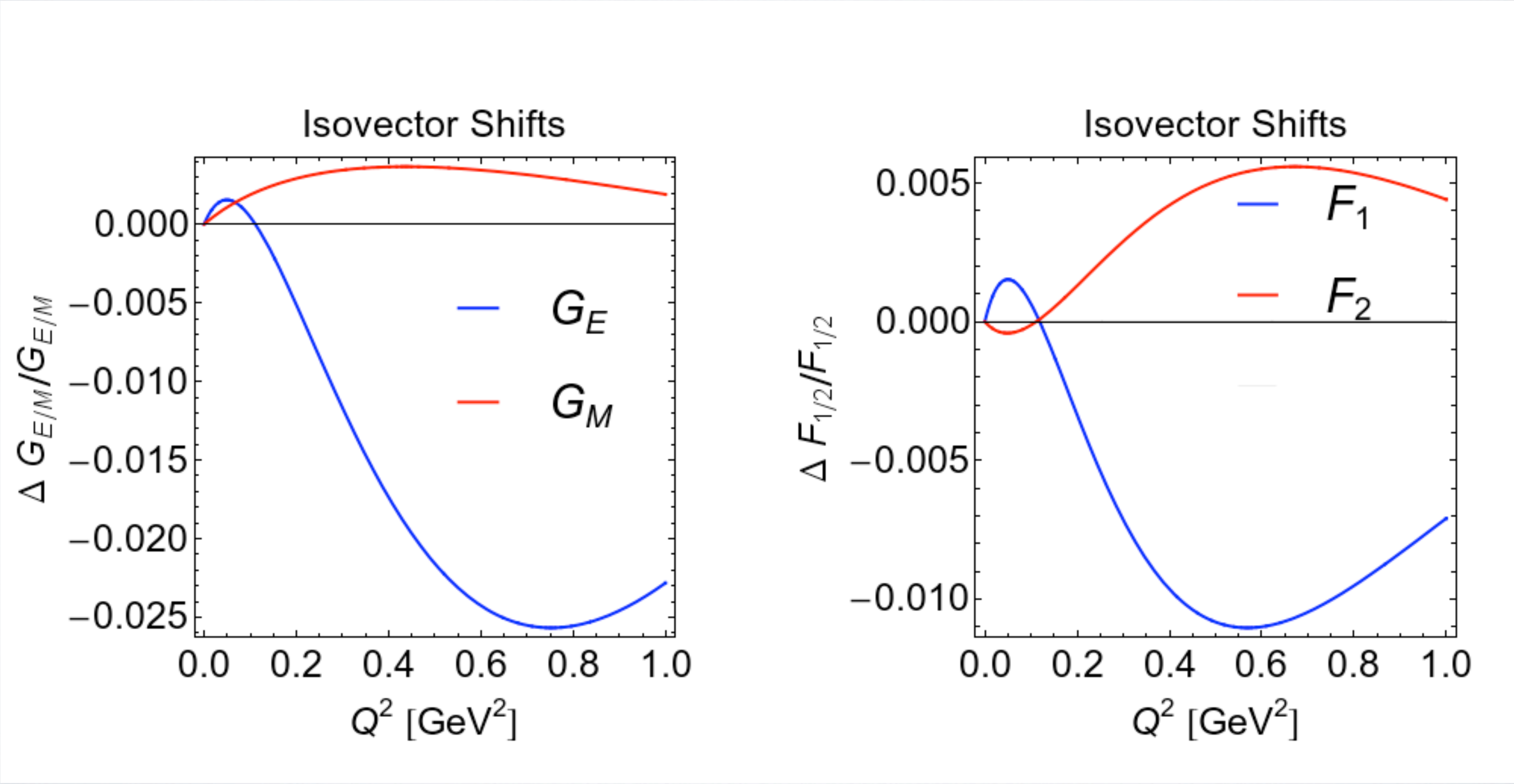
G. Miller, E. Piasetzky & G. Ron, Phys. Rev. Lett. 101, 082002 (2008)

Isovector / Isoscalar Separation

Reminder: IV=p-n, IS=p+n

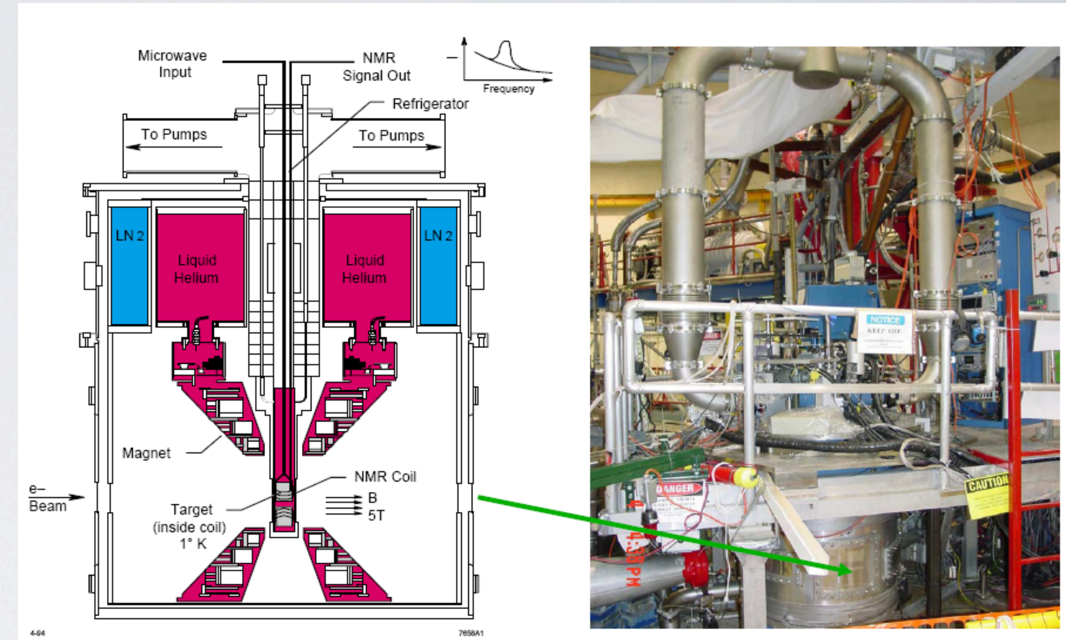
Important for Lattice QCD (Isovector)

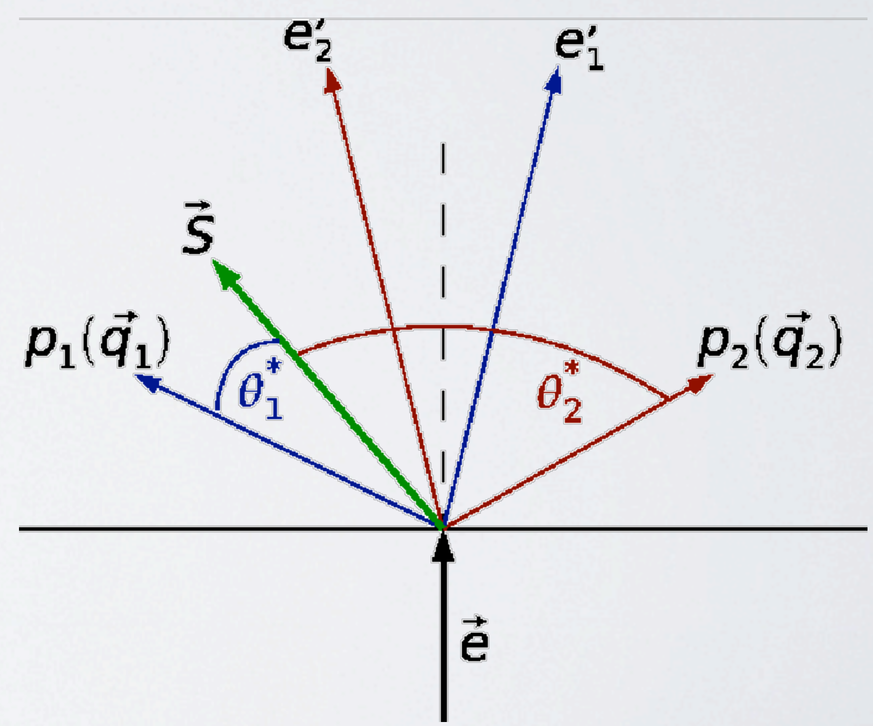
Plot shows the fractional change in the isovector form factors when using J. Arrington's new vs. old parametrizations (for the proton).



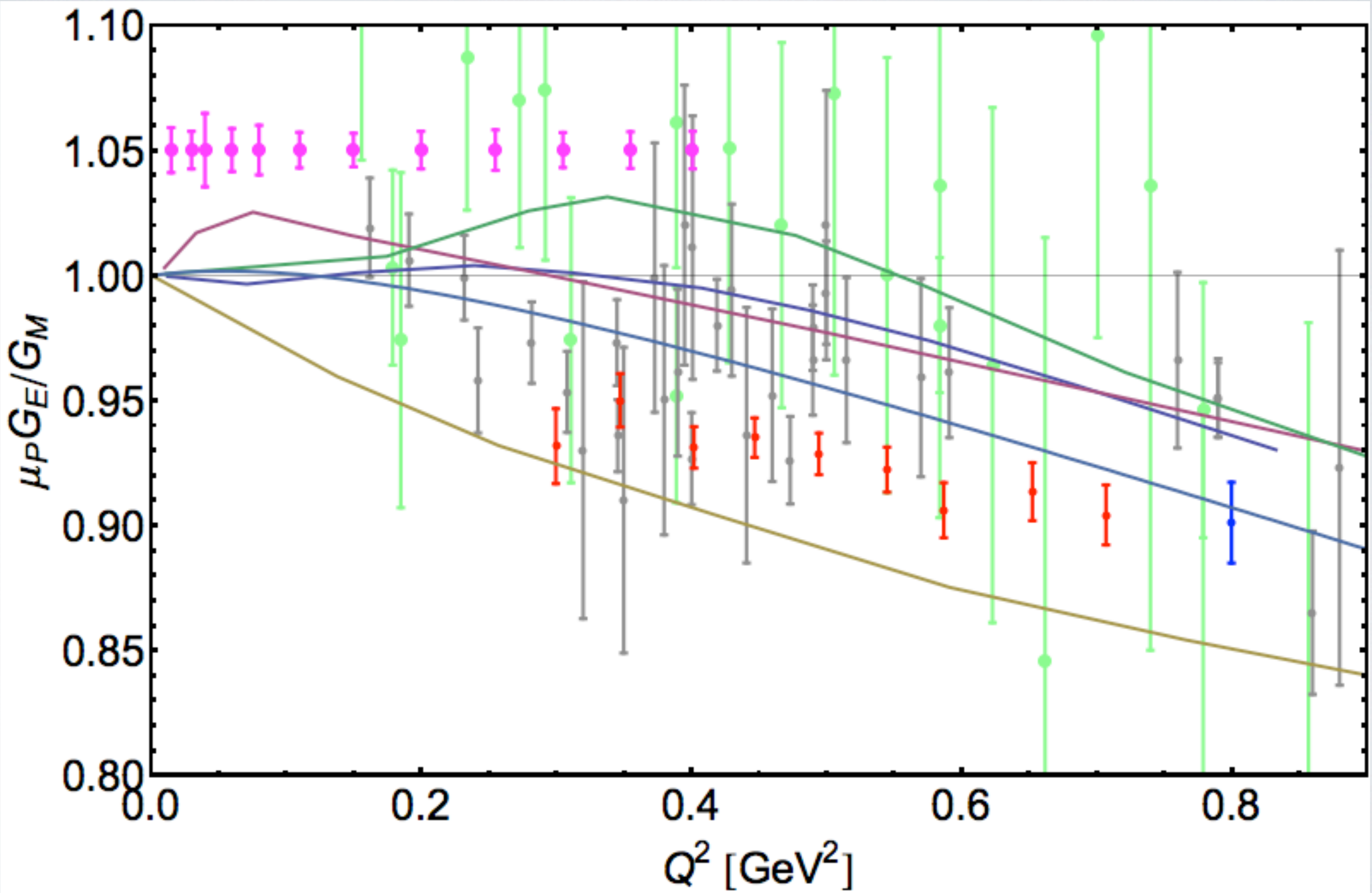
E08007 - Part II

- High precision (< 1%) survey of the FF ratio at Q^2=0.01 - 0.4 GeV^2.
- Beam-target asymmetry measurement by electron scattering from polarized NH_3 target.
- Electrons detected in two matched spectrometers.
- Ratio of asymmetries cancels systematic errors → only one target setting to get FF ratio.
- Designed to overlap E08007-I and Bates BLAST.
- Scheduled for Dec 2011 / Jan 2012.

