האוניברסיטה העברית בירושלים
The Hebrew University of Jerusalem

The proton form factors at low Q^2

new results and future measurements

Guy Ron
Hebrew University of Jerusalem

Short Range Correlations in Nuclei and Hard QCD Phenomena, Trento
Nov 16, 2011

The proton form factors at low Q^2

new results and future measurements

Coffee break 10:45 – 11:15

11:15 Daniele Treleani

"Collisions of protons with light nuclei shed new light on nucleon structure"

11:40 Guy Ron

"The proton form factors at low Q^2 - new results and future measurements"

Sho

LUNCH BREAK 12:45 – 2:00

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INTERNATIONAL WORKSHOP
on
SHORT RANGE CORRELATIONS IN NUCLEI AND HARD QCD PHENOMENA
ECT*, Trento, November 14-18, 2011
DRAFT of the PROGRAM

(talks 25’ + 10’ discussion)

Coffee break 10:45 – 11:15

11:15 Daniele Treleani

"Collisions of protons with light nuclei shed new light on nucleon structure"

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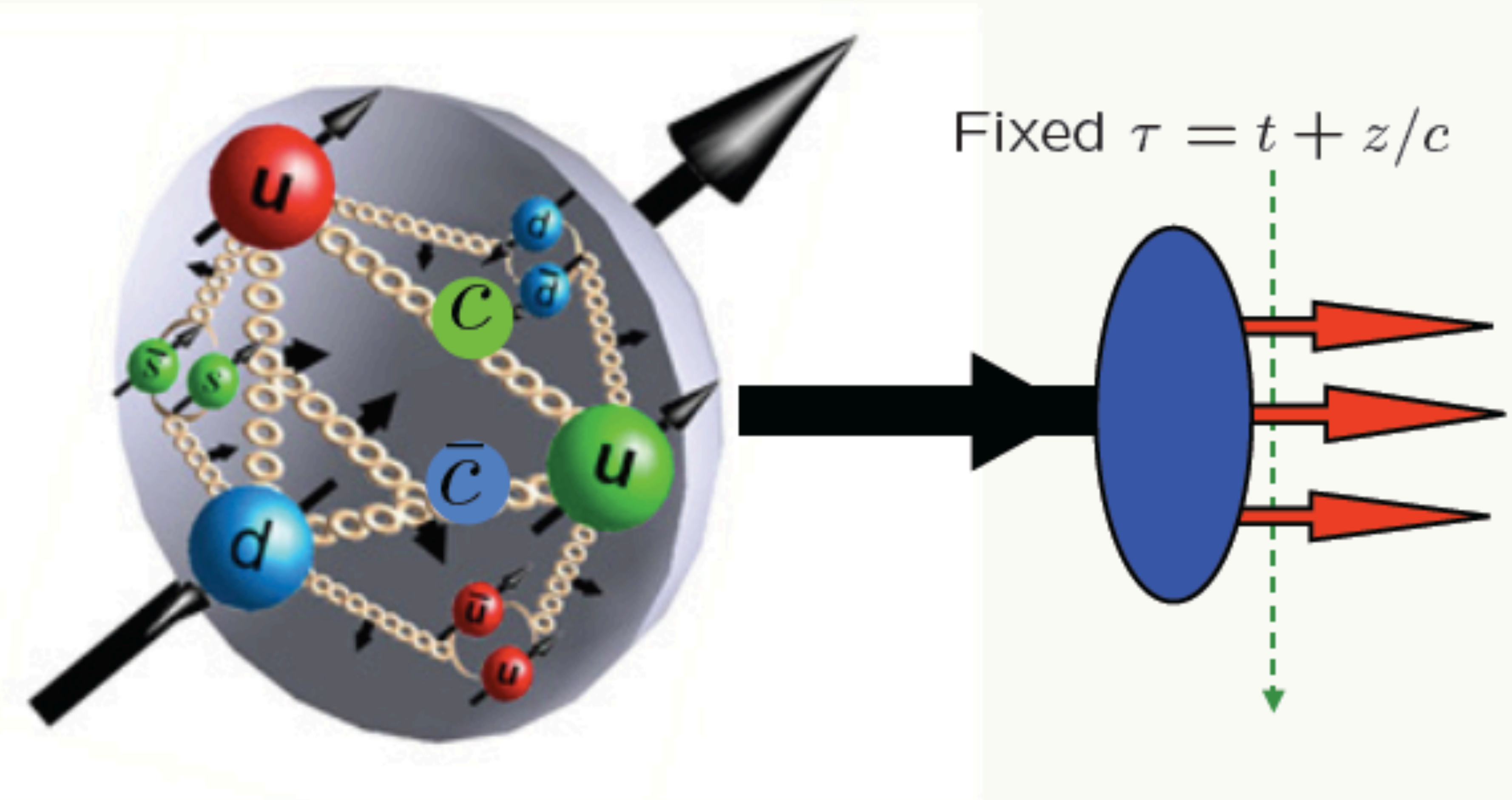
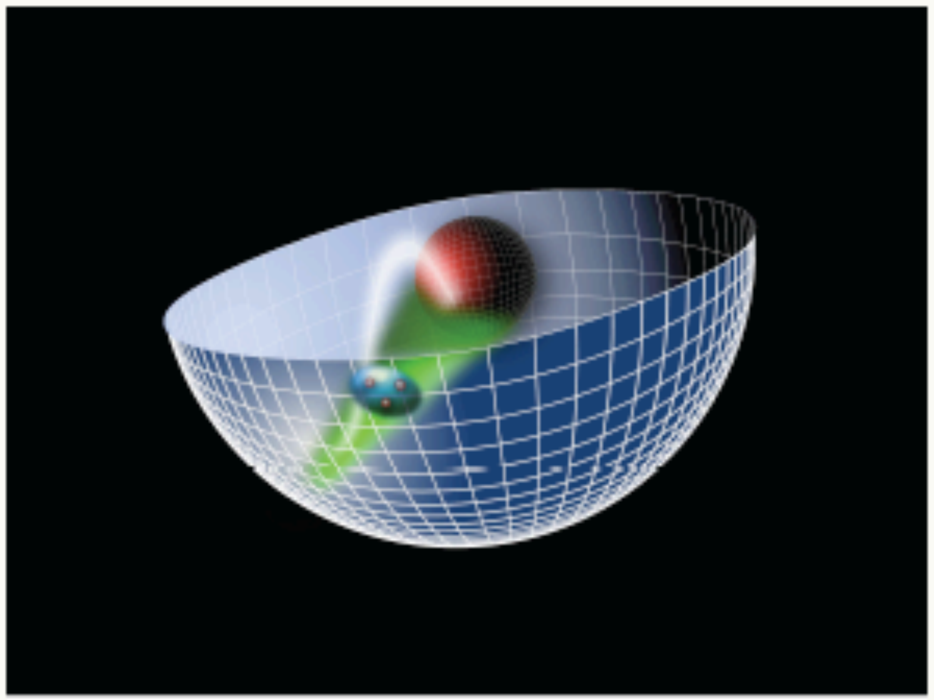
Sho

LUNCH BREAK 12:45 – 2:00

Light-Front Holography and Novel QCD Phenomena





Light-Cone 2011 *Applications of light-cone coordinates to highly relativistic systems*

I·L·C·A·C

Stan Brodsky

SLAC NATIONAL ACCELERATOR LABORATORY

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OUTLINE

- Nucleon Structure 101.
- Measuring the nucleon Form Factors.
- Experimental Results.
- Impacts.

Nucleon Structure

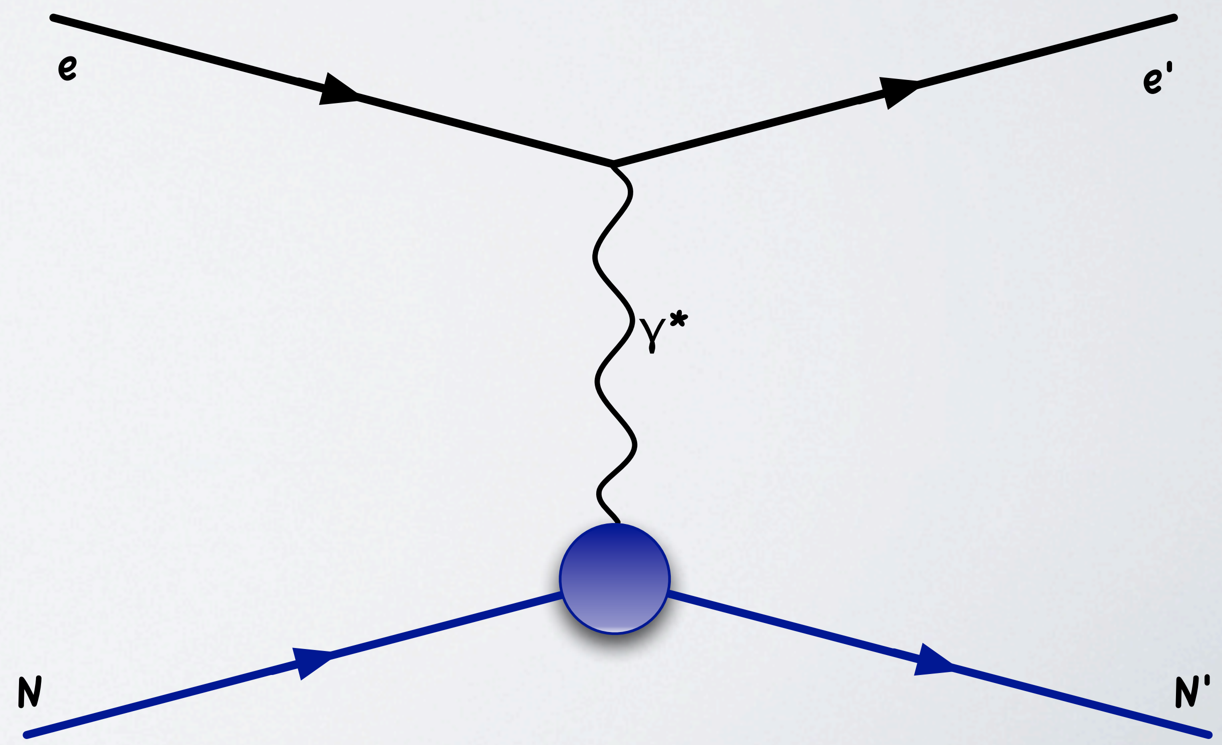
- Nucleons are spin-1/2 particles.
- But measured magnetic moment is $\mu_p \sim 2.793\mu_N$ $\mu_n \sim -1.91\mu_N$
- Nucleons are not pointlike (also known from Deep Inelastic Scattering).
- Complex internal structure generated by interactions between pointlike (dressed?) constituents (quarks/partons).
- Even more complex behavior comes from virtual constituents ("sea" quarks, gluons).

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

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



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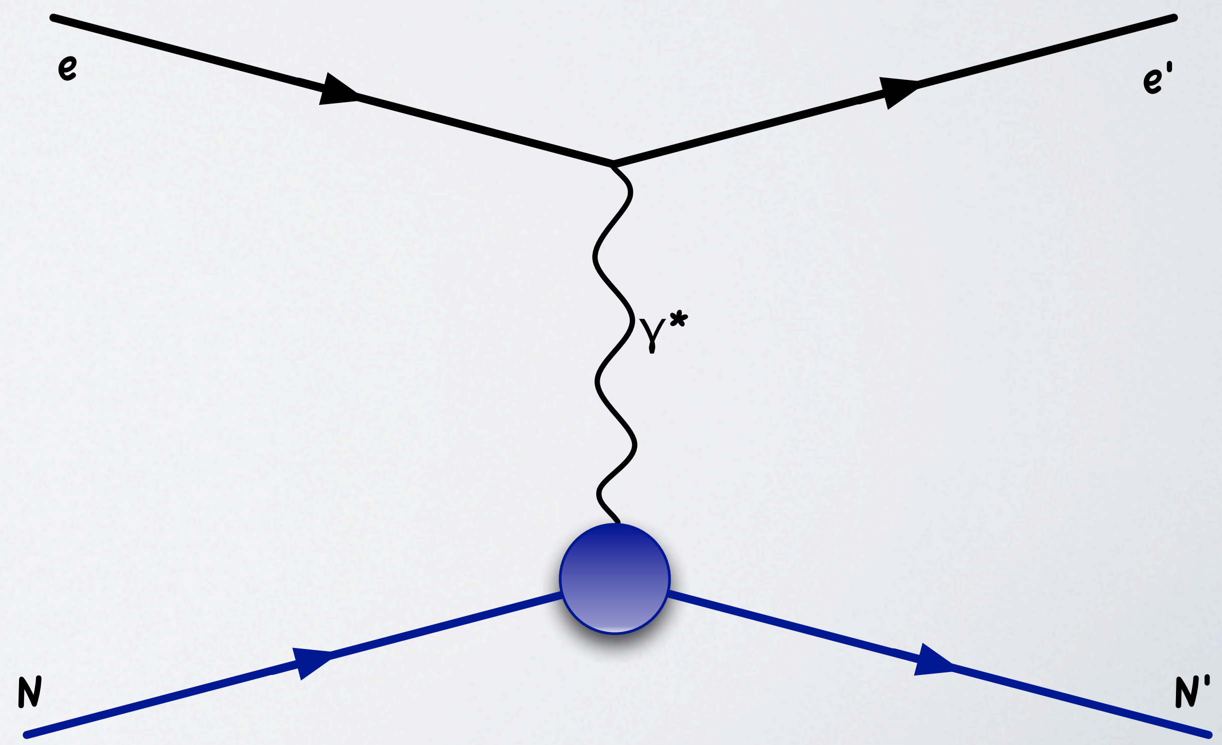
Rutherford - Point-Like

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

Mott - Spin-1/2

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



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Mott - Spin-1/2

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

Rosenbluth - Spin-1/2 with Structure

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

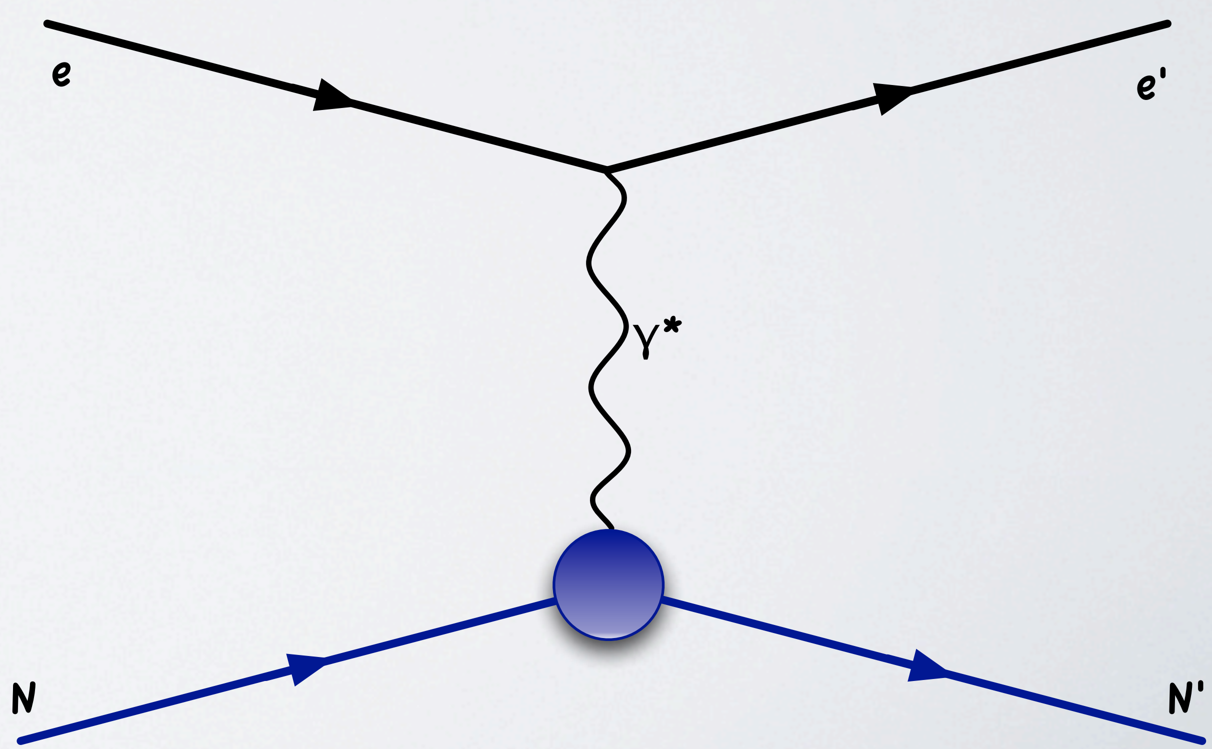
$$G_E^p(0) = 1 \qquad G_E^n(0) = 0$$

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

Sometimes written using:

$$G_E = F_1 - \tau F_2$$

$$G_M = F1 + F_2$$



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

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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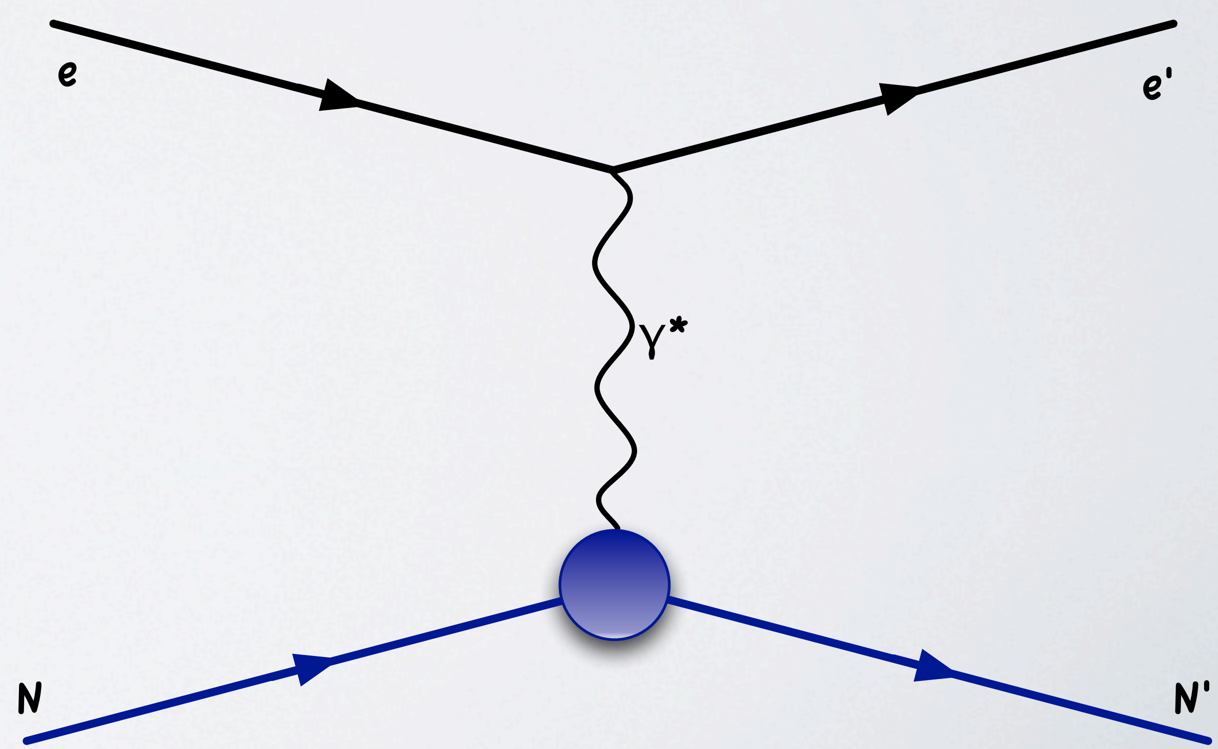

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IN THE BREIT FRAME....

It can be shown that...

The Hadronic Current

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

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

Explicitly

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

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

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

THE NAIVE INTERPRETATION

$$G_E(Q^2) = \int \rho_{Ch}(\vec{r}) e^{i\vec{q}\cdot\vec{r}} d^3r$$

$$\sim \int \rho_{Ch}(\vec{r}) d^3r - \frac{q^2}{6} \int \rho_{Ch}(\vec{r}) \vec{r}^2 d^3r + \cdots$$

$$\sim Ch - \frac{q^2}{6} \left\langle r^2 \right\rangle_{Ch} + \cdots$$

$$G_M(Q^2) = \int \rho(\vec{r})_M e^{i\vec{q}\cdot\vec{r}} d^3r$$

$$\sim \mu - \frac{q^2}{6} \left\langle r^2 \right\rangle_M + \cdots$$

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

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 picture transition.
- EM structure expected to change in the nuclear medium.

Measurement Techniques

Rosenbluth Separation

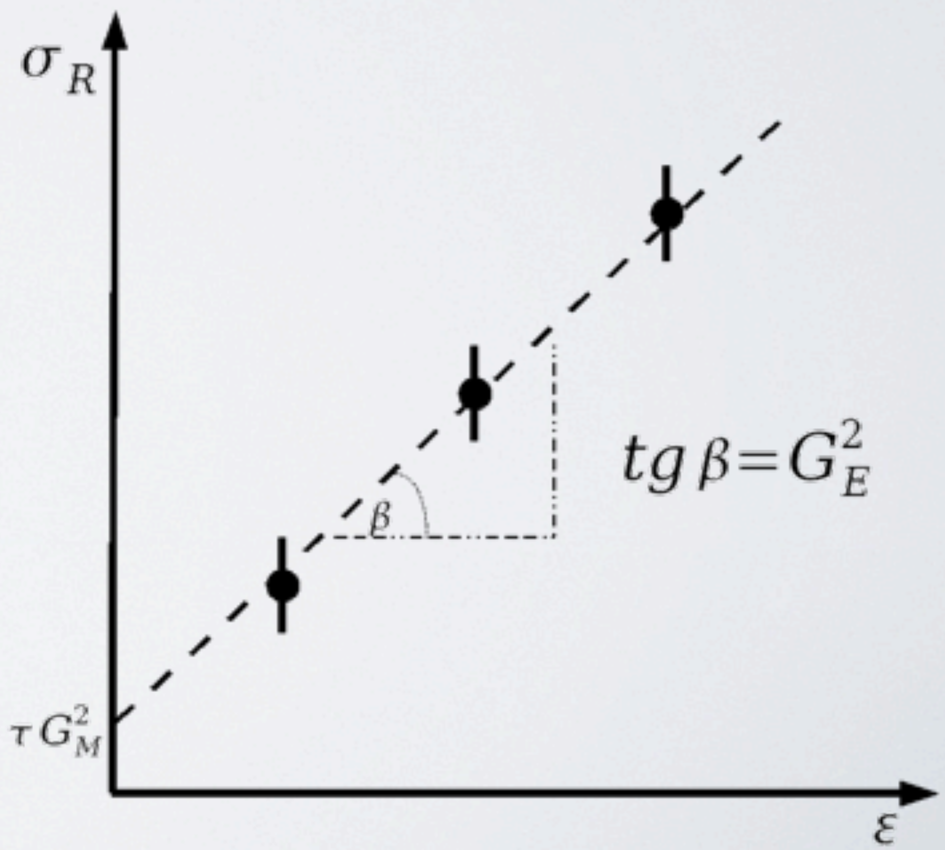
$$\sigma_R = (d\sigma/d\Omega)/(d\sigma/d\Omega)_{\text{Mott}} = \tau G_M^2 + \varepsilon G_E^2$$

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

- Linear fit to get intercept and slope.

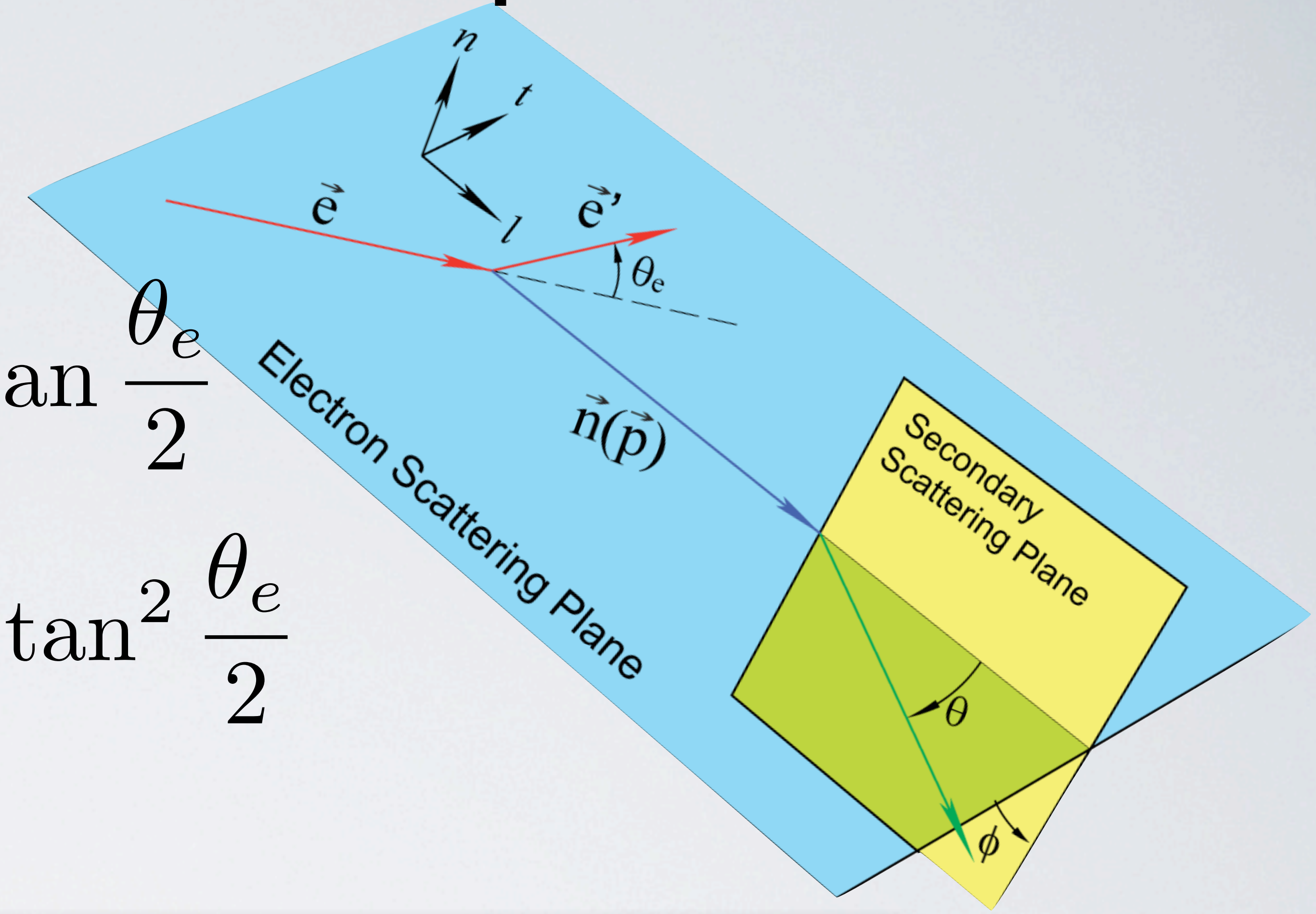
- But... G_M suppressed for low Q^2 (and G_E for high).

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



Measurement Techniques

Recoil Polarization



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

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

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

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

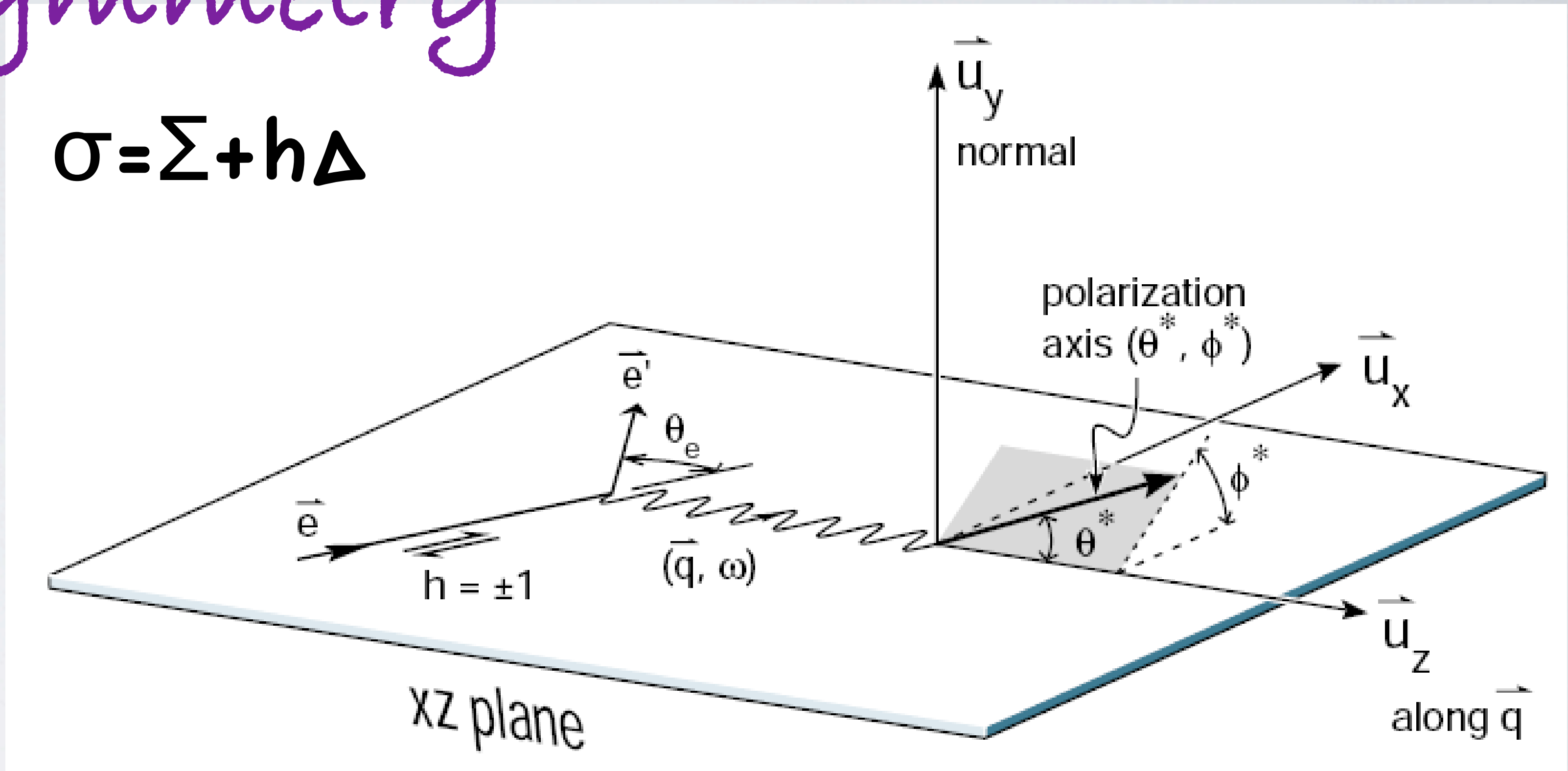
- A single measurement gives ratio of form factors.
- Interference of "small" and "large" terms allow measurement at practically all values of Q^2.

Measurement Techniques

Beam-Target Asymmetry

Polarized Cross Section: σ=Σ+hΔ

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

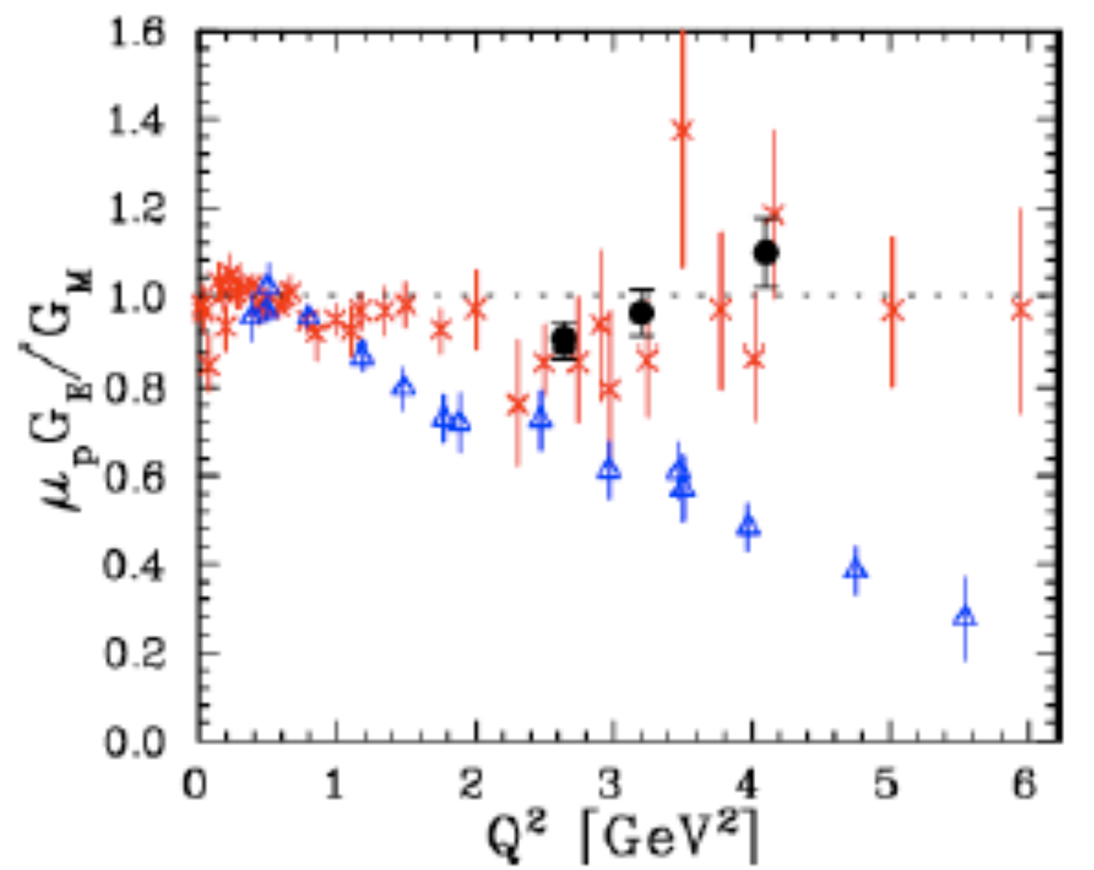


$$\mathcal{A} = f P_b P_t \frac{\overbrace{a\, cos\theta^* G_M^2}^{A_T} + \overbrace{b\, sin\theta^*\ cos\phi^* G_E G_M}^{A_{LT}}}{c G_M^2 + d G_E^2}$$