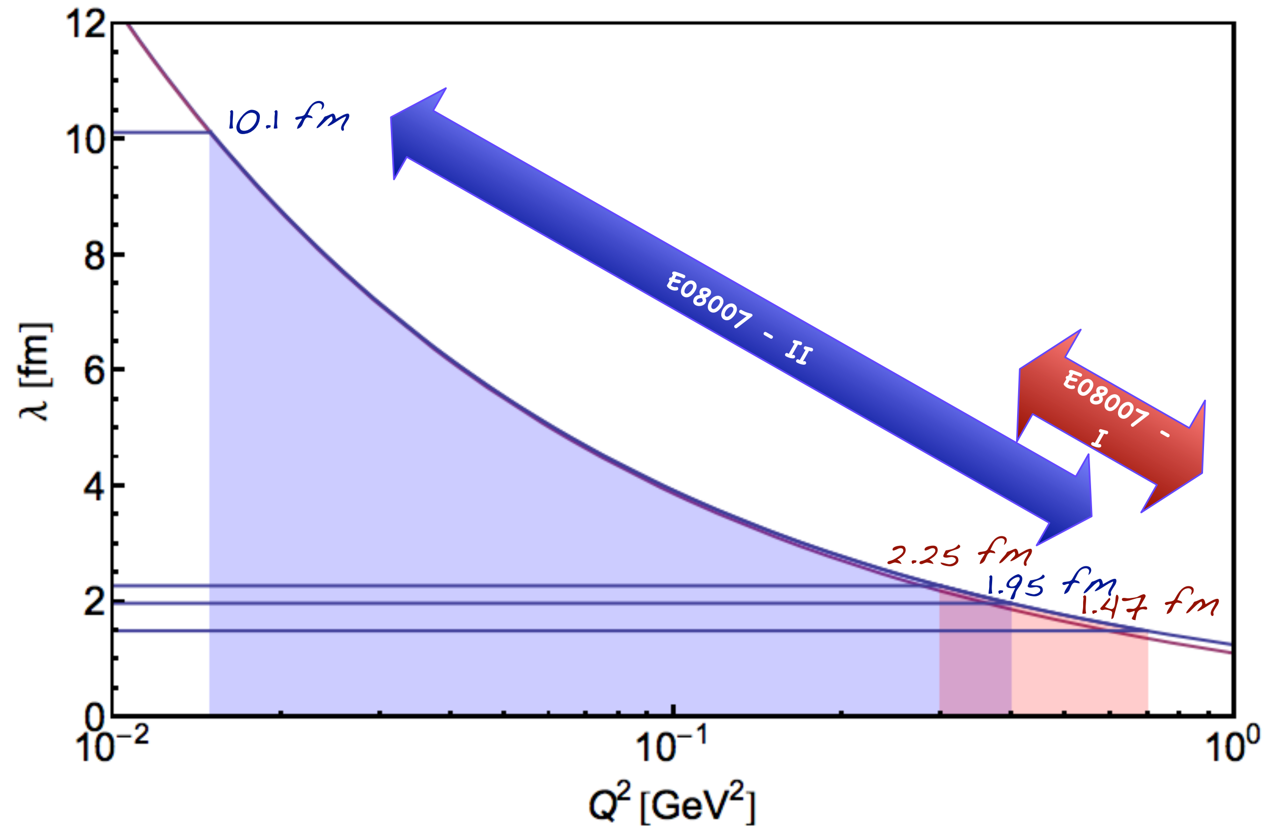


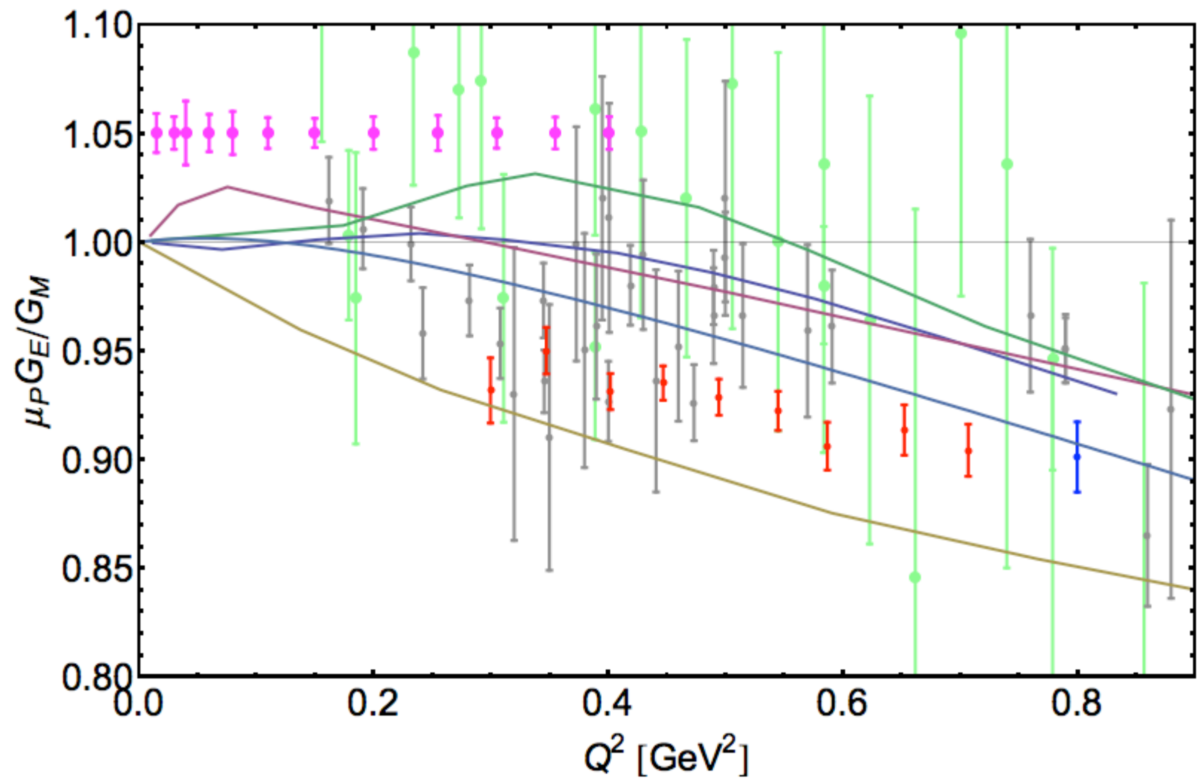


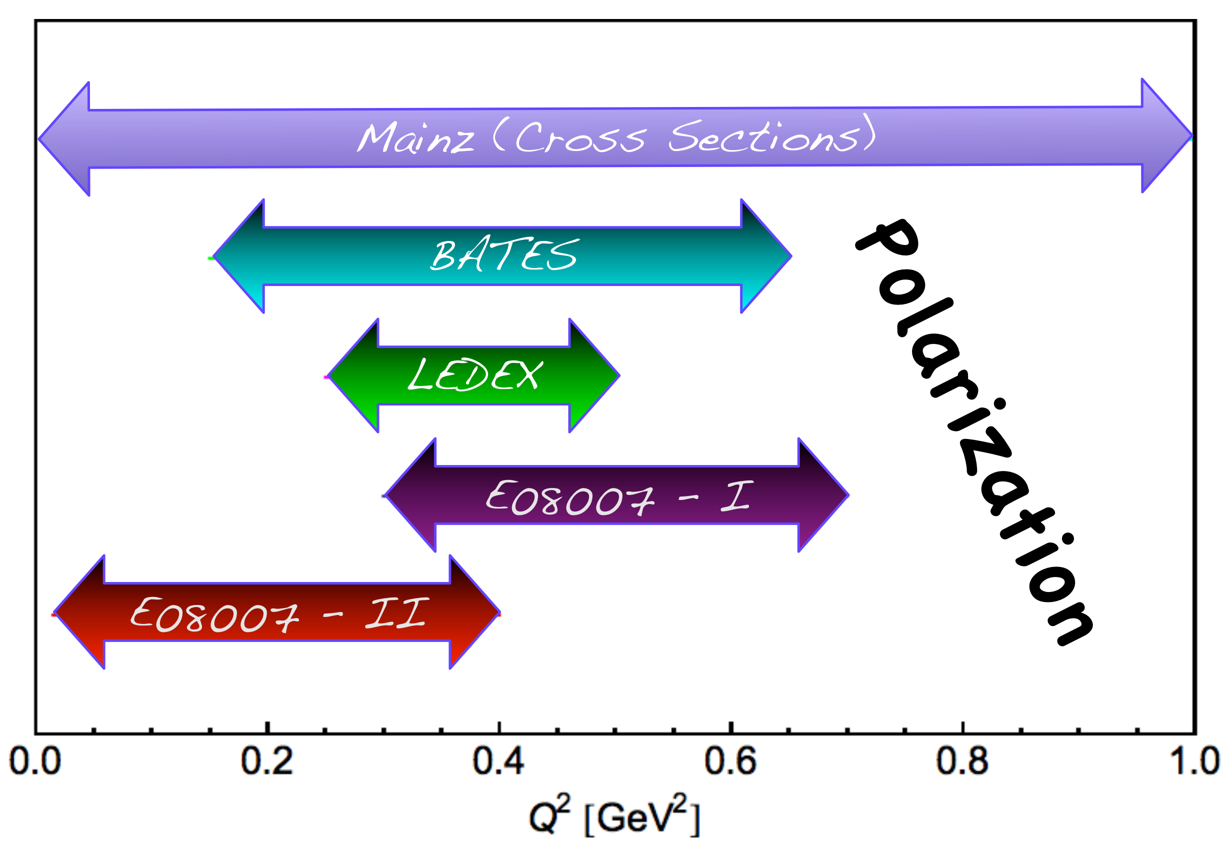
E08007 - Part II
Projected uncertainties

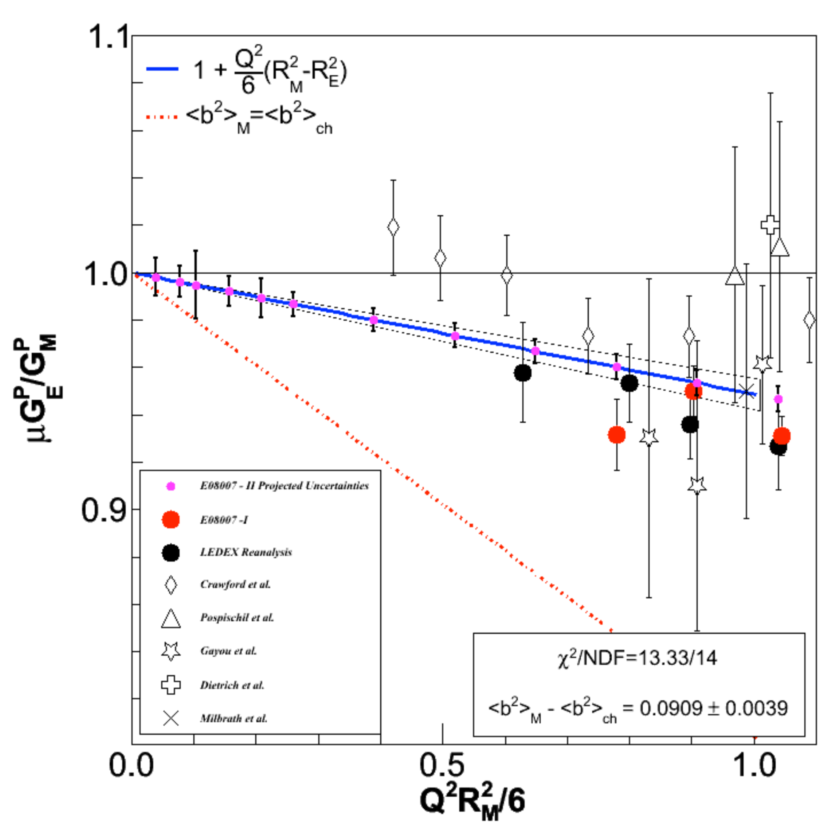


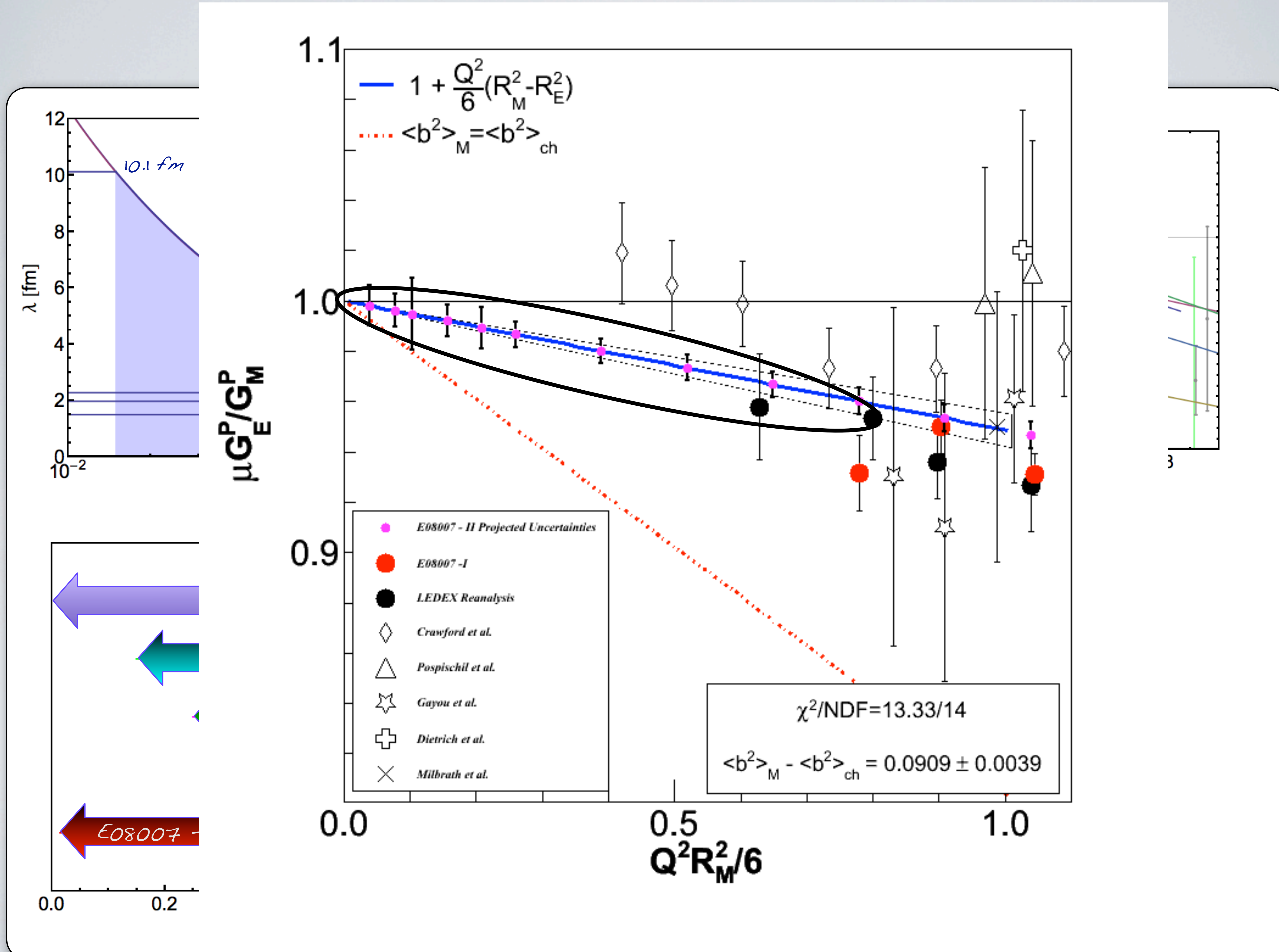
E08007 Coverage











1 + Q²/6 (R²M - R²E)
<b²>M=<b²>ch
μGᴾE/Gᴾ M
Q²R²M/6
E08007 - II Projected Uncertainties
E08007 -I
LEDEX Reanalysis
Crawford et al.
Pospischil et al.
Gayou et al.
Dietrich et al.
Milbrath et al.
χ²/NDF=13.33/14
<b²>M - <b²>ch = 0.0909 ± 0.0039
1.1
1.0
0.9
0.0
0.5
1.0
λ [fm]
10.1 fm
12
10
8
6
4
2
0
10⁻²
E08007 -
0.0
0.2

Summary - Part I

- Form factors are physical, model-independent, observable of the nucleon.
- Many discoveries over the years have changed our understanding of one of the basic constituents of matter.
- While high energy (and Q^2) are, of course, important, there is great significance to performing low Q^2 measurements (only real way to discriminate between EFTs).
- Very high precision measurements are now possible and required for high precision experiments.
- It seems that there is no evidence (at least in the FF ratio) for narrow structures.
- One more high precision, low Q^2 experiment before the 12 GeV upgrade. Limited number of candidate facilities for more low Q^2 experiments.

Atoms = Electrons + Nuclei + EM Interactions

Nucleus = Protons + Neutrons + Strong Interaction of Hadrons

Nucleon = Constituent Quarks + Strong Interaction of quarks

Constituent Quarks = Quarks + gluons + Strong Interaction

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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Simple picture is totally false, but extremely effective

What happens to the nucleons under these conditions?

Nuclei Are Changed in the Nucleus

One (and 1/2) examples - out of many

1. **Neutron lifetime:** $\tau_{1/2}^{free} \sim 15\,\mathrm{min} \rightarrow \tau_{1/2}^{bound} = \infty$

But this is of course a binding effect:

$$M_p + M_e < M_n$$

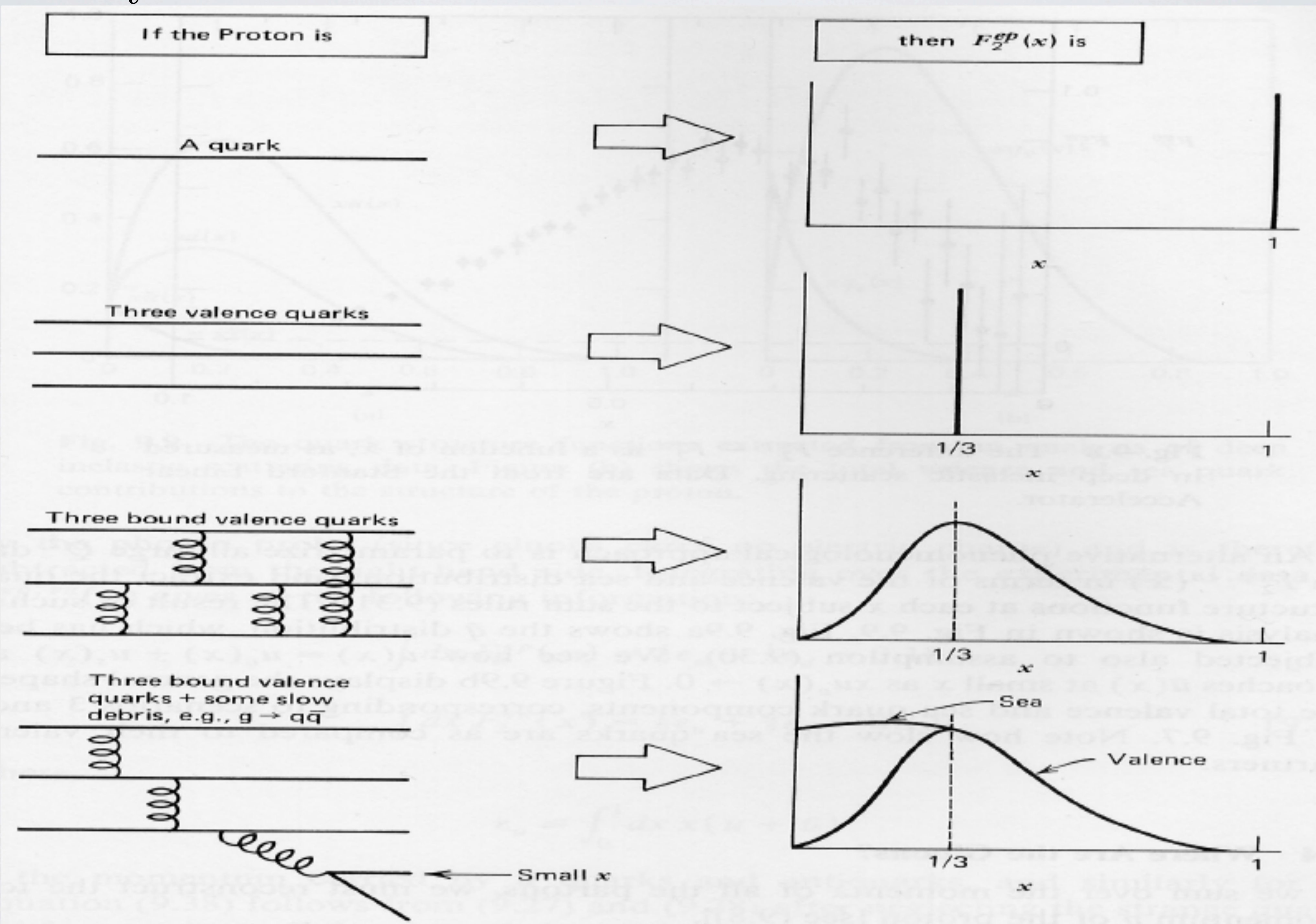
$$(M_n - M_p - M_e) < B_d$$

2. **The EMC Effect**

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

Naive Expectation:

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

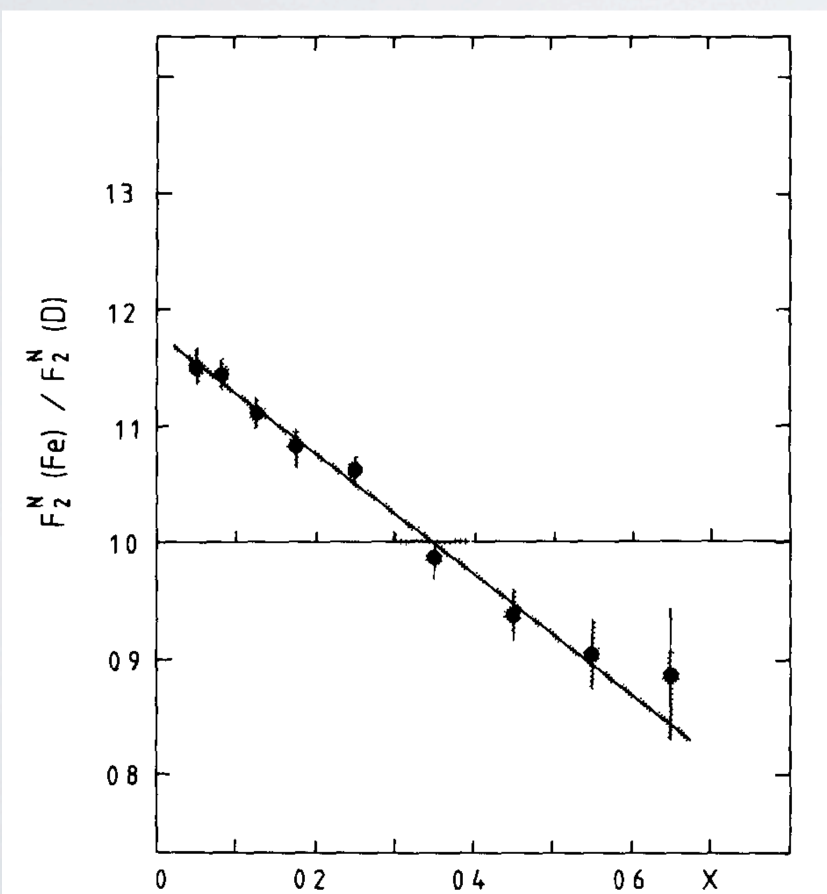
The EMC Effect

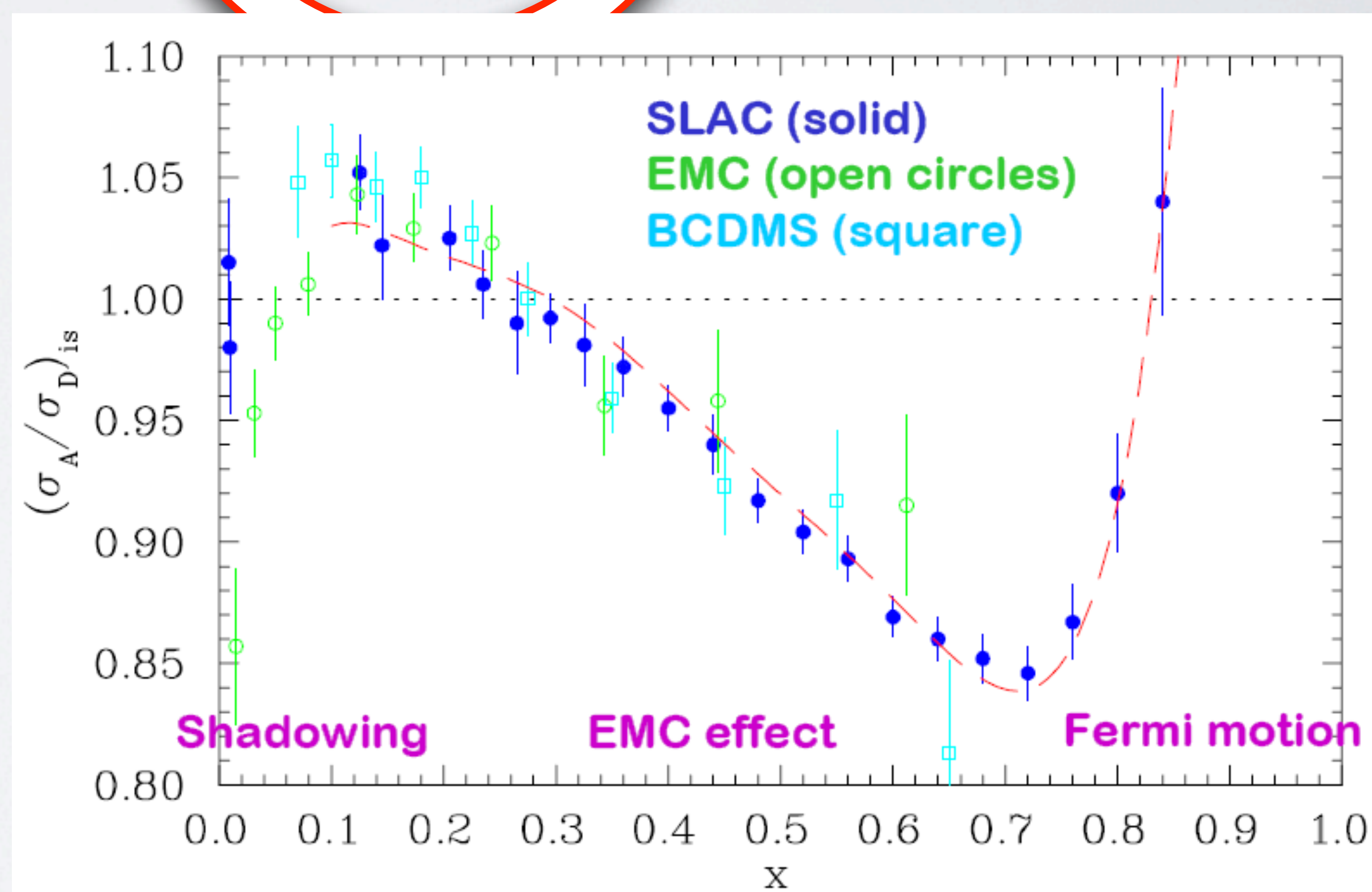
Excess of low momentum quarks and depletion of high momentum quarks in Nuclei.

finding a quark with

tion x in the nucleon.

Expectation: $(A - Z)F_2^n$





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.

The EMC Effect (and others)

Some possible explanations

Conventional:

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  pions in
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Unconven

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And many more....

More models than

model
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everything.

EMC

Everyone's Model is Cool

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.
- "Orthogonal" to previous measurements.

Polarization observable are...

- Related to form factor (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)

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 (*explained in a sec....*).
- Take the super-ratio to remove systematic effects.

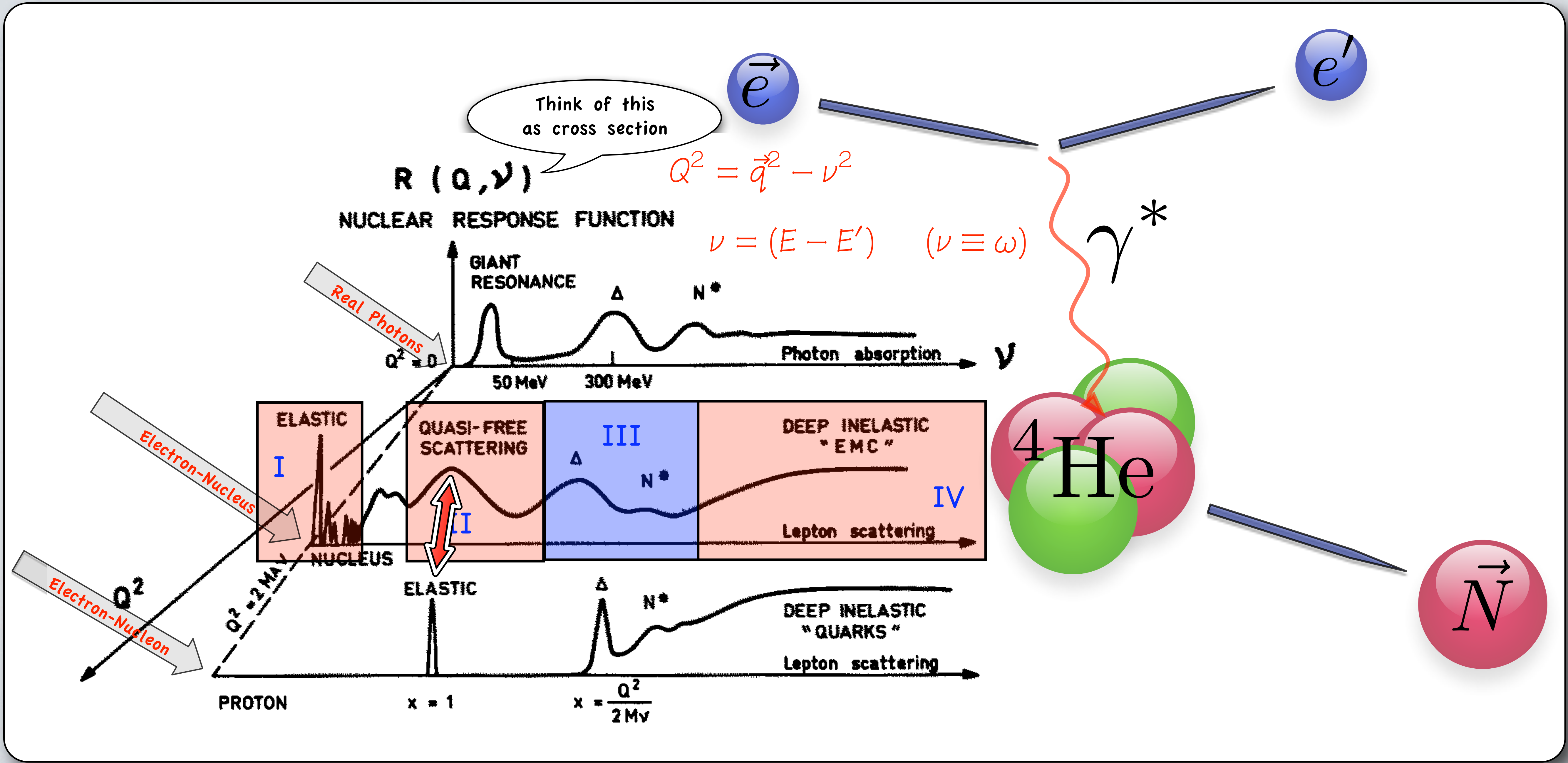
Theory

- 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).