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 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?*

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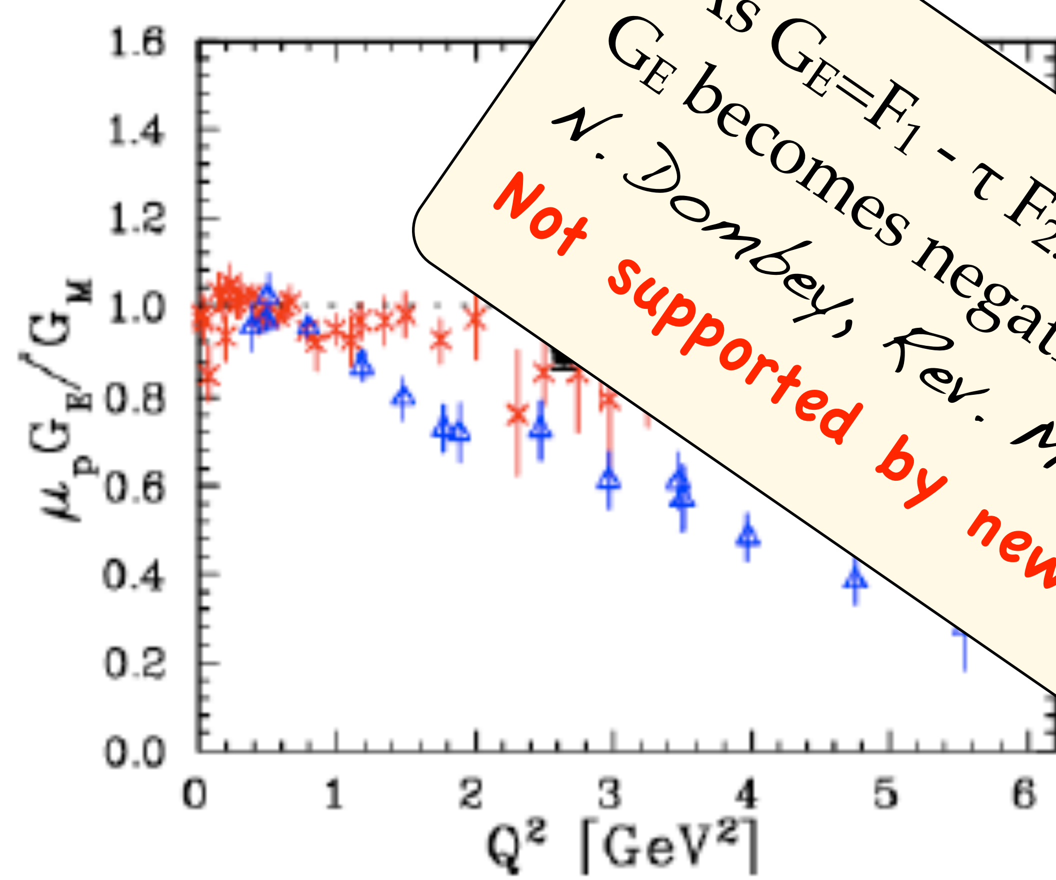


I. Qattan *et al.*, Phys. Rev. Lett. **94**, 142301 (2005).

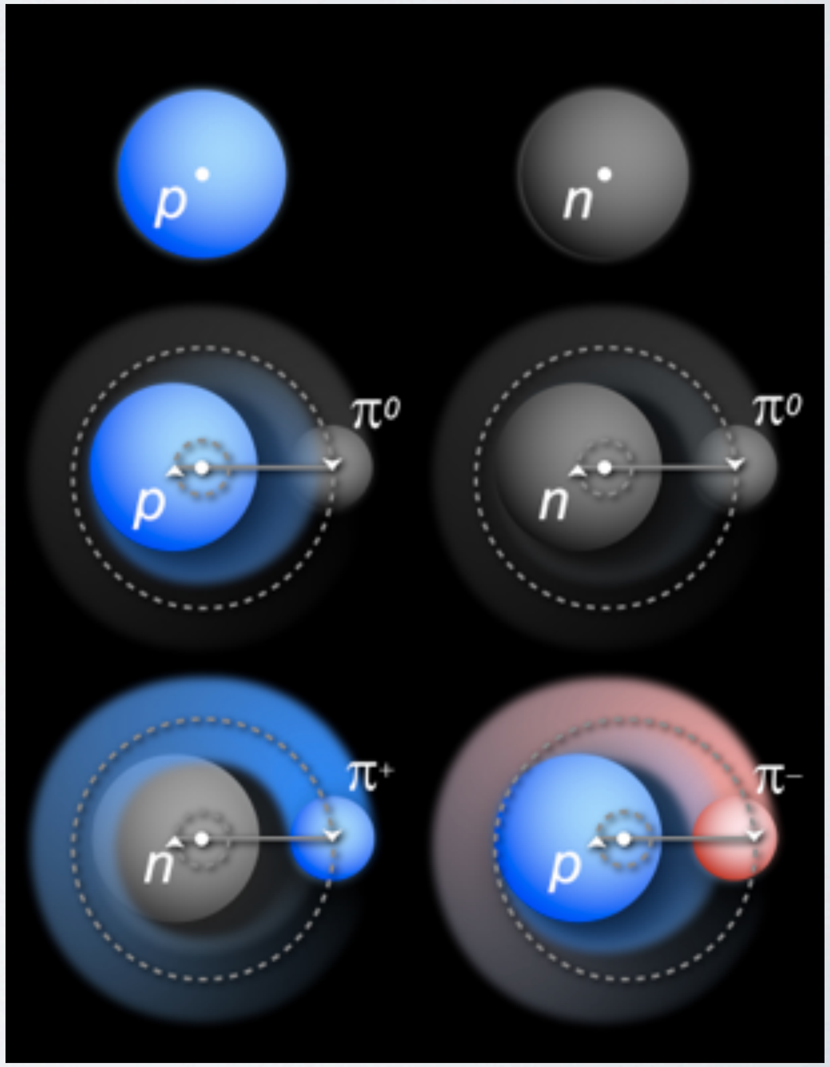
"As $G_E = F_1 - \tau F_2$, it is a priori quite likely that G_E becomes negative for large values of k^2" - N. Dombey, Rev. Mod. Phys. 41, 1 (1969). -

Not supported by new results.

- 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,...).

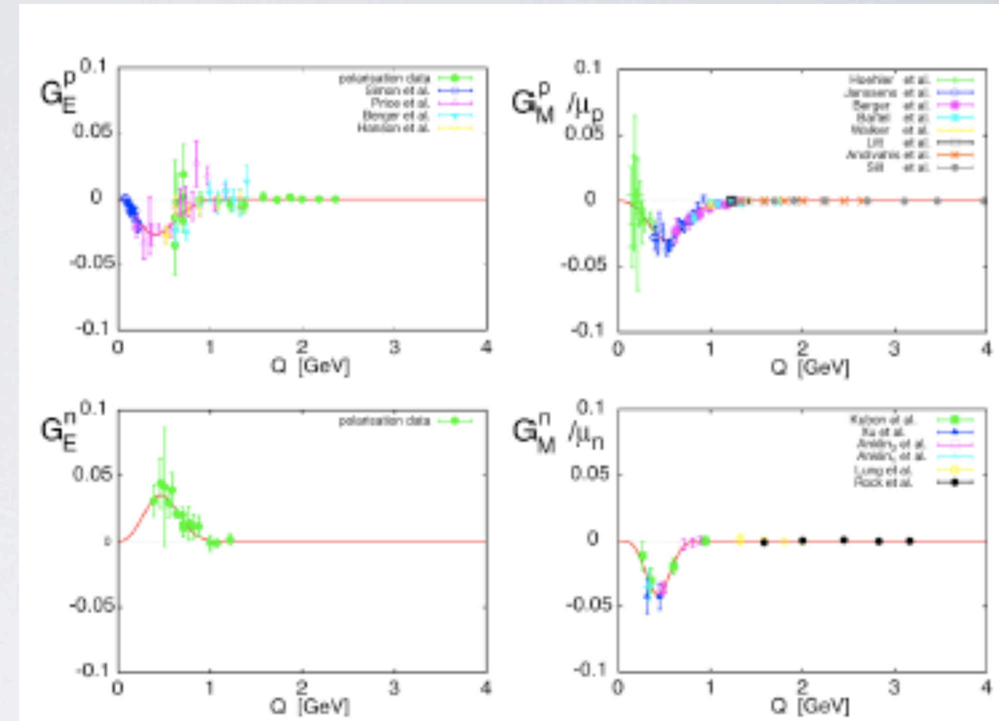


Low Q^2 Notable Results

Friedrich & Walcher analysis

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

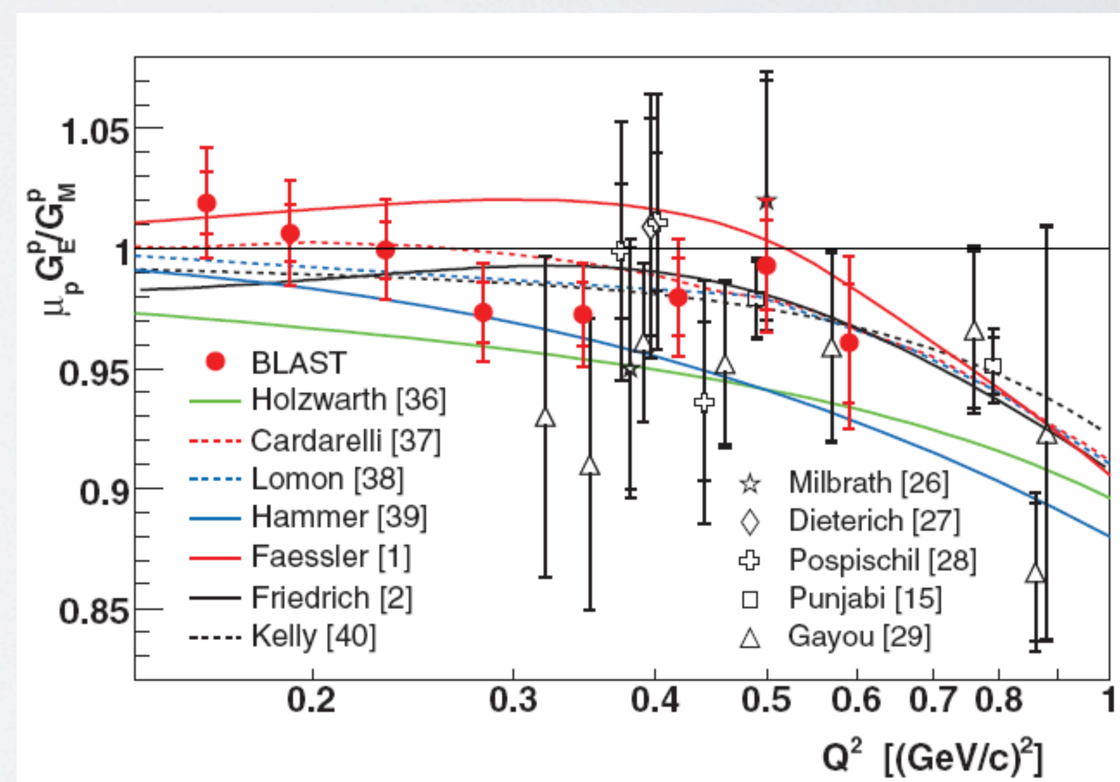
- Bump/dip (+2 dipoles) structure in all 4 form factors.
- Possibly interpreted as effects of a virtual meson cloud.



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.



The JLab low Q^2 program
Proton FFs

- LEDEX - Single arm proton measurement
  - 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
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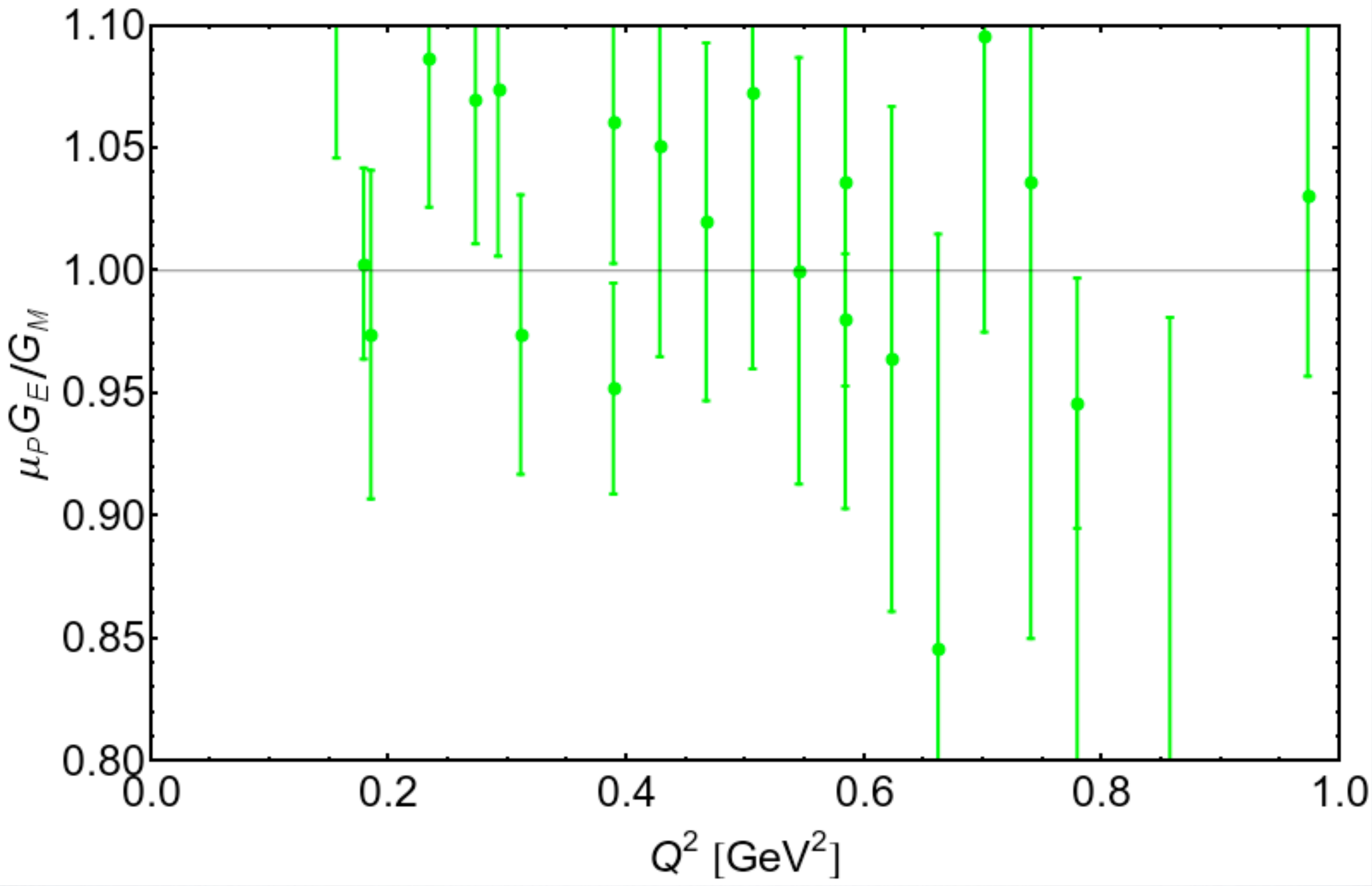
  - 8 Q^2 data points (0.25 - 0.5 GeV^2) with ~ 1.5% uncertainty on best data points.
  - Led to the proposal of:
- E08-007 - Two arm experiment (proton + tagged electron for bck suppression)
  - A dedicated 2 part experiment to map the proton FF ratio at low Q^2.
  - First part used recoil polarization 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