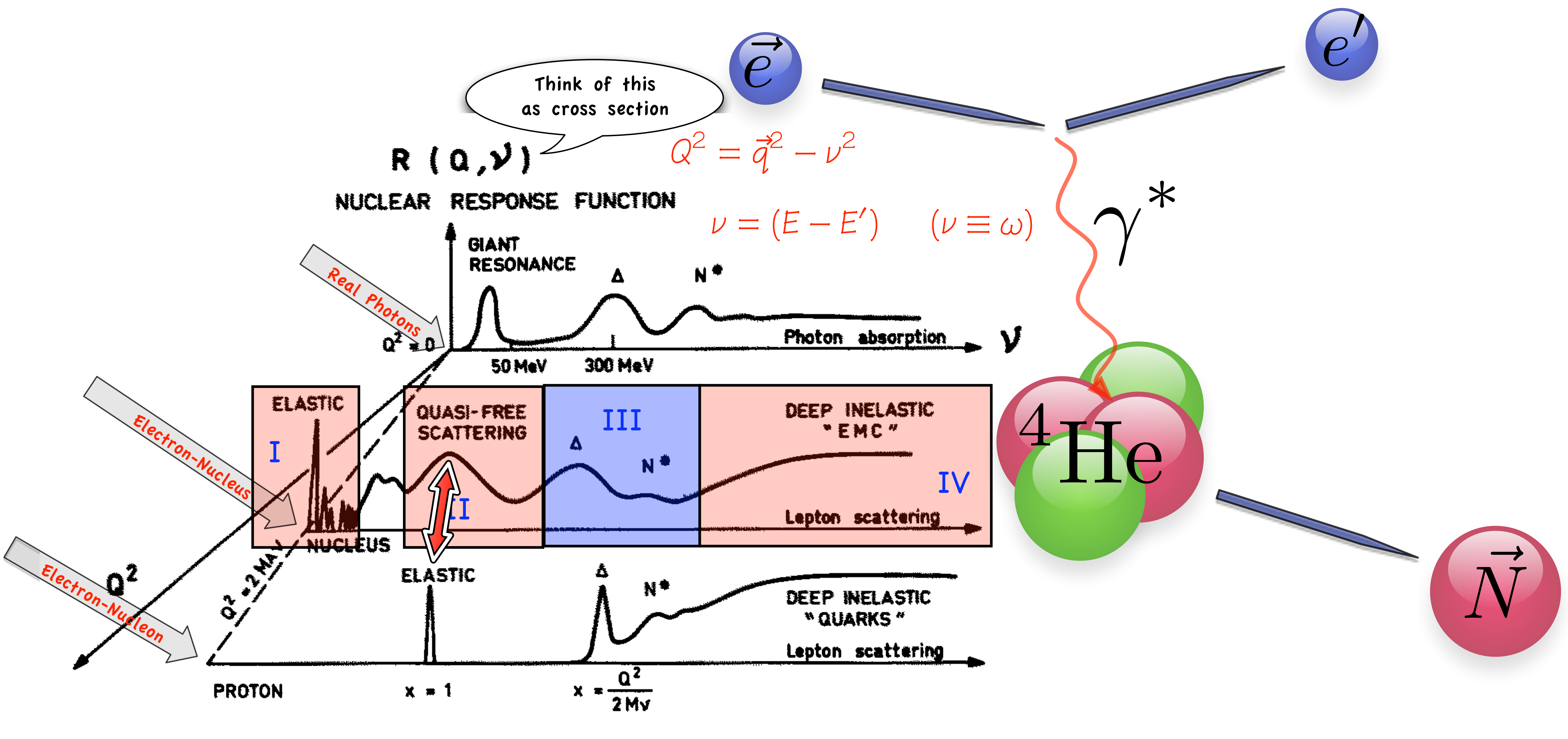


Quasi-Free Scattering

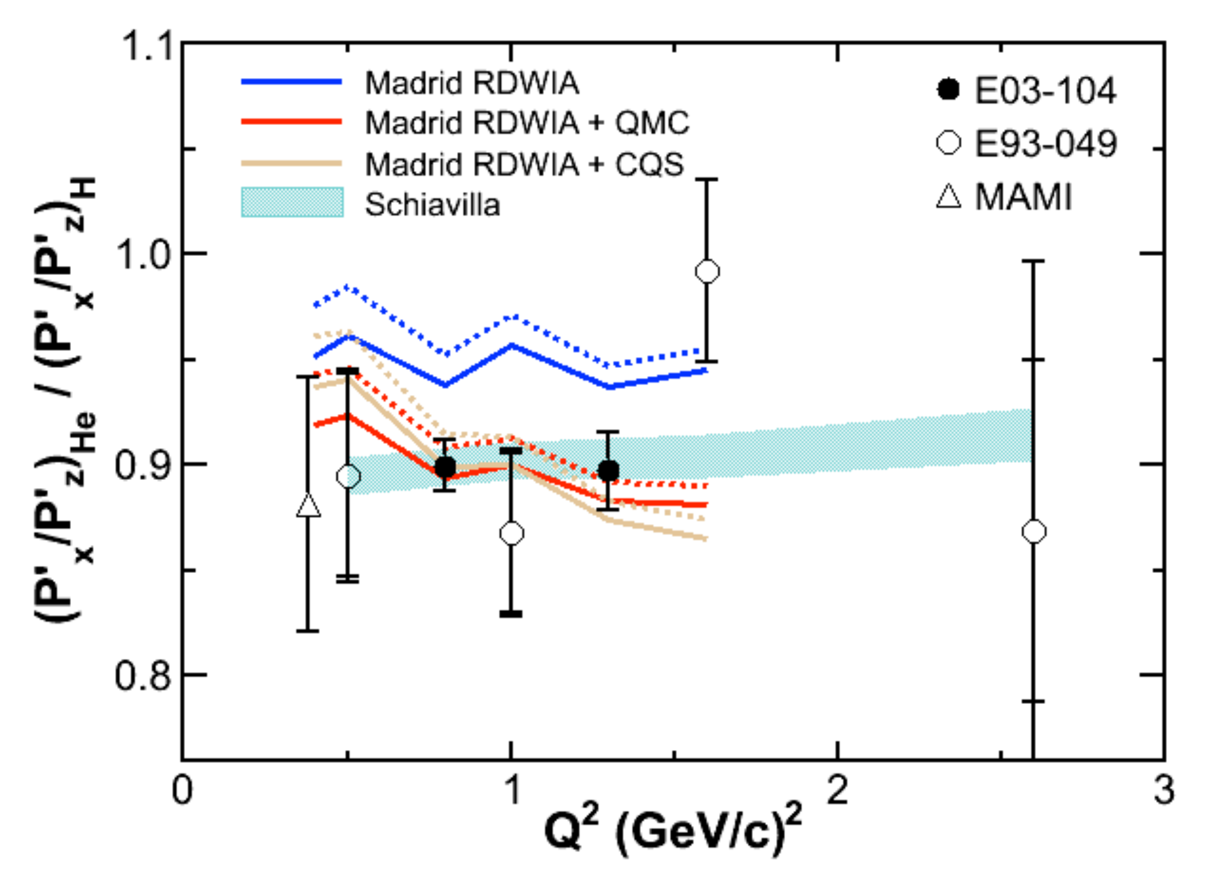
• Electron scatters off Nucleon in the nucleus

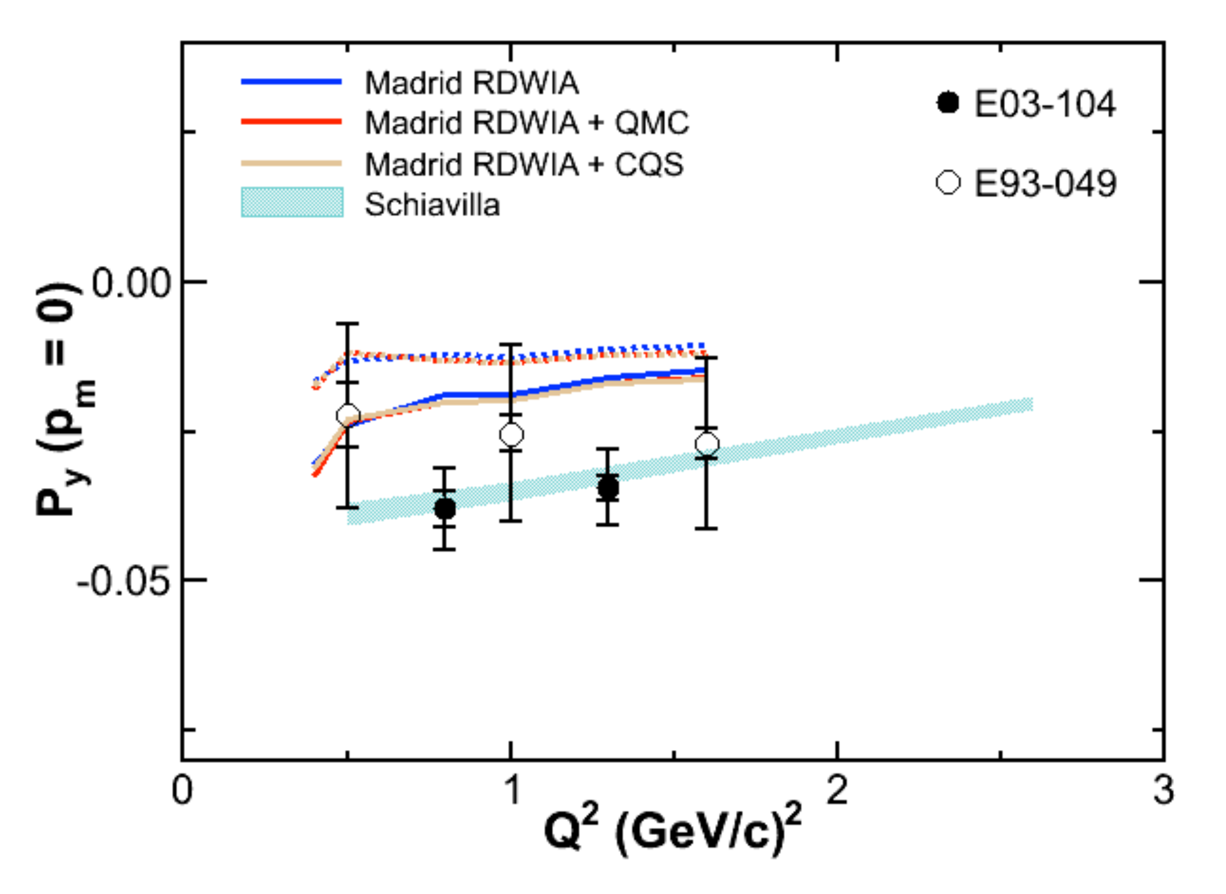
Effectively a "free" nucleon in the mean-field of the nucleus.

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



$^4He(\vec{e}, e'\vec{p})^3H$ Results





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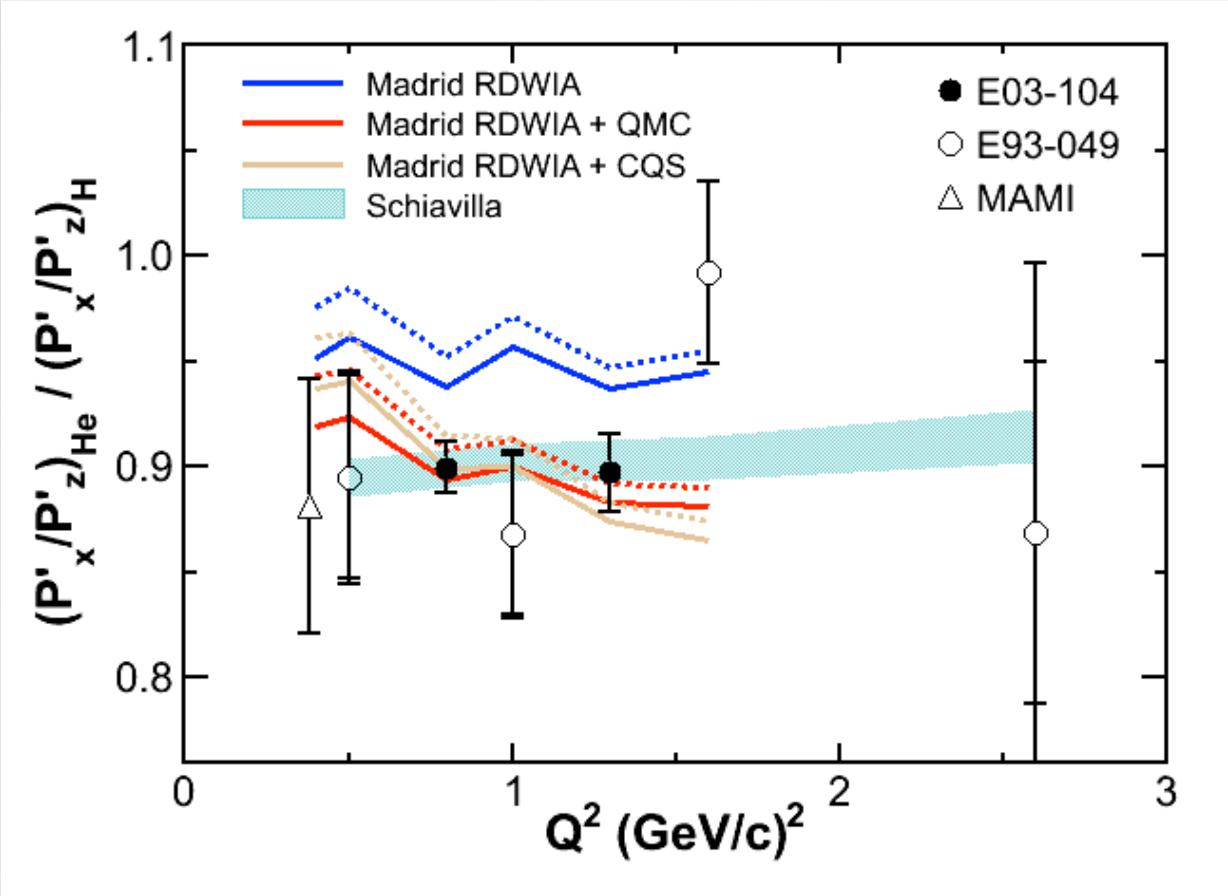
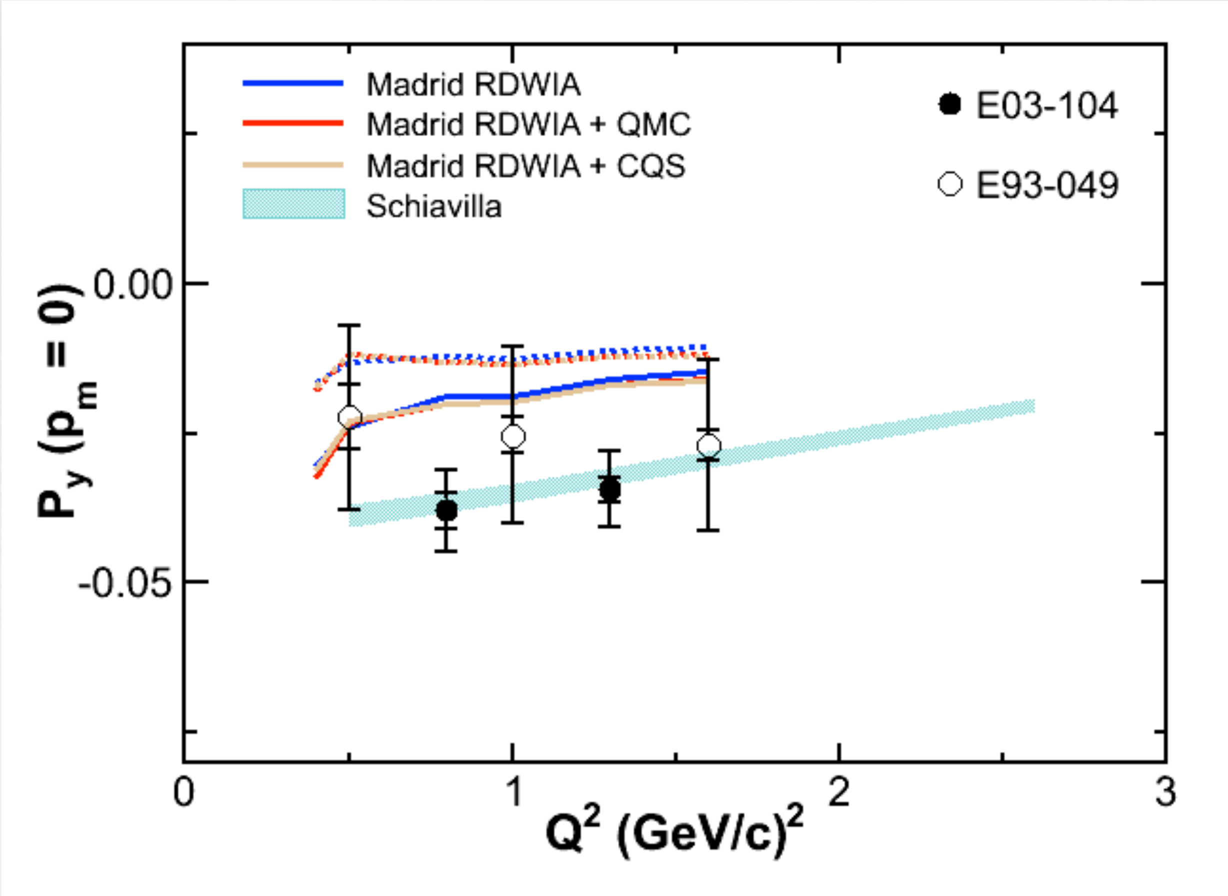
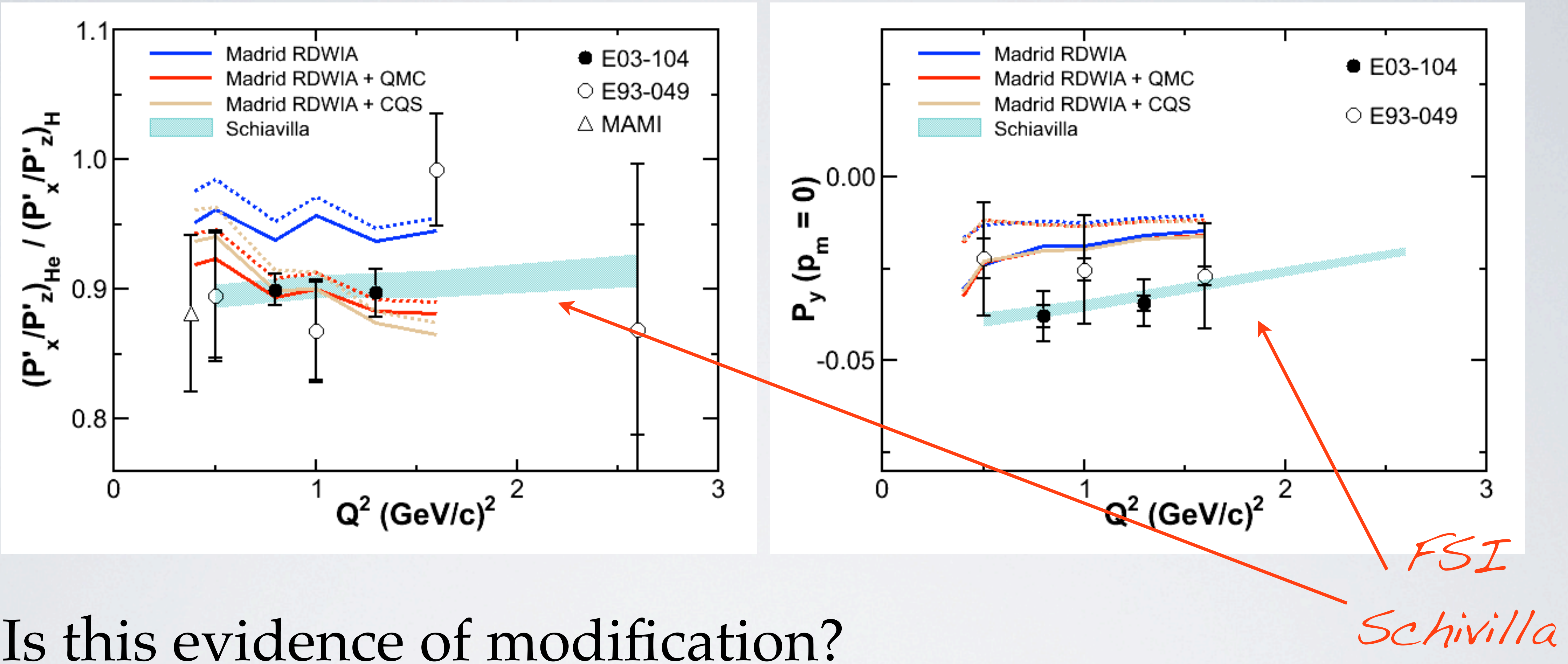




- Is this evidence of modification?

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



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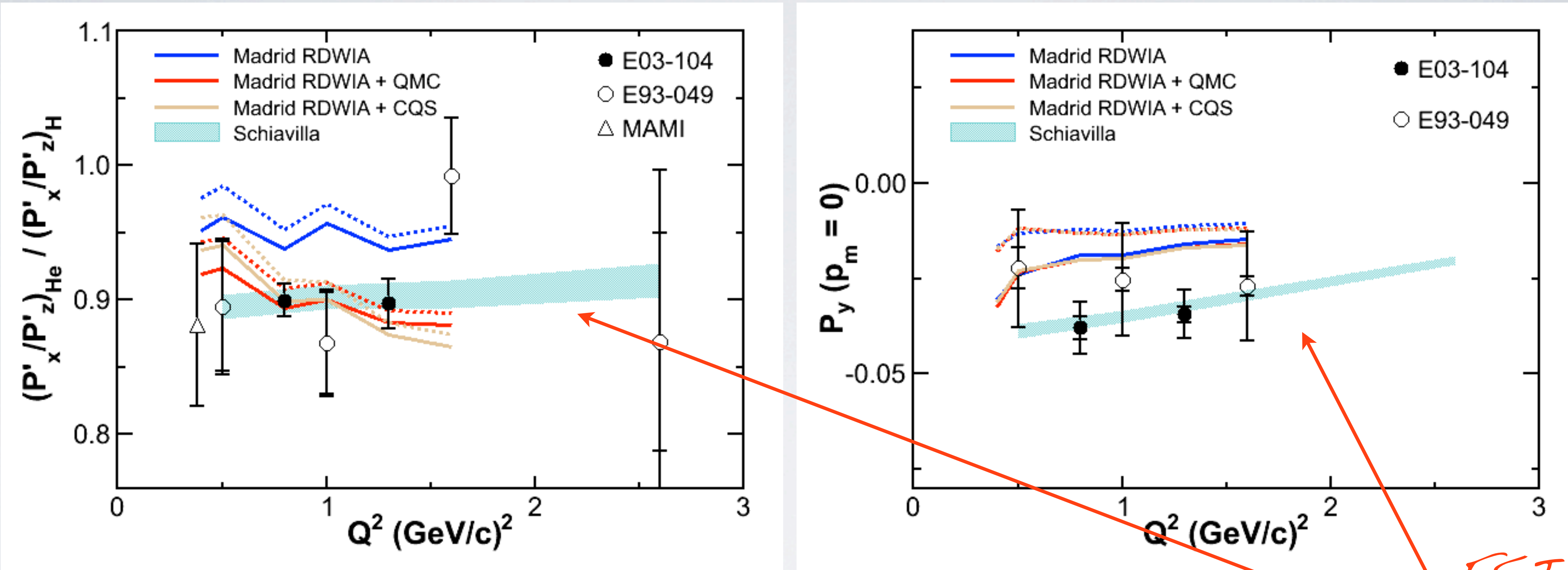

- Is this evidence of modification?
- FSI in this calculation not constrained by independent measurement! a proof of concept rather than a strong result.
- FSI constrained by P_y - independent (of electron scattering) data?

A Hand Waving Explanation

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:

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

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

Radius enters quadratically.

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

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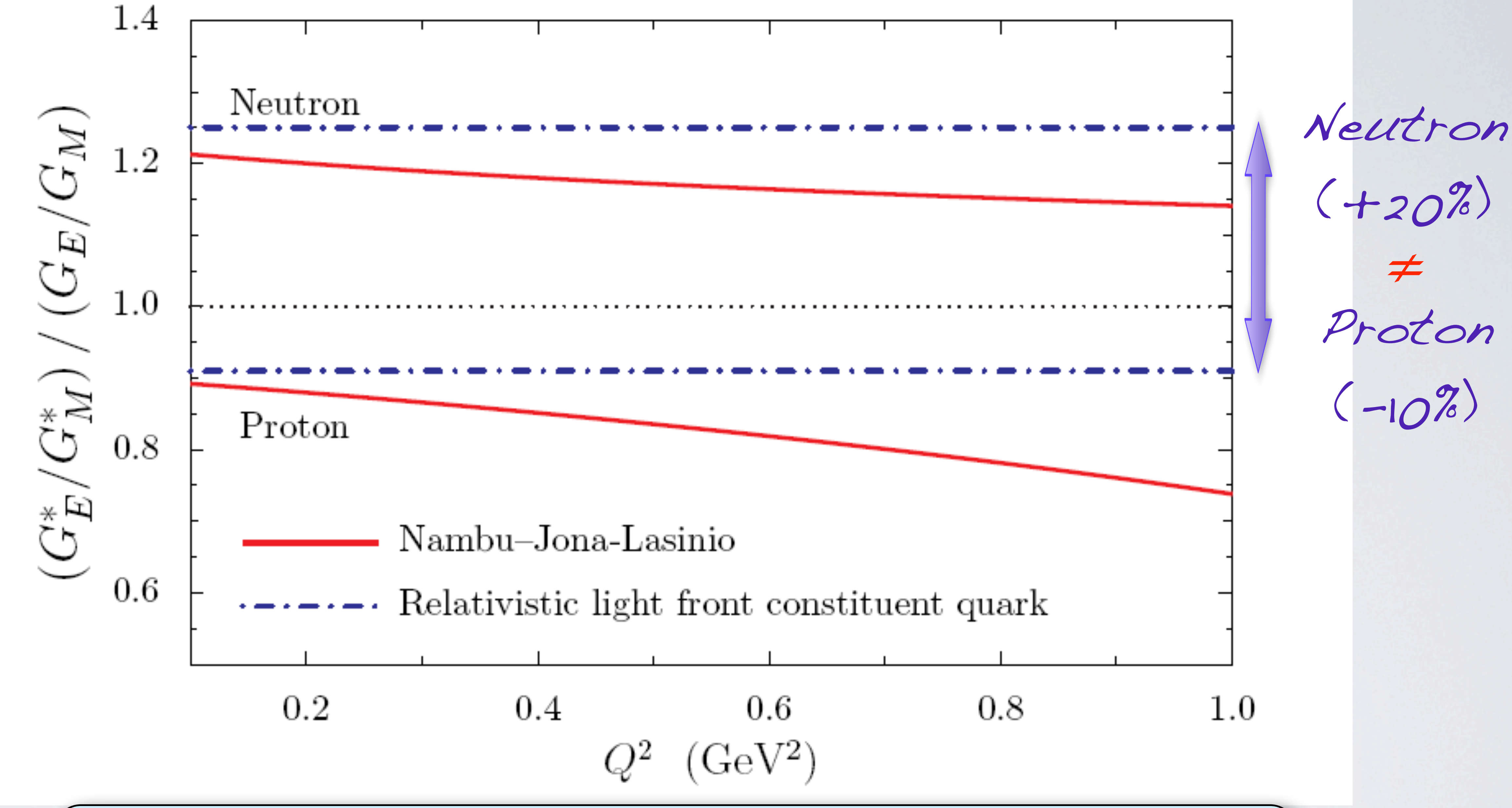
Is this just handwaving????

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!