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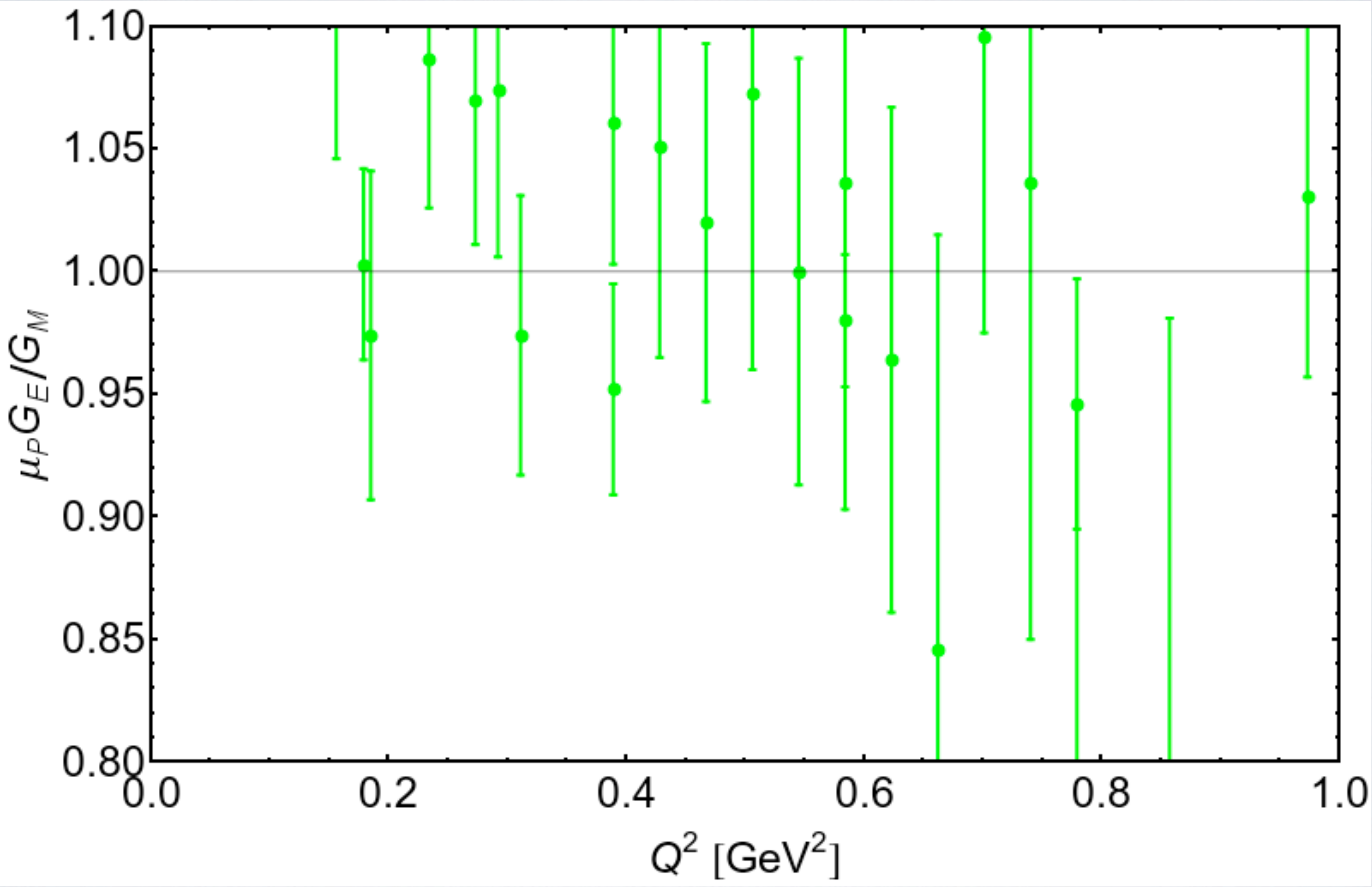
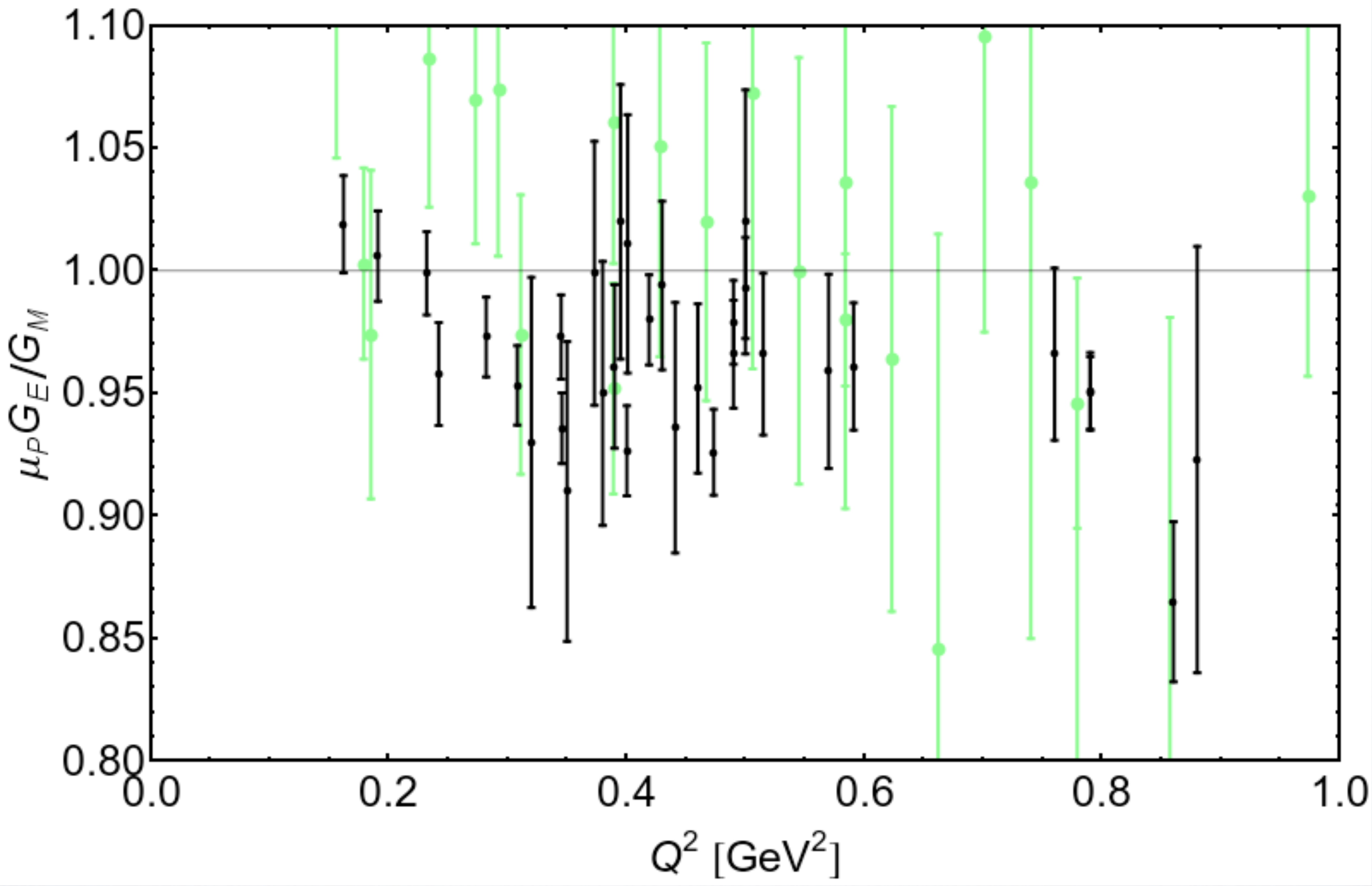


A Sense of Scale

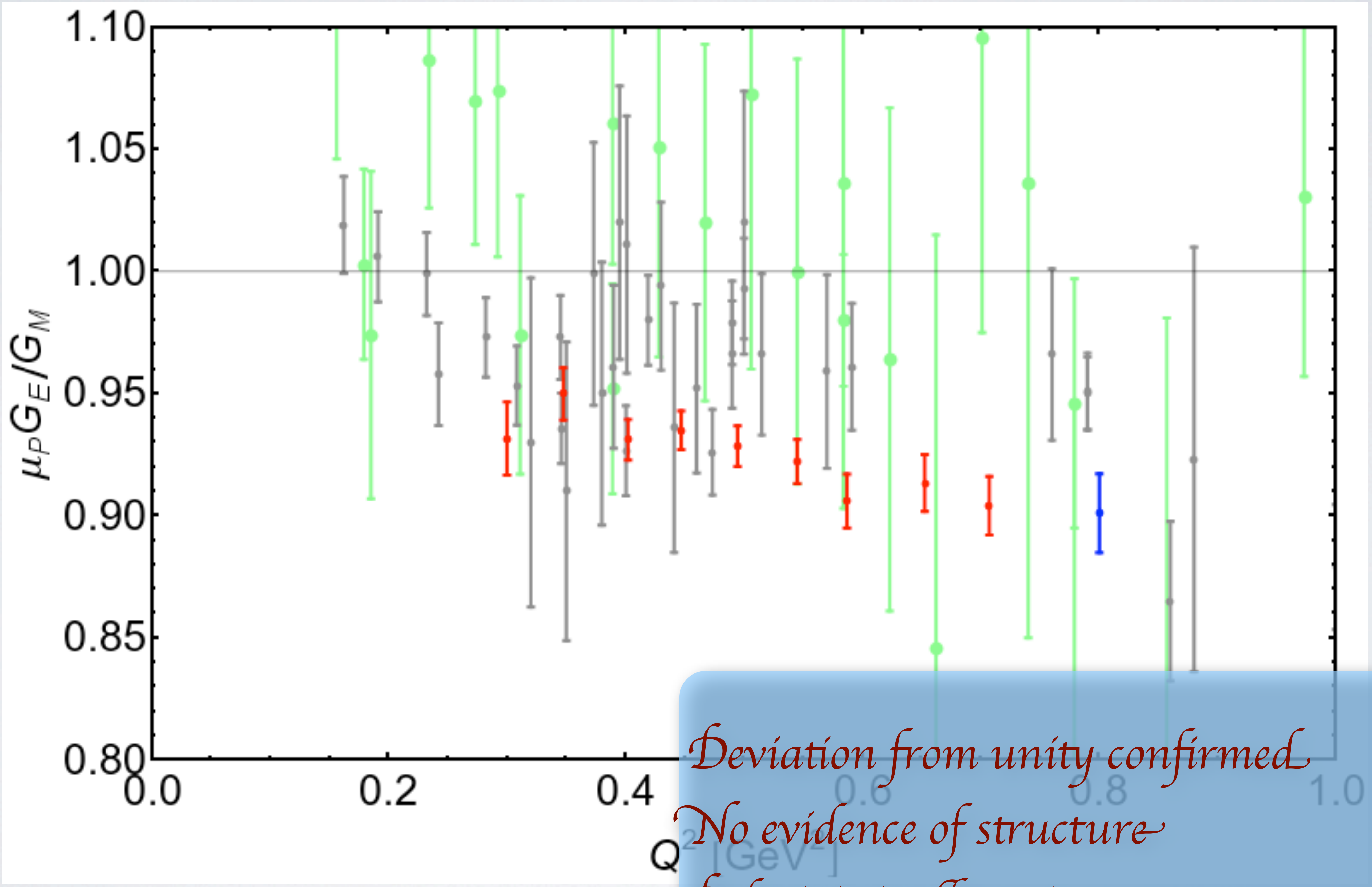
World Polarization Data



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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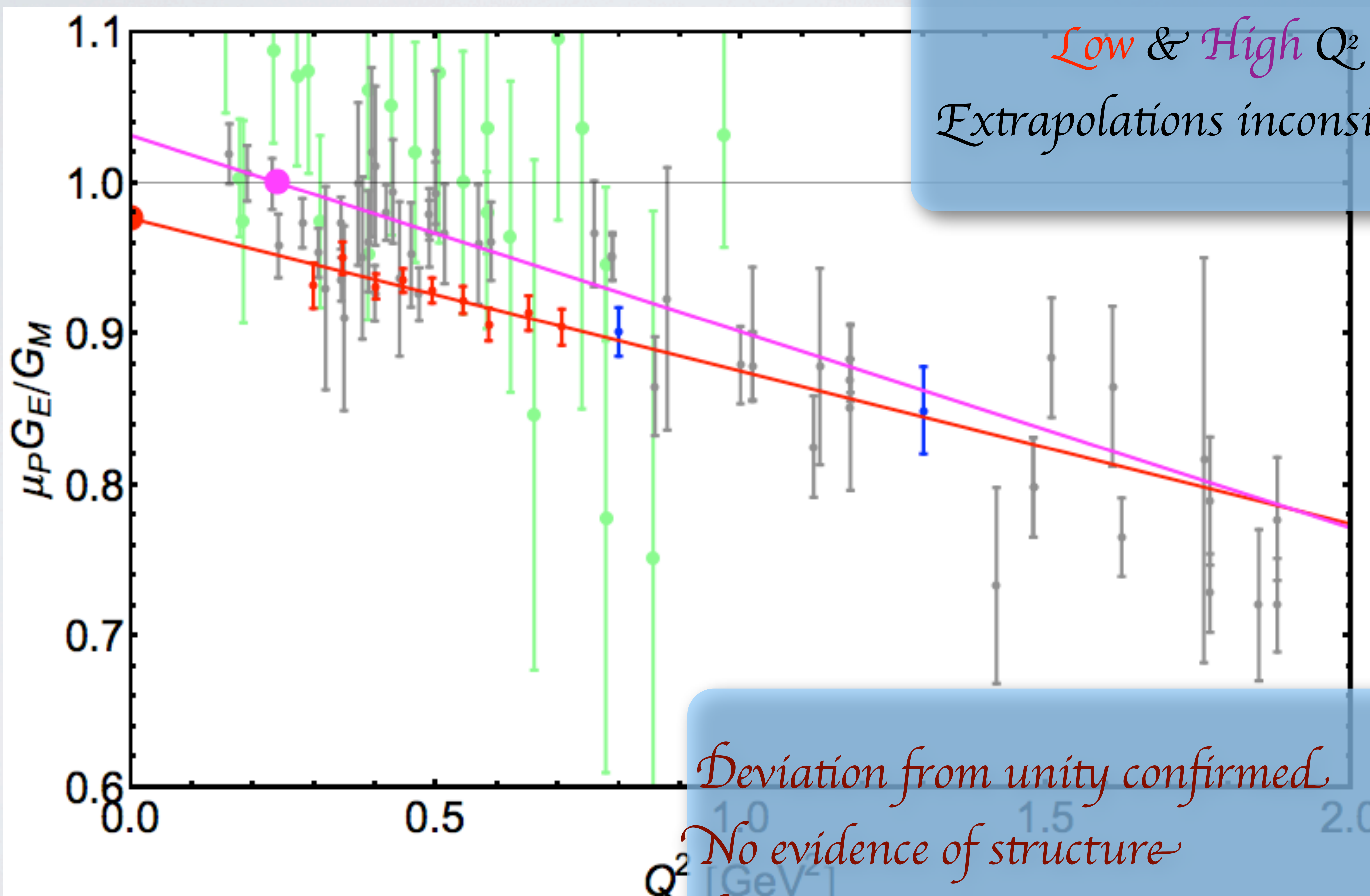


Low & High Q^2

Extrapolations inconsistent.

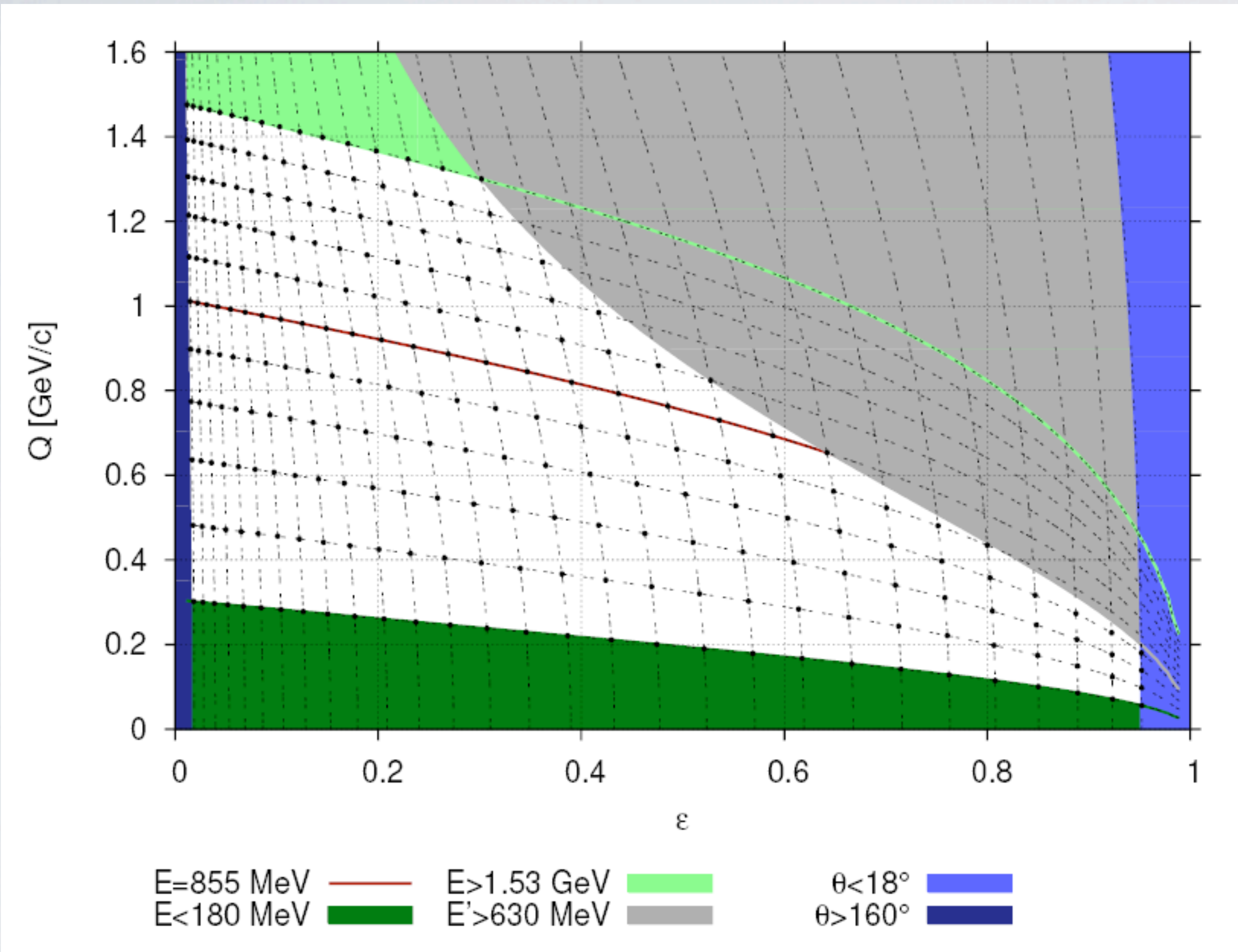
Deviation from unity confirmed

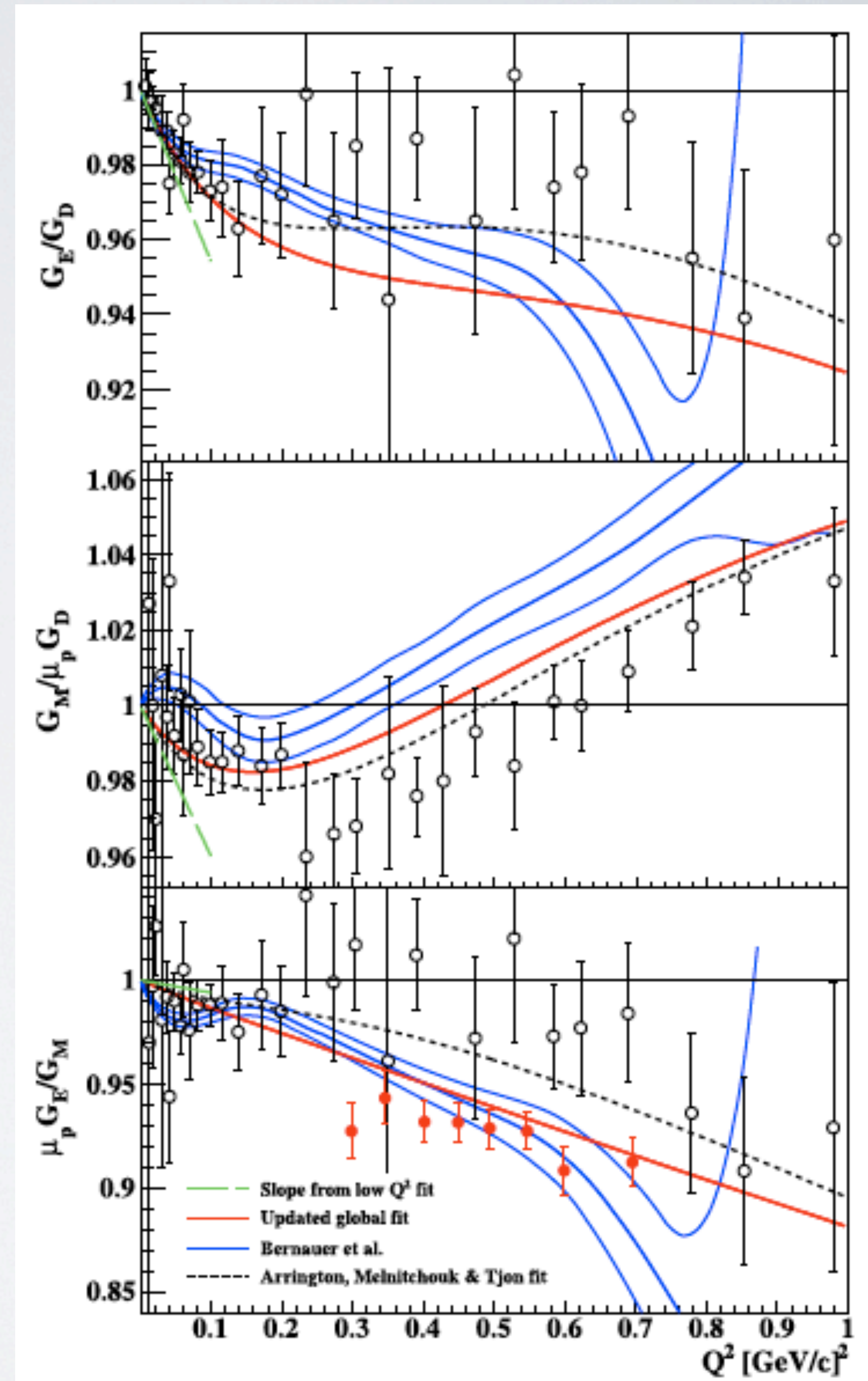
No evidence of structure

Relativistic effects important even at low Q^2

Mainz A1 Measurement

High precision low Q^2



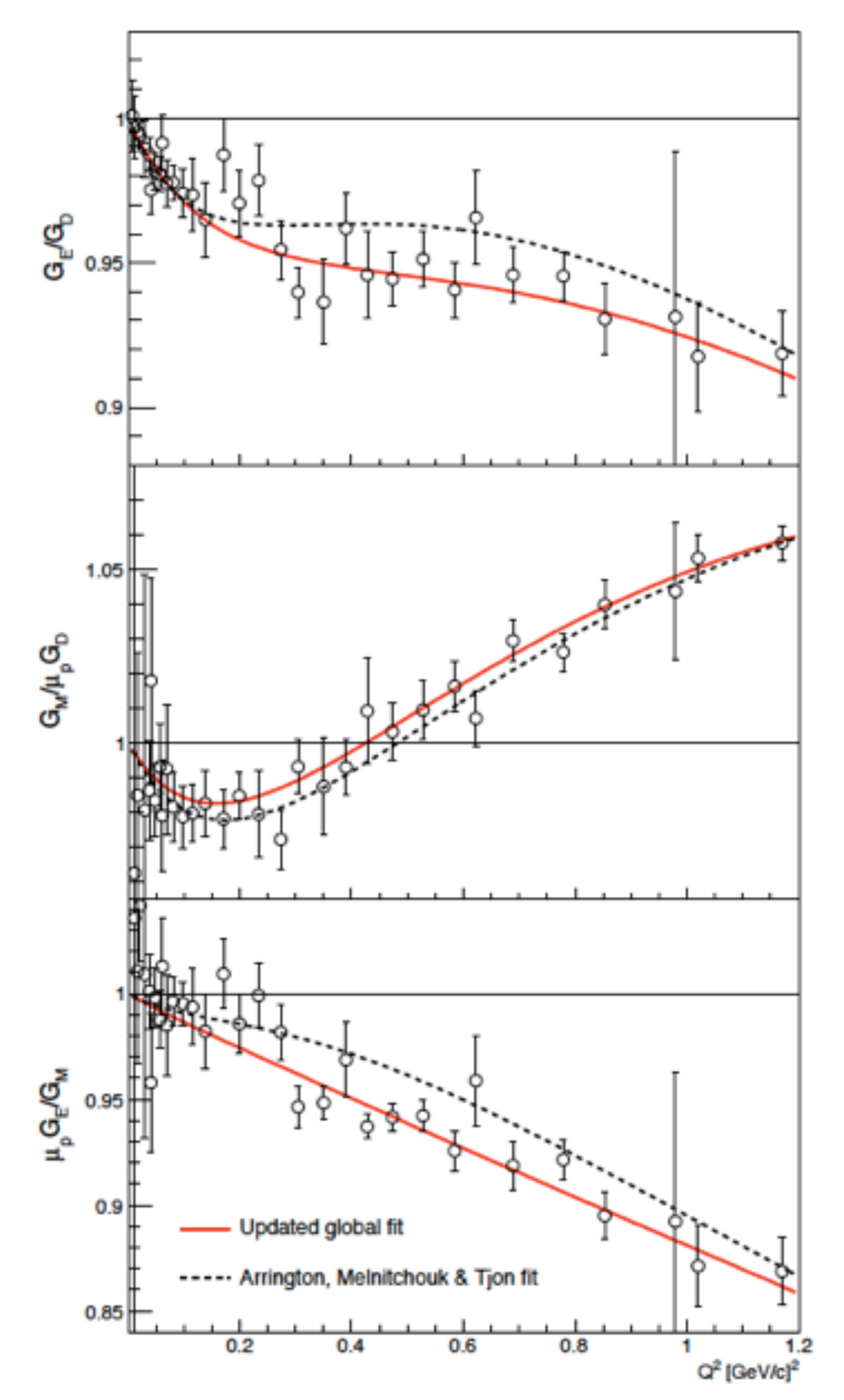


$$\langle r_E^2\rangle^{\frac{1}{2}} = 0.879(5)_{\text{stat.}}(4)_{\text{syst.}}(2)_{\text{model}}(4)_{\text{group}}\ \text{fm},$$

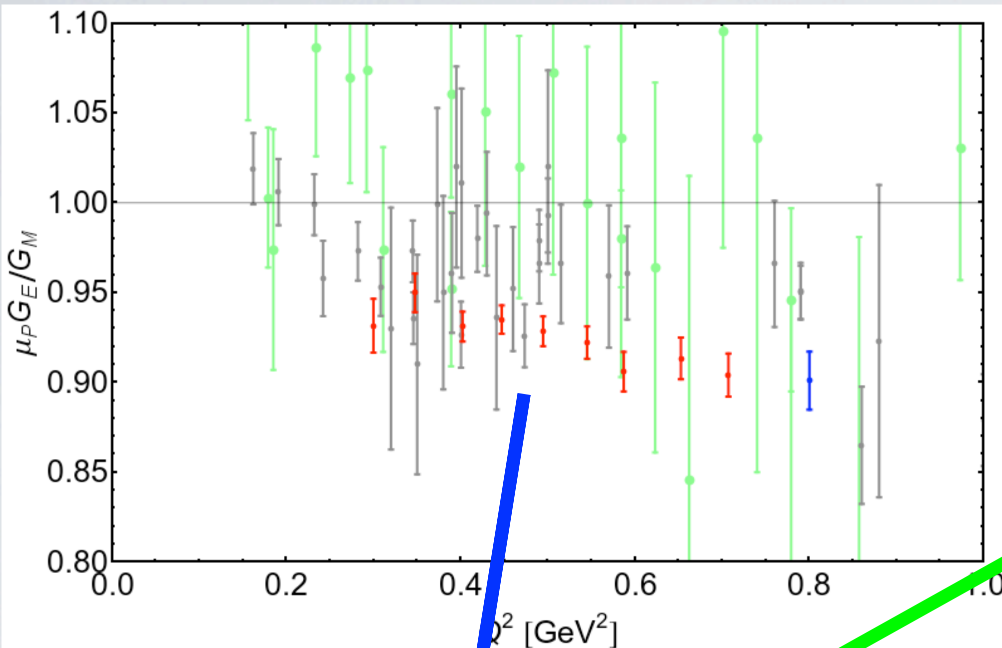
$$\langle r_M^2\rangle^{\frac{1}{2}} = 0.777(13)_{\text{stat.}}(9)_{\text{syst.}}(5)_{\text{model}}(2)_{\text{group}}\ \text{fm}.$$

What we've learned - Recent Fits

- Plots compare (2007) AMT fit to fit using newest data.
- New fits reduce G_E by ~ 2%.
- Slope as $Q^2 \rightarrow 0$ changed (impacts radii).



Extracting the individual FFs



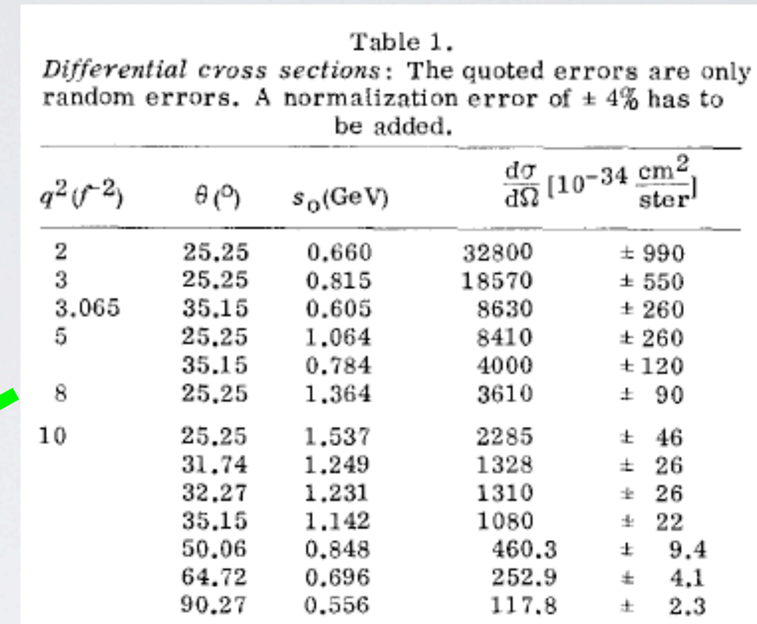
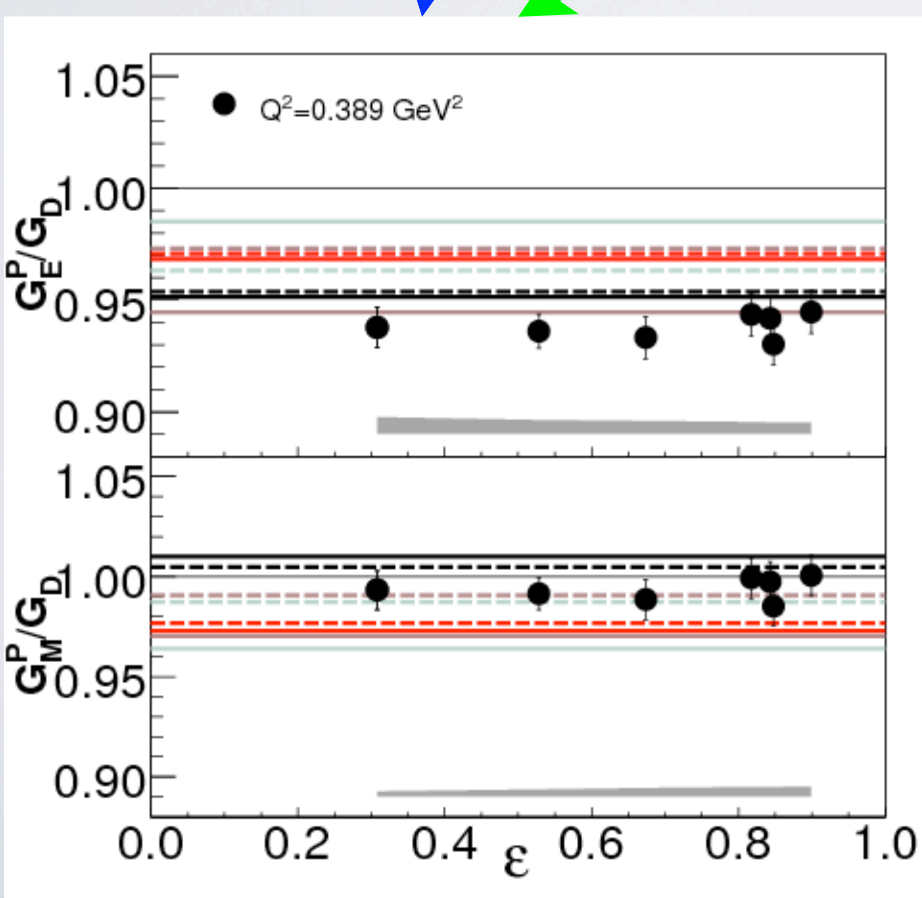


Table 1.
Differential cross sections: The quoted errors are only random errors. A normalization error of ± 4% has to be added.