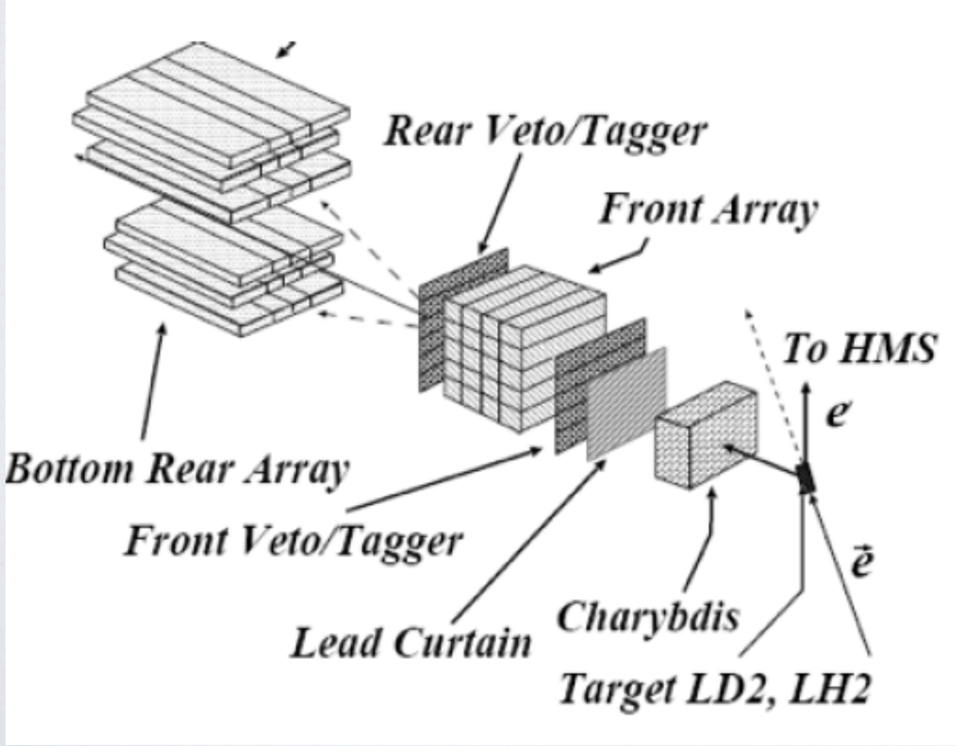
LOI-10-007

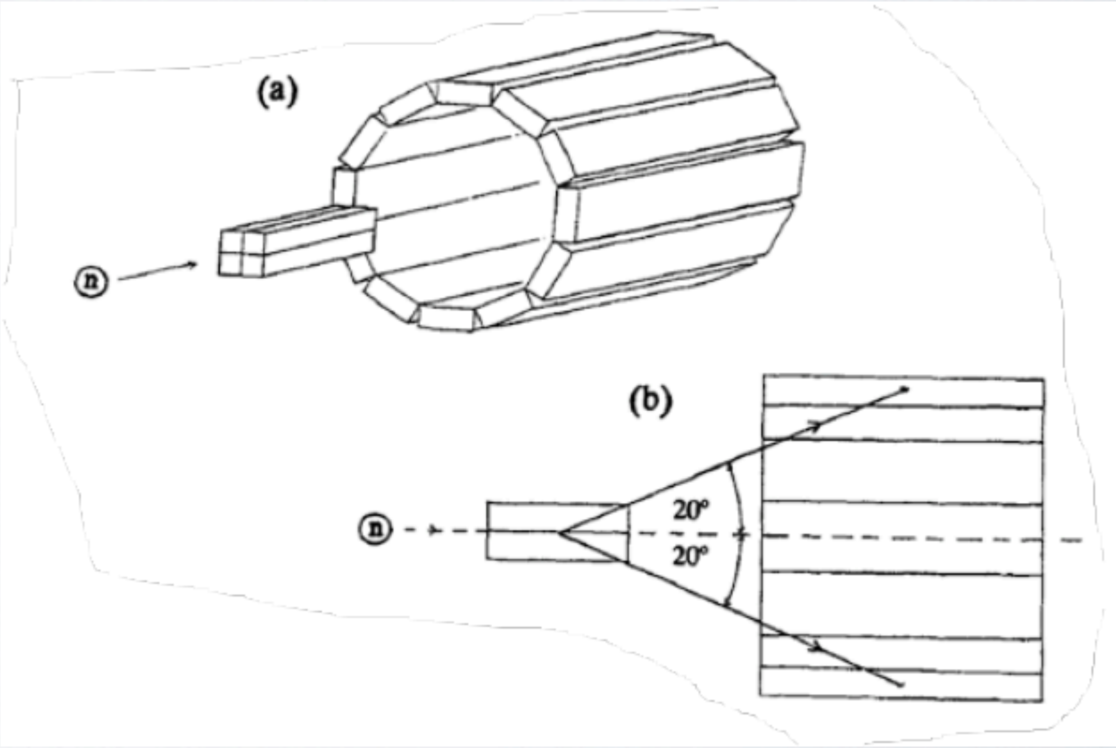
A New Proposed Experiment

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

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

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





LOI-10-007

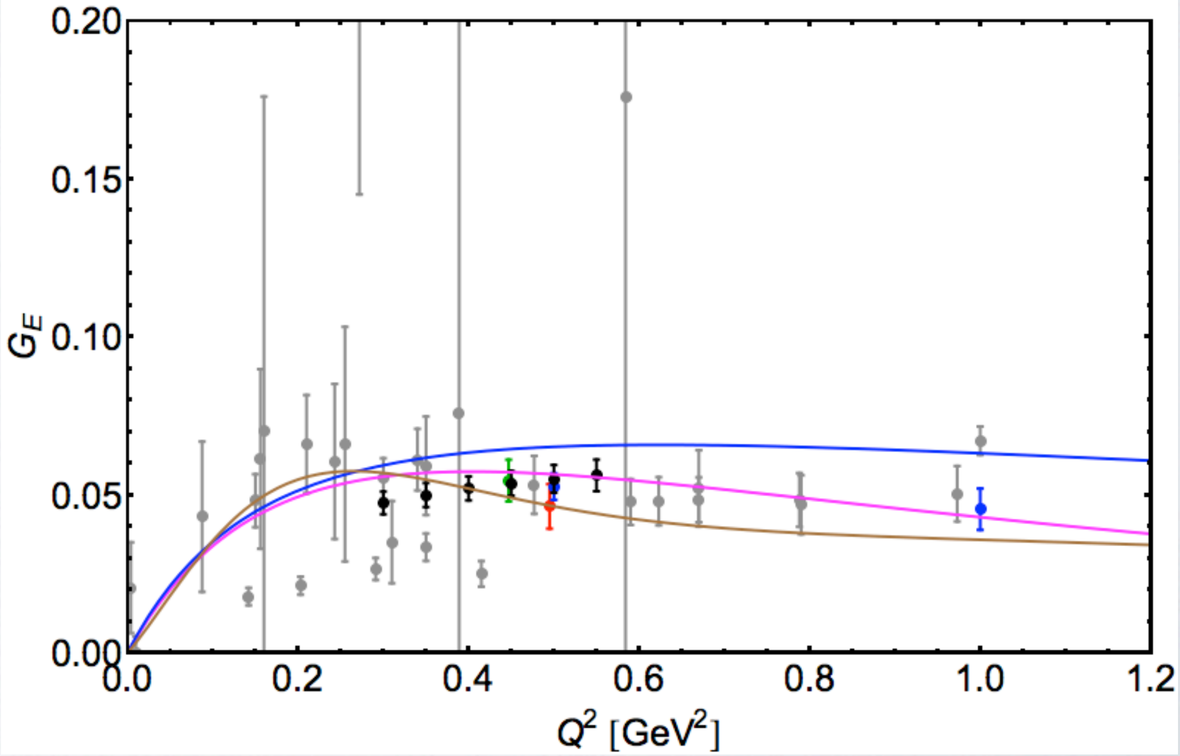
A New Proposed Experiment

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

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

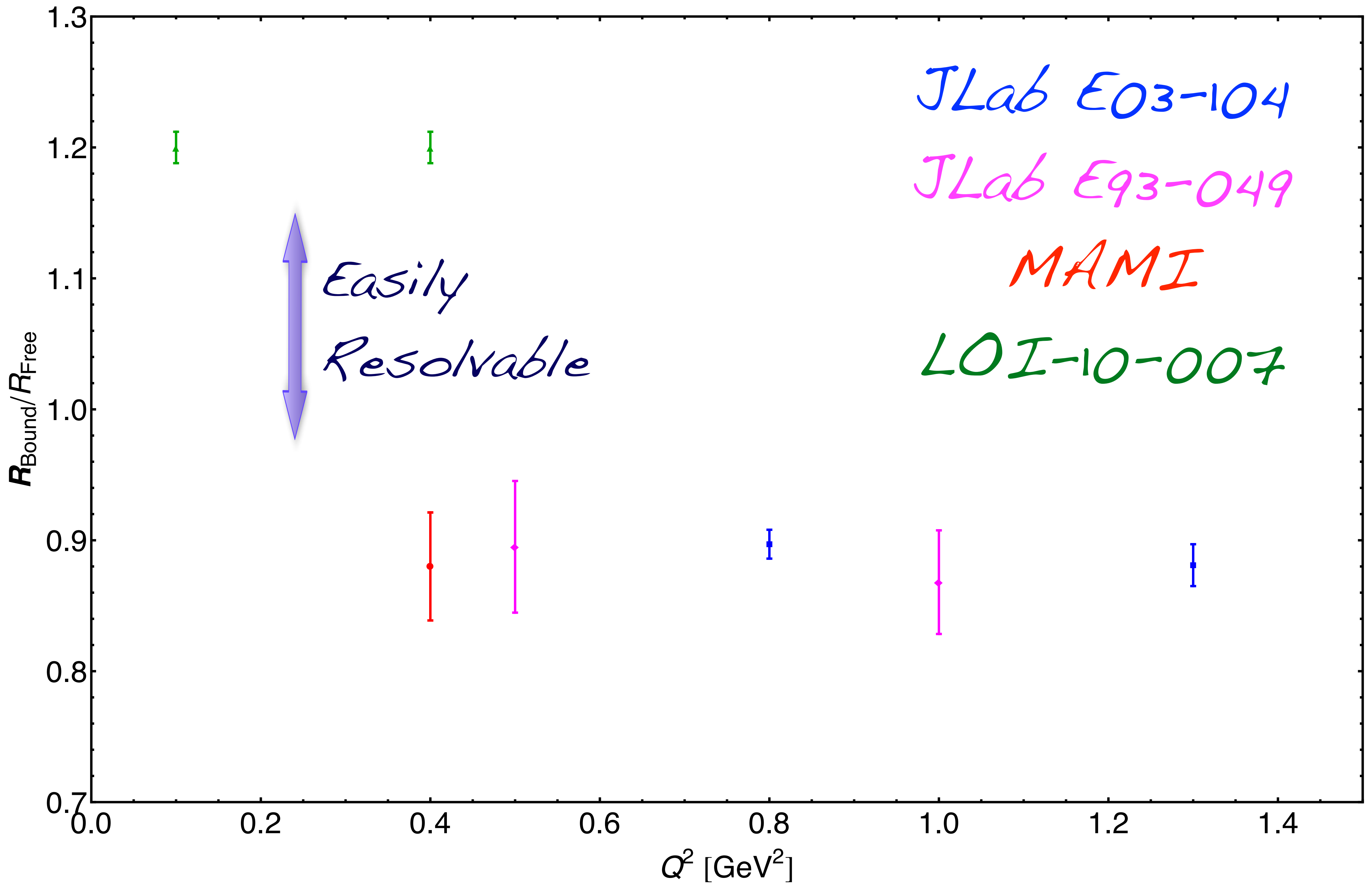
$$\left.\frac{dG_E^n(Q^2)}{dQ^2}\right|_{Q^2=0.4} = 0$$

- 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.



How Well Can we do This?

LOI-10-007 Projected



Summary

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

LOI-10-007 Approved by JLab PAC

Much work still ahead in the coming year - collaborators are very welcome

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

Either way - sometimes a poisonous and painful question.....

Take Home Messages

Even 90 years after the discovery of the proton we still find unanswered questions about the nucleons.

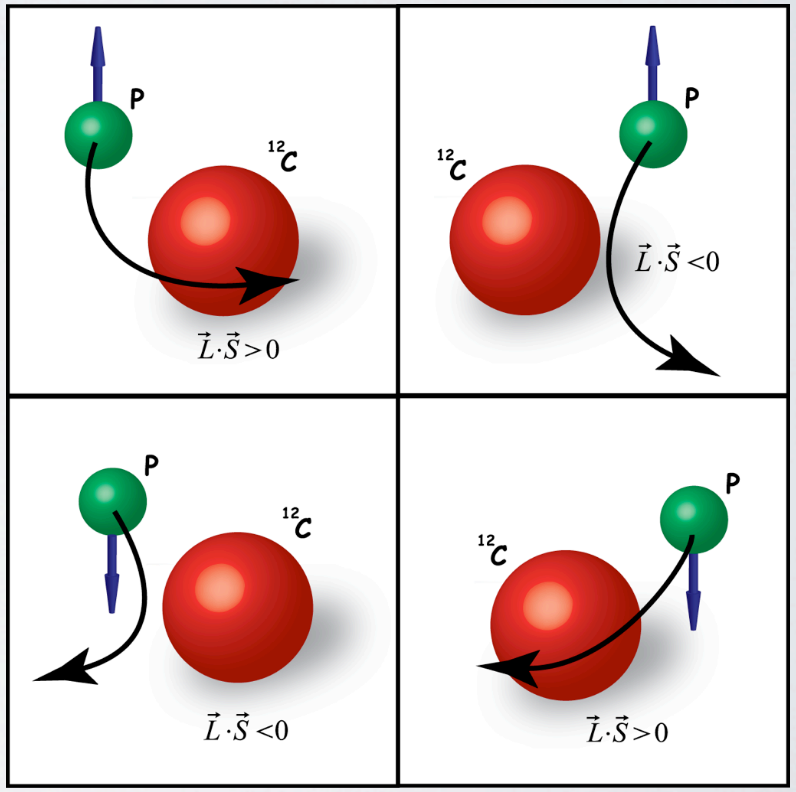
Nuclei are not simple collections of nucleons (at least not at low energy).