$q^2 (f^{-2})$	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

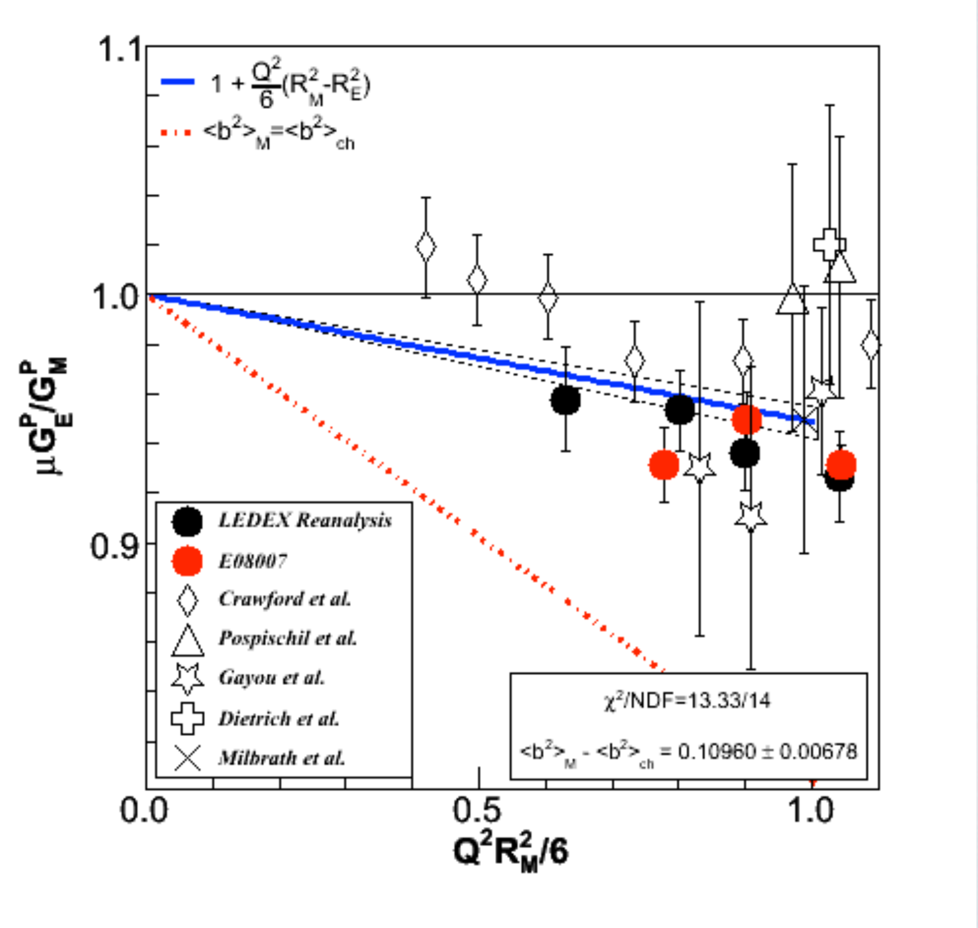
- Sachs FFs cannot be related to charge/magnetization densities:
- Relativistic effects (Lorentz contraction).
- Initial/Final states not identical (cannot be interpreted as density).
- Can be shown that F_1 & F_2 are 2D transforms of charge and magnetization densities.
- Low Q^2 expansion gives:

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

- And fit to data gives:

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

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



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

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

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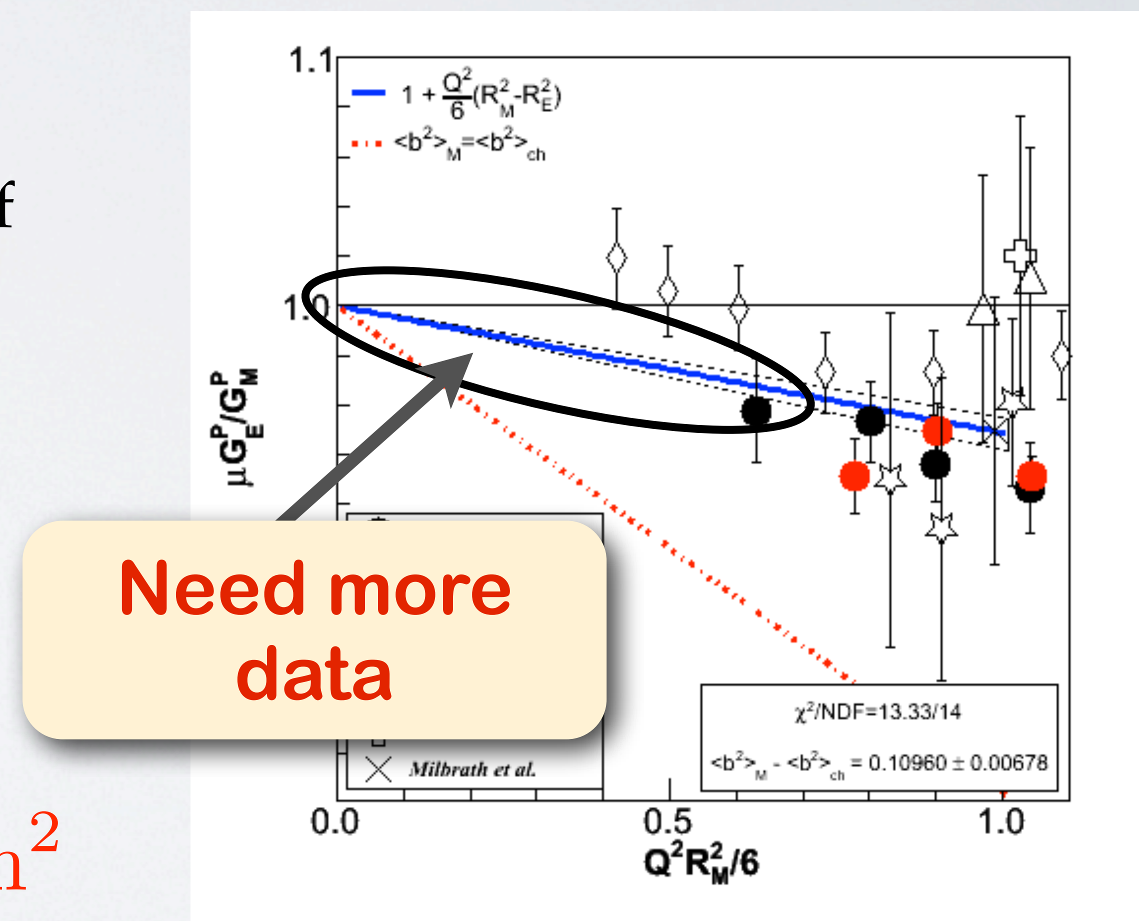

G. Miller, Phys. Rev. Lett. 99, 112001 (2007)

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

What we've learned

Charge Densities

- *Actually needs to be modified. But overall conclusion stays.*

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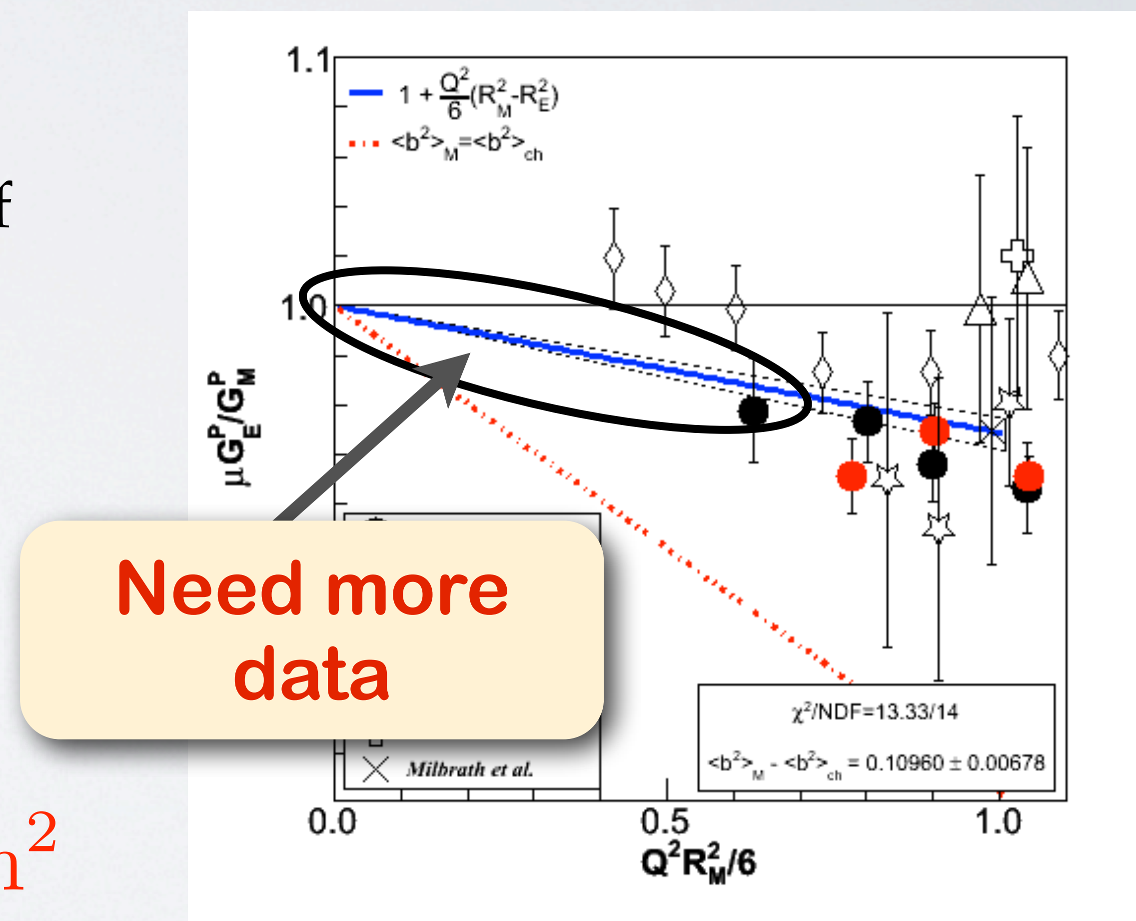
- And fit to data gives:

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



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

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

The Proton Radius

A multitude of extractions

- Low Q^2 Expansion of G_E:

$$G_E^P(Q^2) \sim 1 = 1 - \frac{q^2 \left\langle r^2 \right\rangle}{6} + \cdots$$

- Lattice QCD in the Chiral limit.

- Hydrogen Lamb shift.

- Muonic Hydrogen Lamb shift.

The Proton Radius

A multitude of extractions

- Low Q^2 Expansion of G_E :

$$G_E^P(Q^2) \sim 1 = 1 - \frac{q^2 \left\langle r^2 \right\rangle}{6} + \cdots$$

- Sensitive to functional form chosen for G_E. Also, data at $Q^2 \sim 0$ scarce (non existent).

- Lattice QCD in the Chiral limit.

- Sensitive to lattice size and small perturbations in parameters.

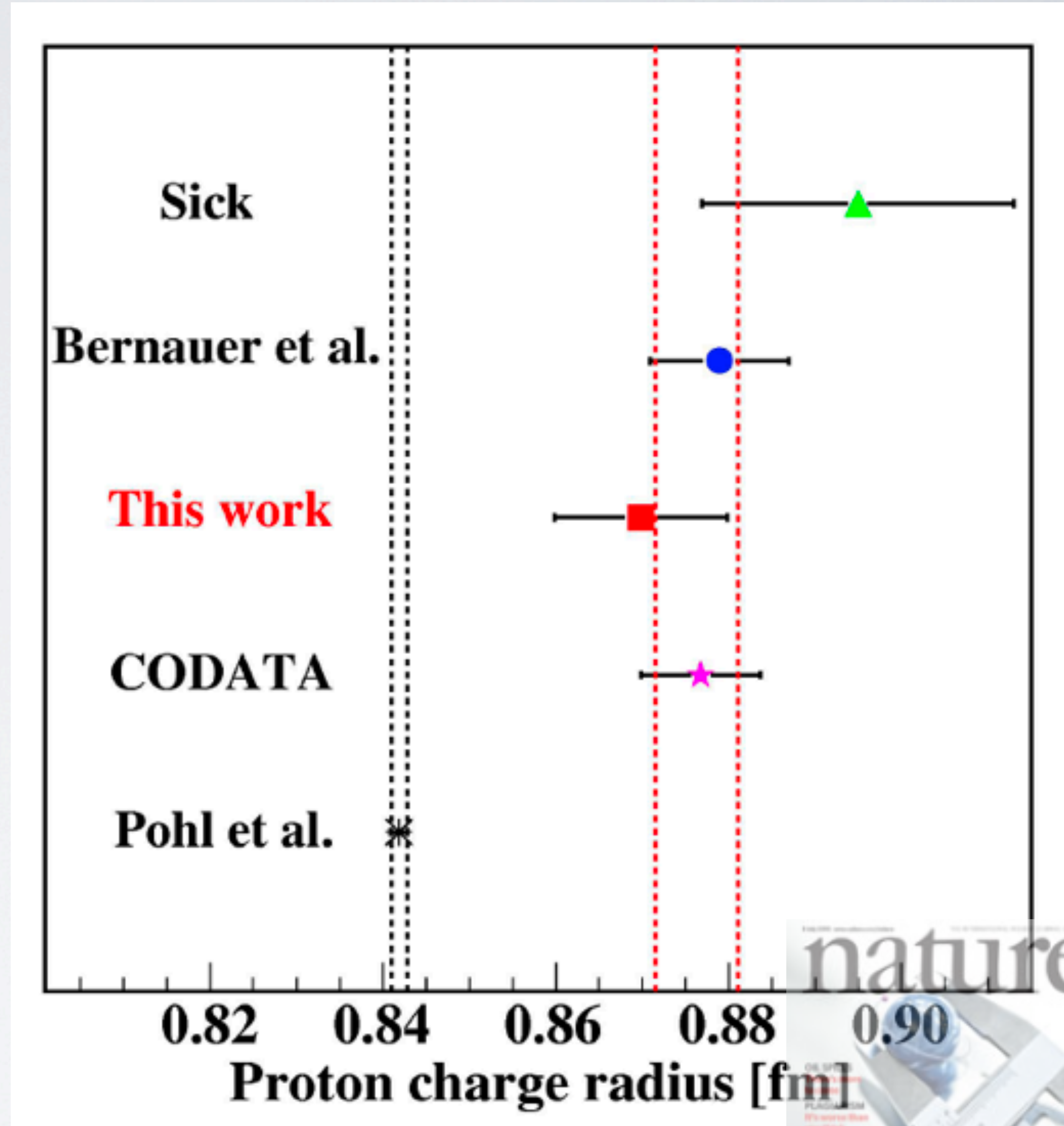
- Hydrogen Lamb shift.

- Muonic Hydrogen Lamb shift.

- Sensitive to different theoretical corrections.

The Proton Radius Puzzle

#	Extraction	$\langle r_E \rangle^2$ [fm]
1	Sick	0.895±0.018
2	CODATA	0.8768±0.0069
3	Mainz	0.879±0.008
4	This Work	0.870±0.010
5	Combined 2-4	0.8764±0.0047
6	Muonic Hydrogen	0.842±0.001



The Proton Radius Puzzle

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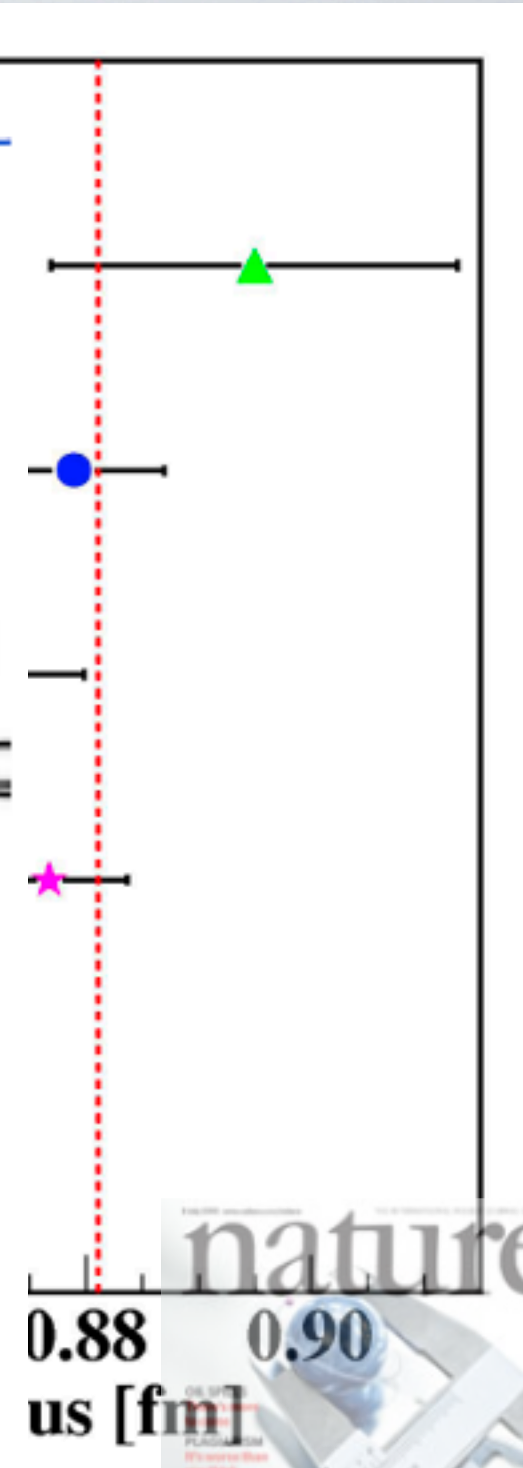


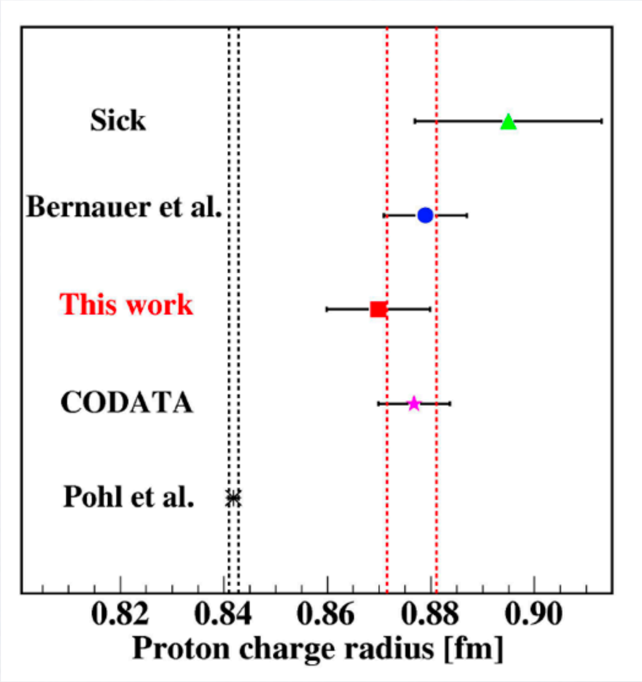
The Proton Radius Puzzle

My Caveats

- Sachs form factors not measured at $Q^2 = 0$.
- Can we even extrapolate Sachs form factors to Q^2 and claim that we get the radius? Extrapolation from relativistic to non-relativistic region.
- Mainz data extracted with no 2-photon corrections (and get a strange magnetic radius).
- Electron scattering results agree well with CODATA (Lamb shift) - seems to indicate electron/muon discrepancy.

My wishlist

- E08007-II to measure very low Q^2 form factors.
- Possible other experiments at low Q^2 (Proton scattering off atomic hydrogen? μp scattering experiment?).
- Another theoretical look at the derivation from muonic Lamb shift.
- Comparison of (as yet unreleased) Zemach radius data from PSI.



The Zemach Radius

- Hyperfine splitting of the hydrogen ground state:

$$E_{hfs}(e^- p) = \left(1 + \Delta_{QED} + \Delta_R^P + \Delta_{h\nu p}^P + \Delta_{\mu\nu p}^P + \Delta_{weak}^P + \Delta_S\right) E_F^P$$

$$\Delta_S = \Delta_Z + \Delta_{pol}, \ \Delta_Z = -2\alpha m_e r_Z \left(1 + \delta_Z^{rad}\right)$$

- Zemach radius (effect of proton internal structure on energy level shift):

$$r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left[G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_P} - 1\right]$$

FF	r_p [fm]	r_Z [fm]	ΔZ [ppm]
AMT	0.885	1.080	−41.43
AS	0.879	1.091	−41.85
Kelly	0.878	1.069	−40.99
F&W	0.808	1.049	−40.22
Dipole	0.851	1.025	−39.29
New	0.868	1.075	−41.22

- Sensitivity to details in the FFs is completely contained in the $Q^2 < 1$ GeV^2 region.

- Leading theoretical uncertainty in one of the most precisely measured experimental quantities (test of QED).

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$\Delta_S = \Delta_Z + \Delta$ …

Note that using different parametrizations results in deviations larger than quoted uncertainty!

- Zemach radiu… …vel shift):

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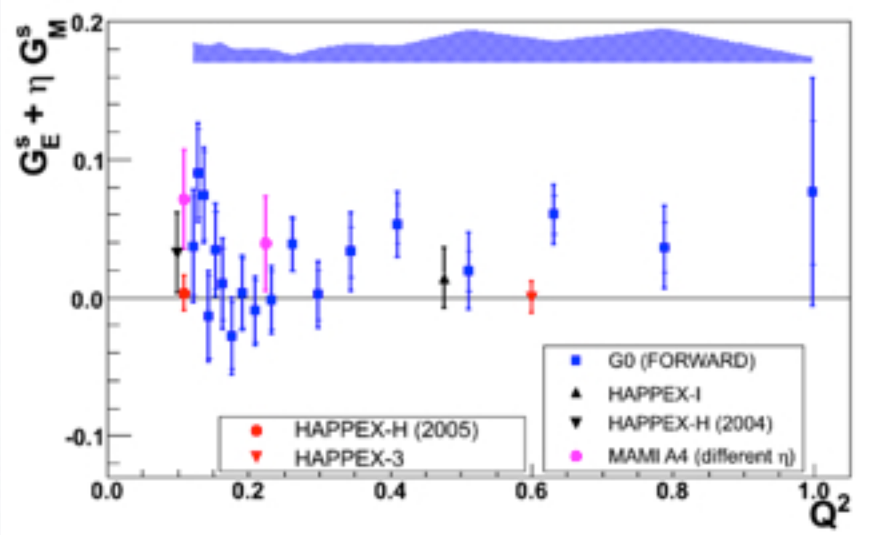
PV Experiments

- Parity violation experiments aim to measure the strange quark content of the nucleon by detecting interference between elastic EM scattering and neutral weak ep scattering.
- Determination of strange quark form factors relies on knowledge of EMFF.
- Shifts of ~ 0.5σ "easy".

Q^2	$\Delta A/\sigma$	$\Delta A/A$	
0.38	0.42	1.6%	G0 FWD
0.56	0.50	1.6%	G0 FWD
1.0	0.30	0.8%	G0 FWD
0.50	0.50	1.7%	HappexII
0.231	0.12	0.2%	G0 BCK
0.65	0.14	0.3%	G0 BCK



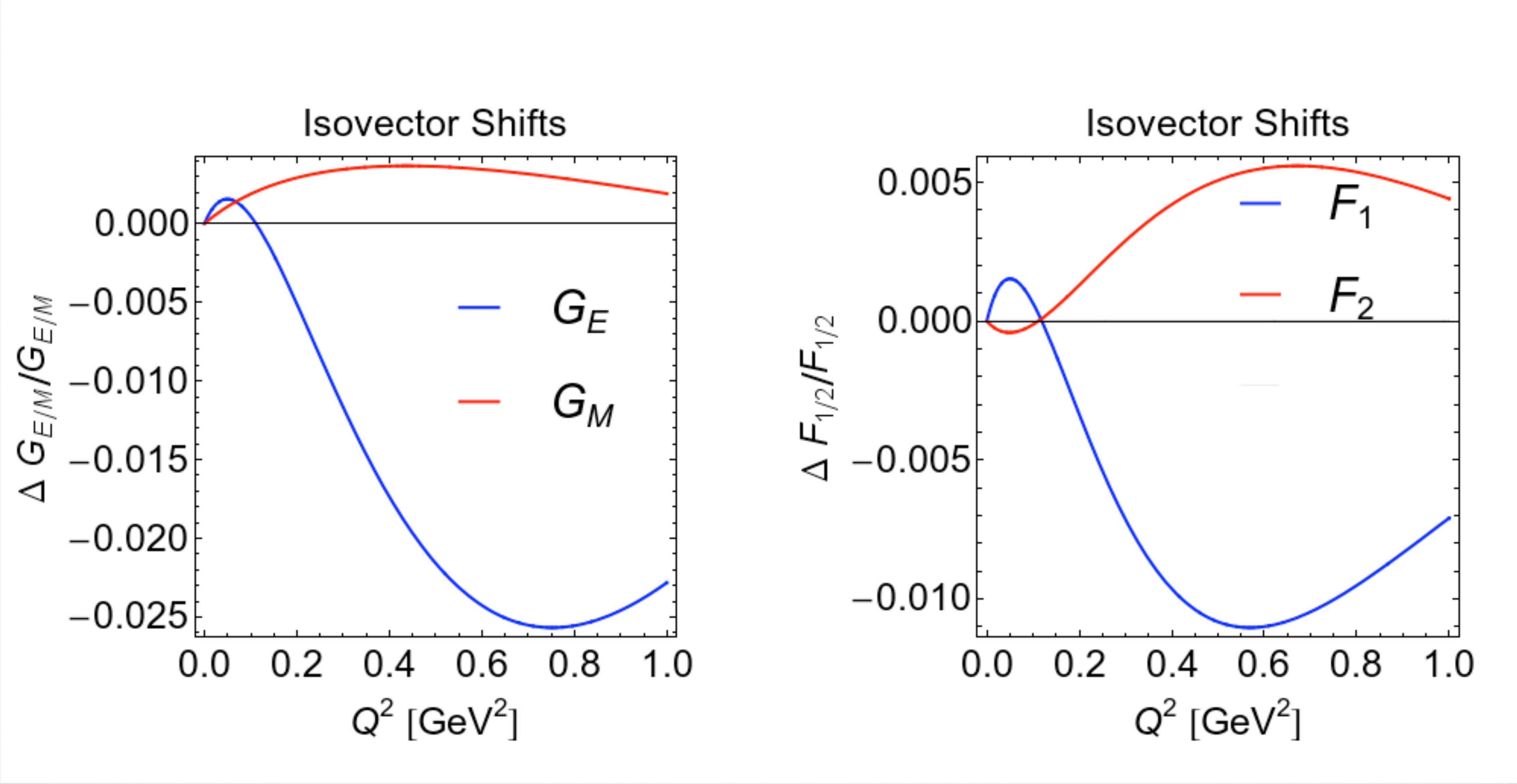
$$A^{PV} = \left[-\frac{G_F M_p^2 Q^2}{\pi\alpha\sqrt{2}}\right]\left[\left(1-4\sin^2\theta_W\right) - \frac{\varepsilon G_E^{p\gamma}\left(G_E^{n\gamma}+G_E^s\right)+\tau G_E^{p\gamma}\left(G_M^{n\gamma}+G_M^s\right)}{\varepsilon\left(G_E^{p\gamma}\right)^2+\tau\left(G_M^{p\gamma}\right)^2}\right] - A_A$$

Isovector / Isoscalar Separation

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

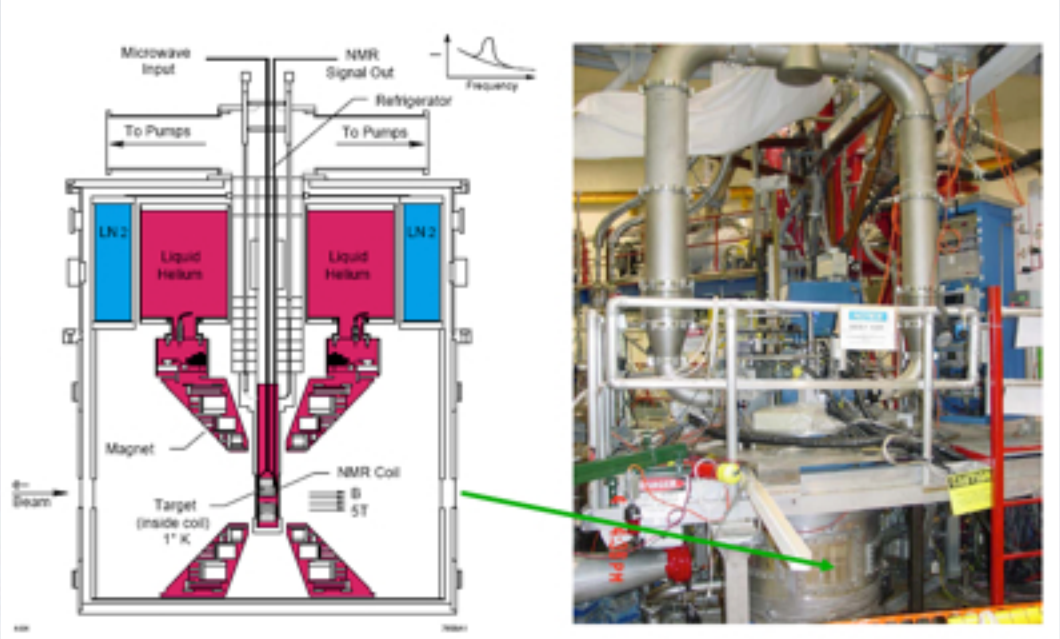
Important for Lattice QCD (Isovector)

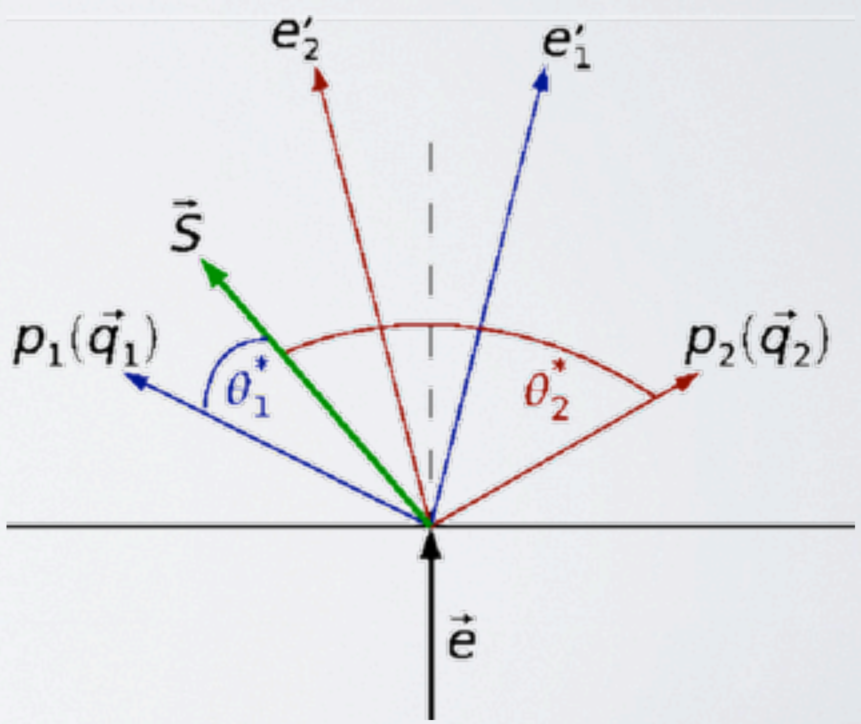
Plot shows the fractional change in the isovector form factors when using J. Arrington's new vs. old parametrizations (for the proton).



E08007 - Part II

- High precision (< 1%) survey of the FF ratio at Q^2=0.01 - 0.16 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- but magnet issues kill that.
- Scheduled for Dec 2011/Jan 2012 (but delayed till Feb 2012!)