Simple nucleon and nuclear systems are a testing ground for QCD/Weak/EM interactions.

We have the capability to access small effects, even in the highly complex nuclear systems.

How to measure the polarization

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



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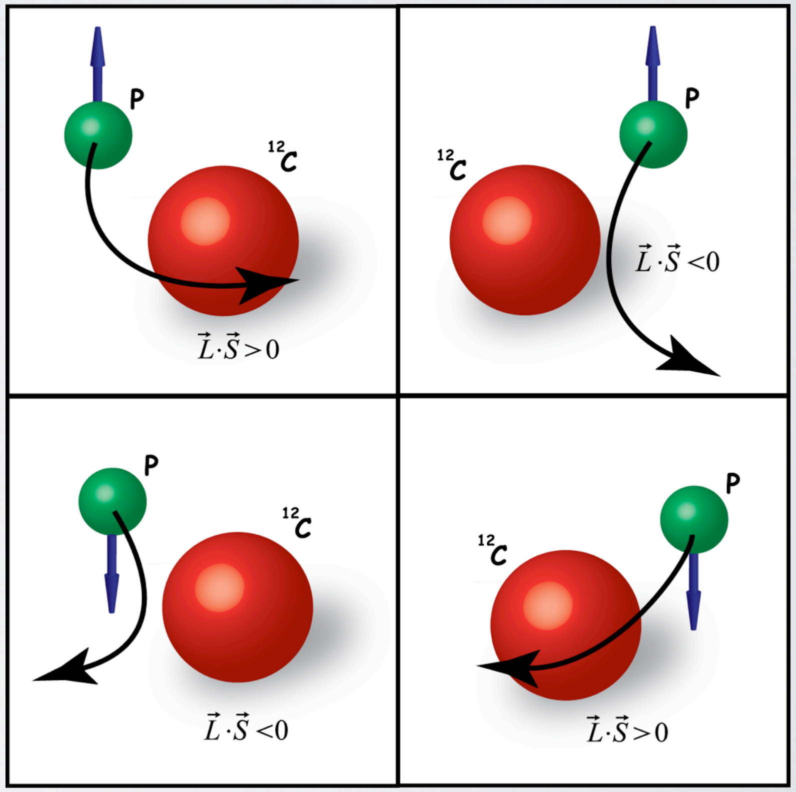

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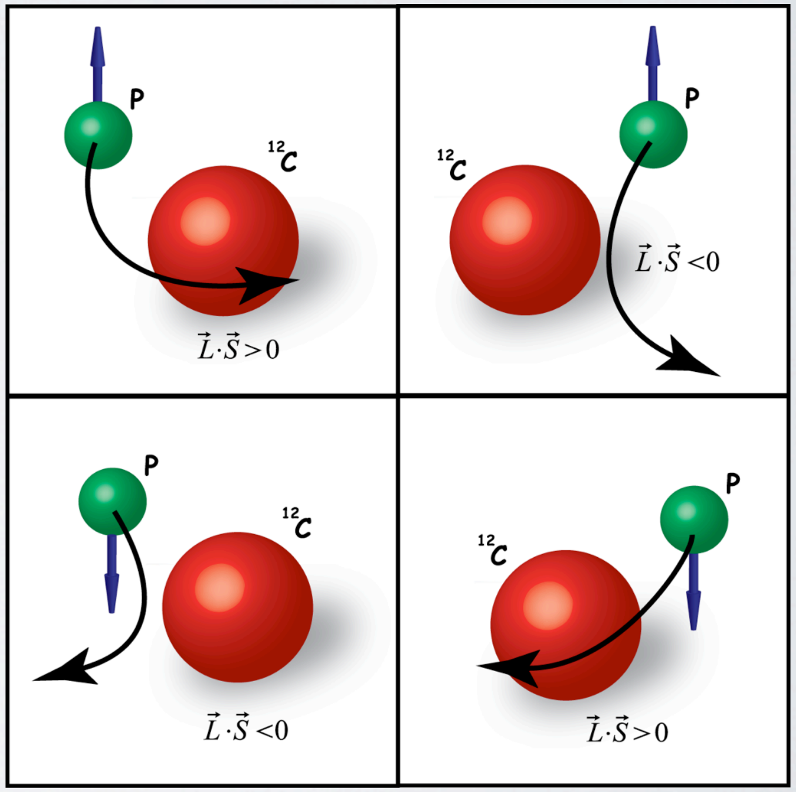

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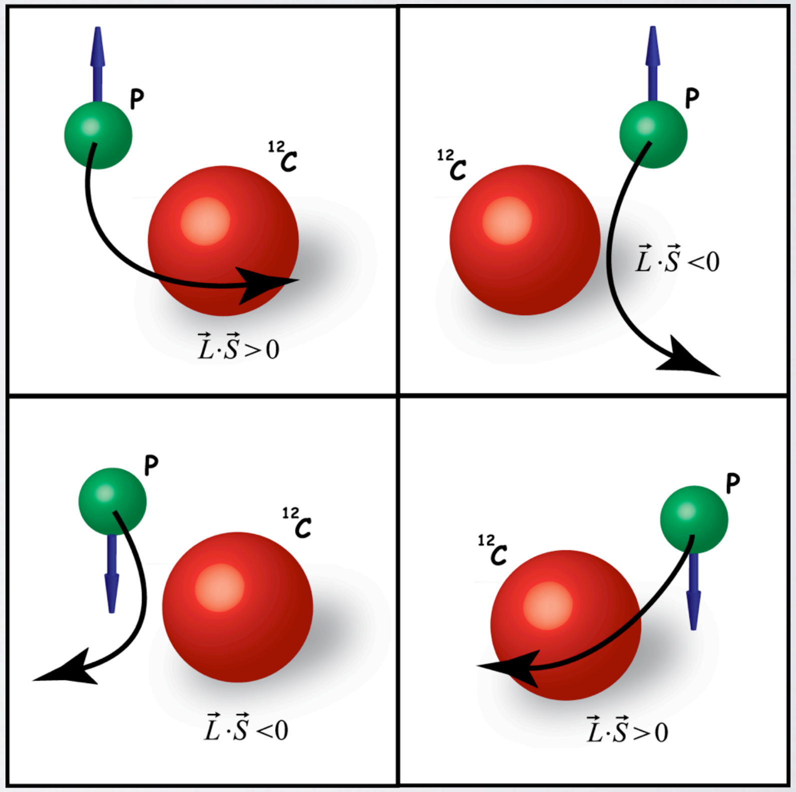


Systematic uncertainties cancel out (to ~0.5%)!

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

And the Experiment?

Experimental Requirements

- Hall A/C?

	Hall A	Hall C
Detectors	HRS + NPol	SHMS + NPol
Minimum θ_e (deg)	6 (with septa)	5.5 (SHMS)
Minimum Q^2 (GeV^2)	0.052	0.044

Q^2 (GeV^2)	E_{Beam} (GeV)	ΔM_{miss} (MeV)	T_n (MeV)	$\lvert\vec{q}\rvert$ (MeV)	θ_n (deg)	θ_e (deg)
0.1	2.2	1.7	53.2	320.6	76.3	8.3
0.4	6.6	3.2	212.8	667.3	68.6	5.58

LOI Kinematics

Both Halls OK but:

- Shielding requirements?
- Scheduling issues.

Beam time request:
950h (physics) for 1% statistical uncertainty in the super-ratio.

And the Experiment?

Experimental Requirements

- Hall A/C?
- Beam polarization stability/measurement.

- Requirements trivial compared to requirements for parity experiments - a non-issue.

And the Experiment?

Experimental Requirements

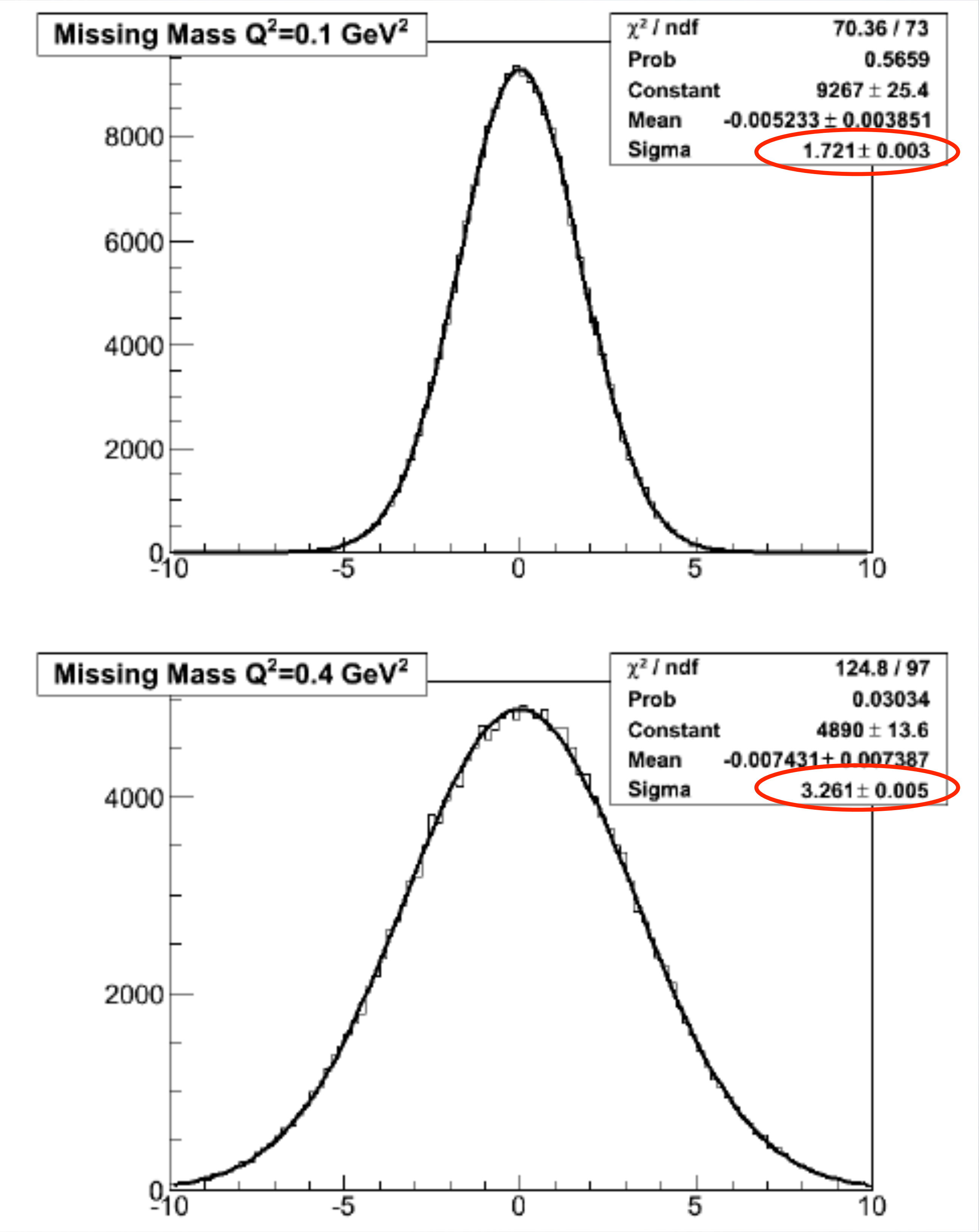
- Hall A/C?
- Beam polarization stability.
- Final state determination.

^{3}He has no bound states.

Binding energy ~7.7 MeV.

Final state determination possible (better at low Q^2).

Missing momentum resolution - under investigation.



And the Experiment?

Experimental Requirements

- Hall A/C?
- Beam polarization stability.
- Final state determination.
- Induced polarization measurement.

P_y measurement crucial for disentangling FSI effects.

Current NPol designs (G^n_E) do not include facility to measure induced polarization (left/right asymmetry).

We are exploring several options to modify the existing design or use a new polarimeter design.

And the Experiment?

Experimental Requirements

- Hall A/C?
- Beam polarization stability.
- Final state determination.
- Induced polarization measurement.
- False asymmetry measurement.

eP elastic? ($P_y = 0$)

Detector rotation?