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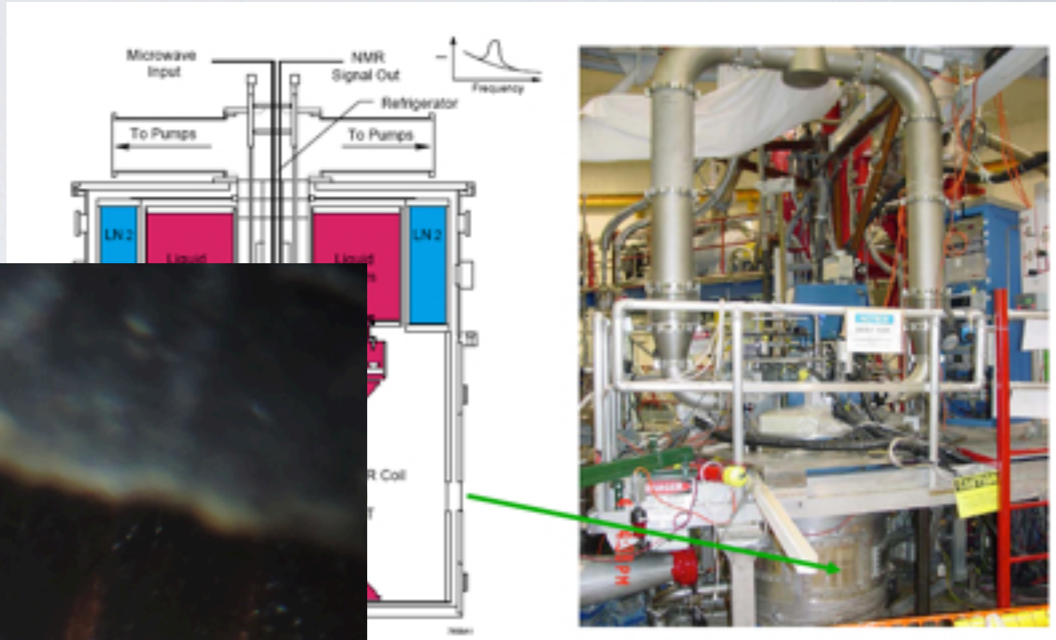
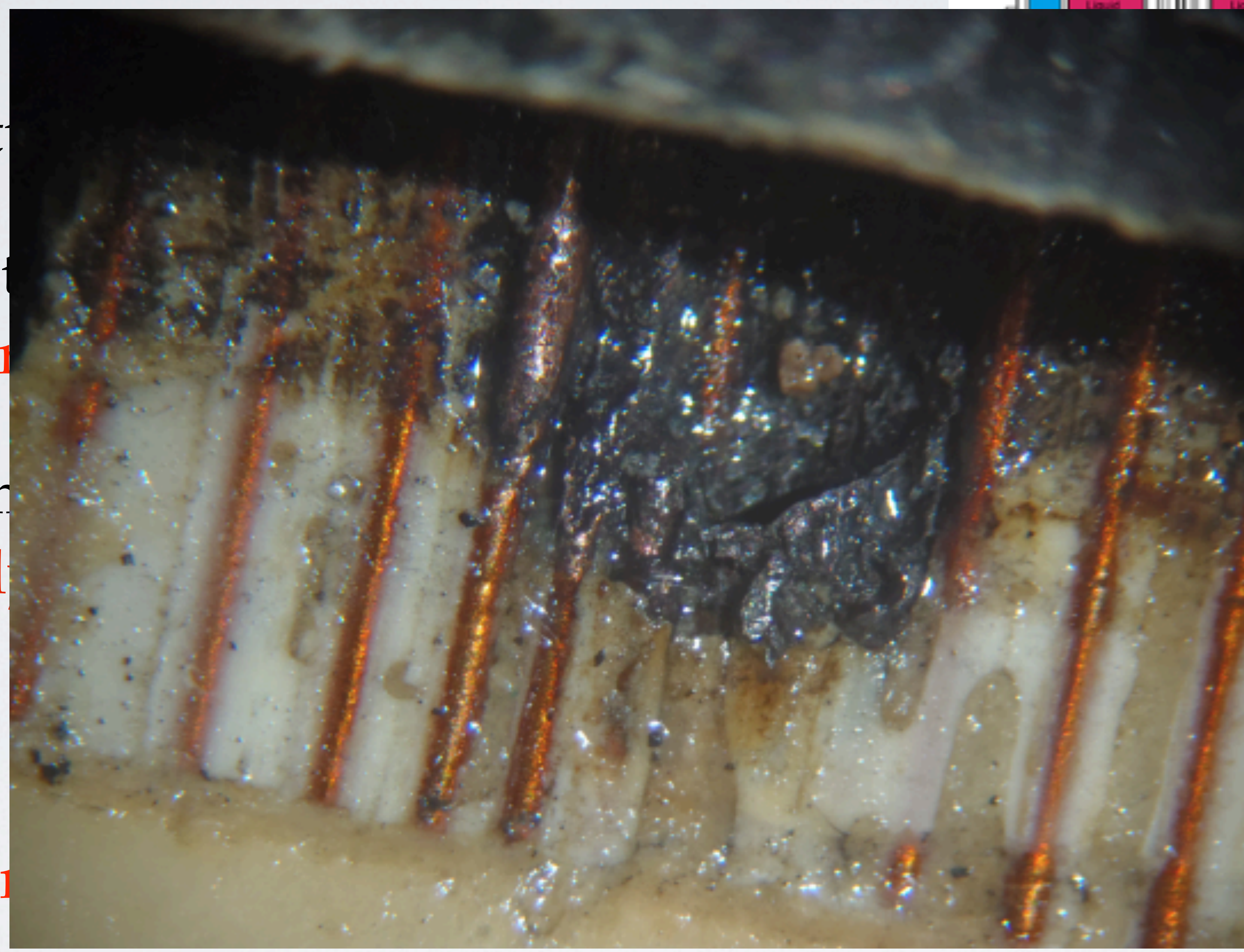
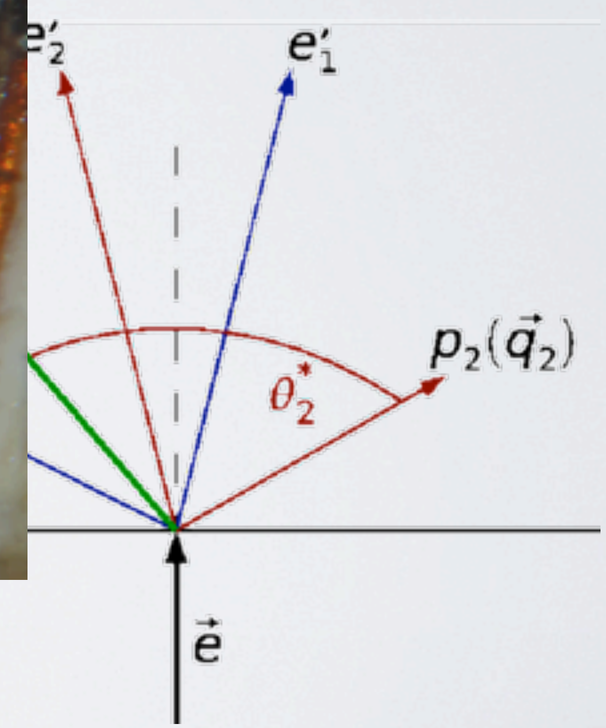


- Beam-target
electron scat



- Electrons de
spectromete

- Ratio of asyr
errors → onl
ratio.



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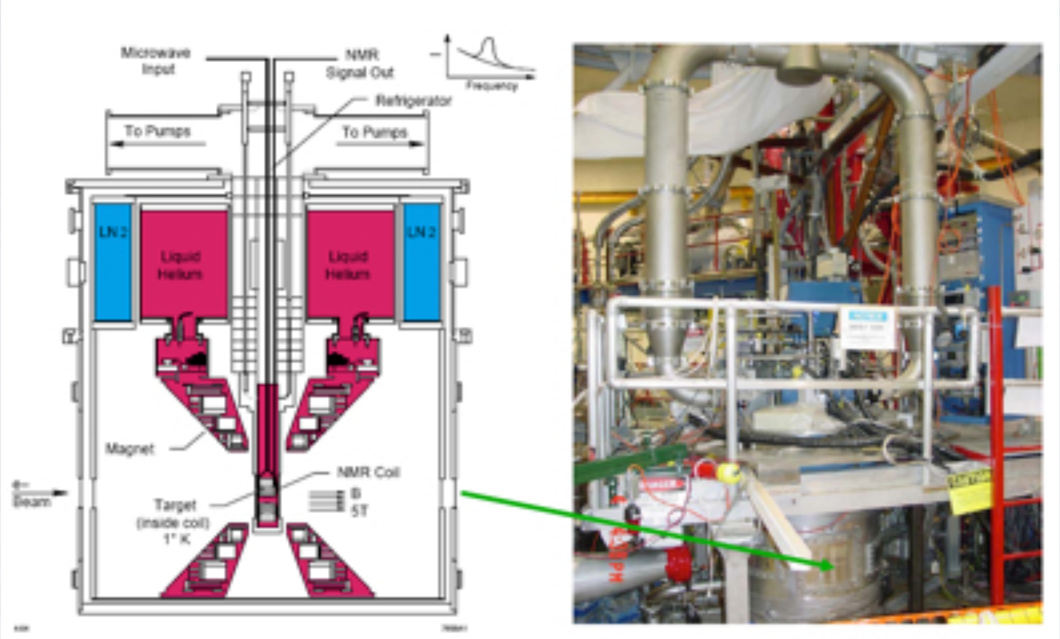

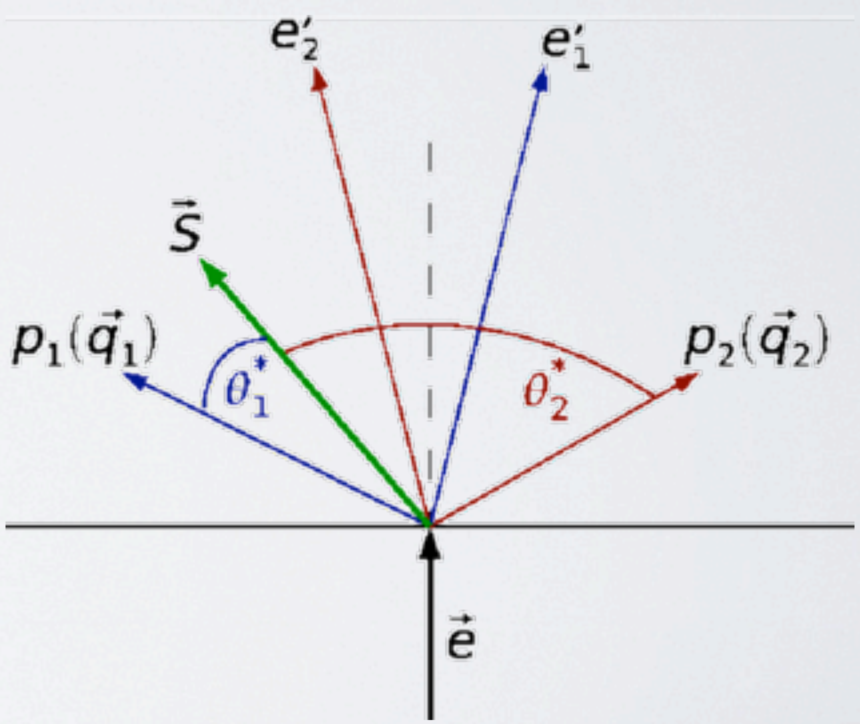

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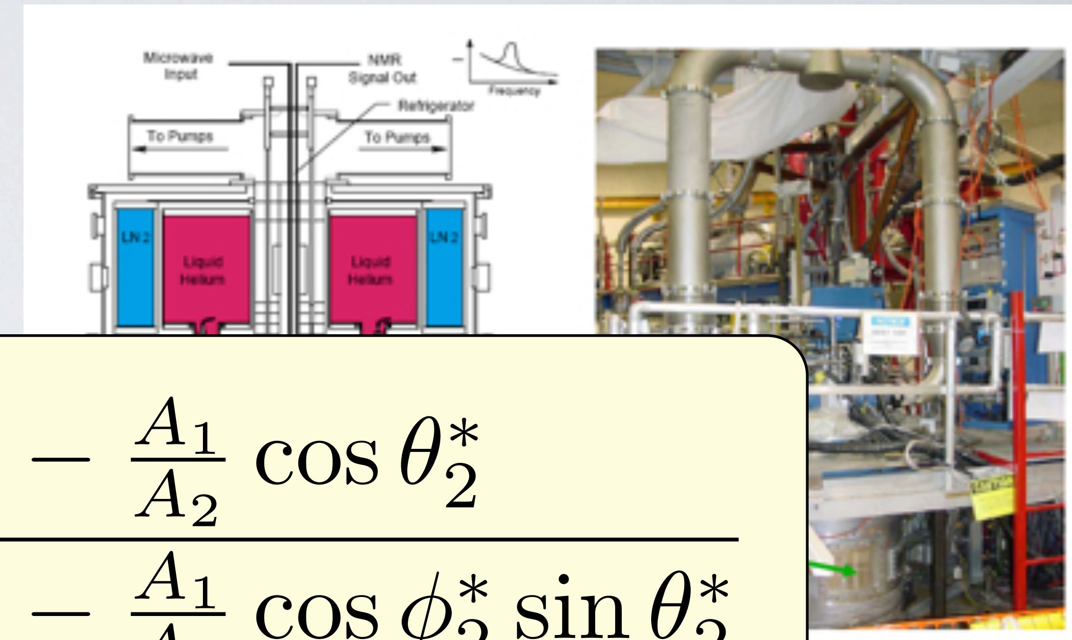
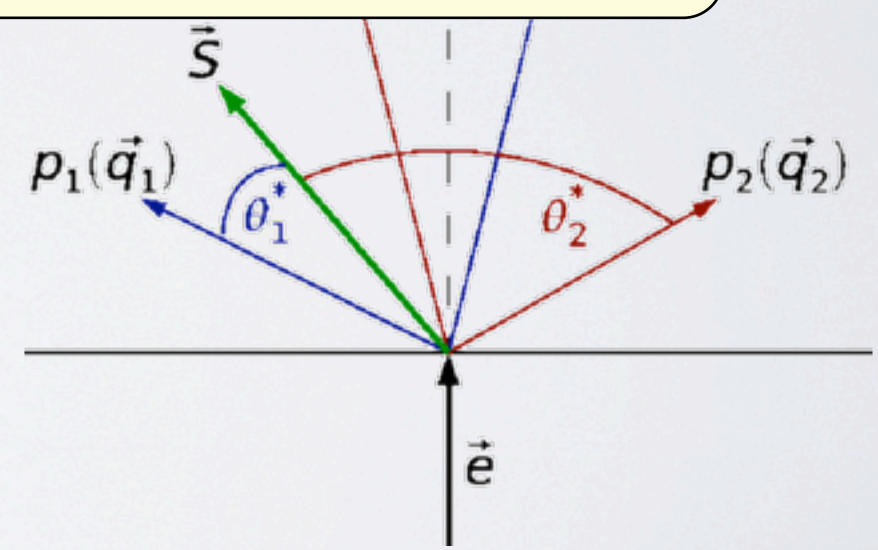
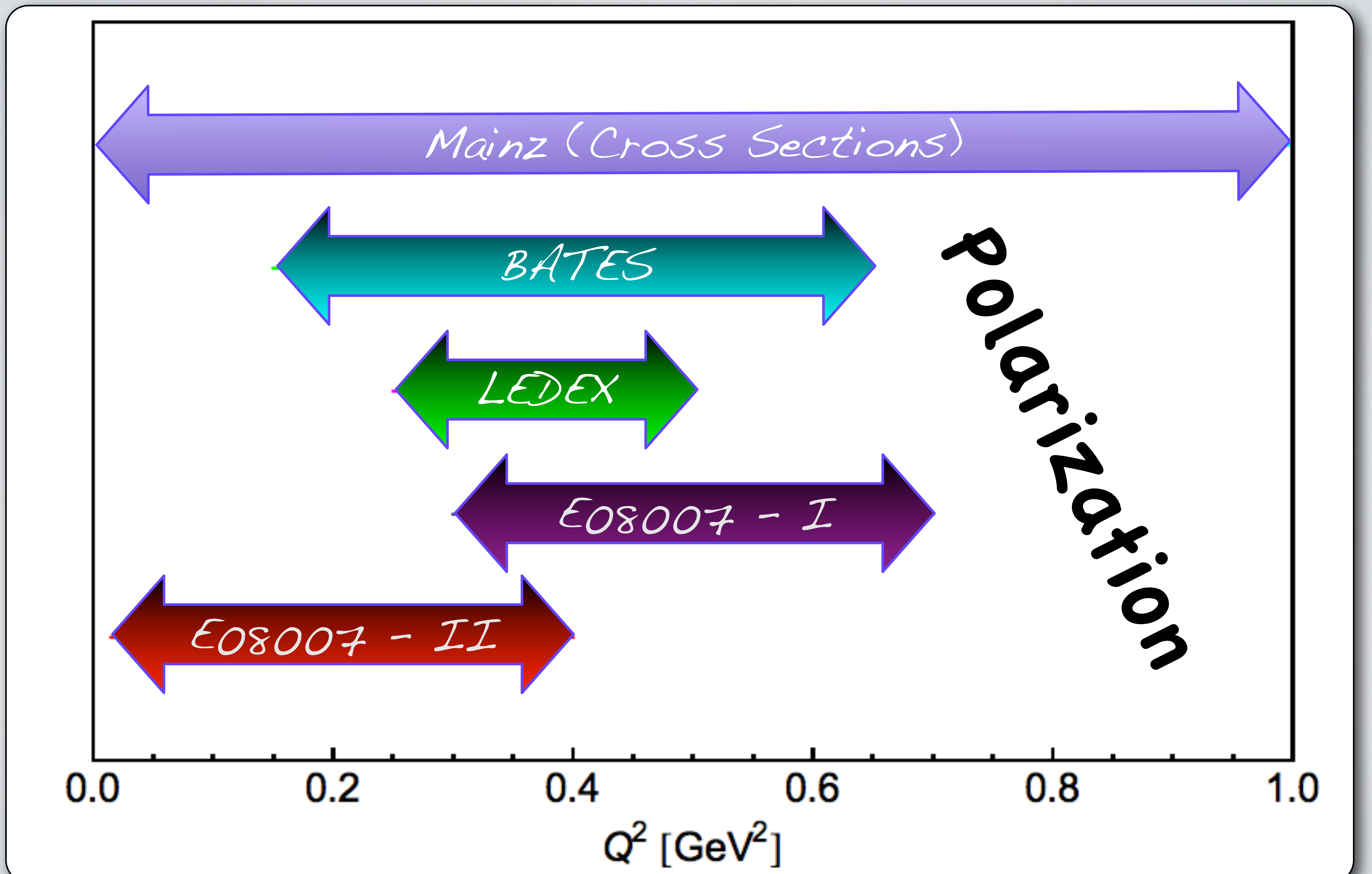


$$\mu_p \frac{G_E^p}{G_M^p} = -\mu_p a(\tau\theta) \frac{\cos\theta_1^* - \frac{A_1}{A_2}\cos\theta_2^*}{\cos\phi_1^*\sin\theta_1^* - \frac{A_1}{A_2}\cos\phi_2^*\sin\theta_2^*}$$

Note no dependence on polarizations/dilution

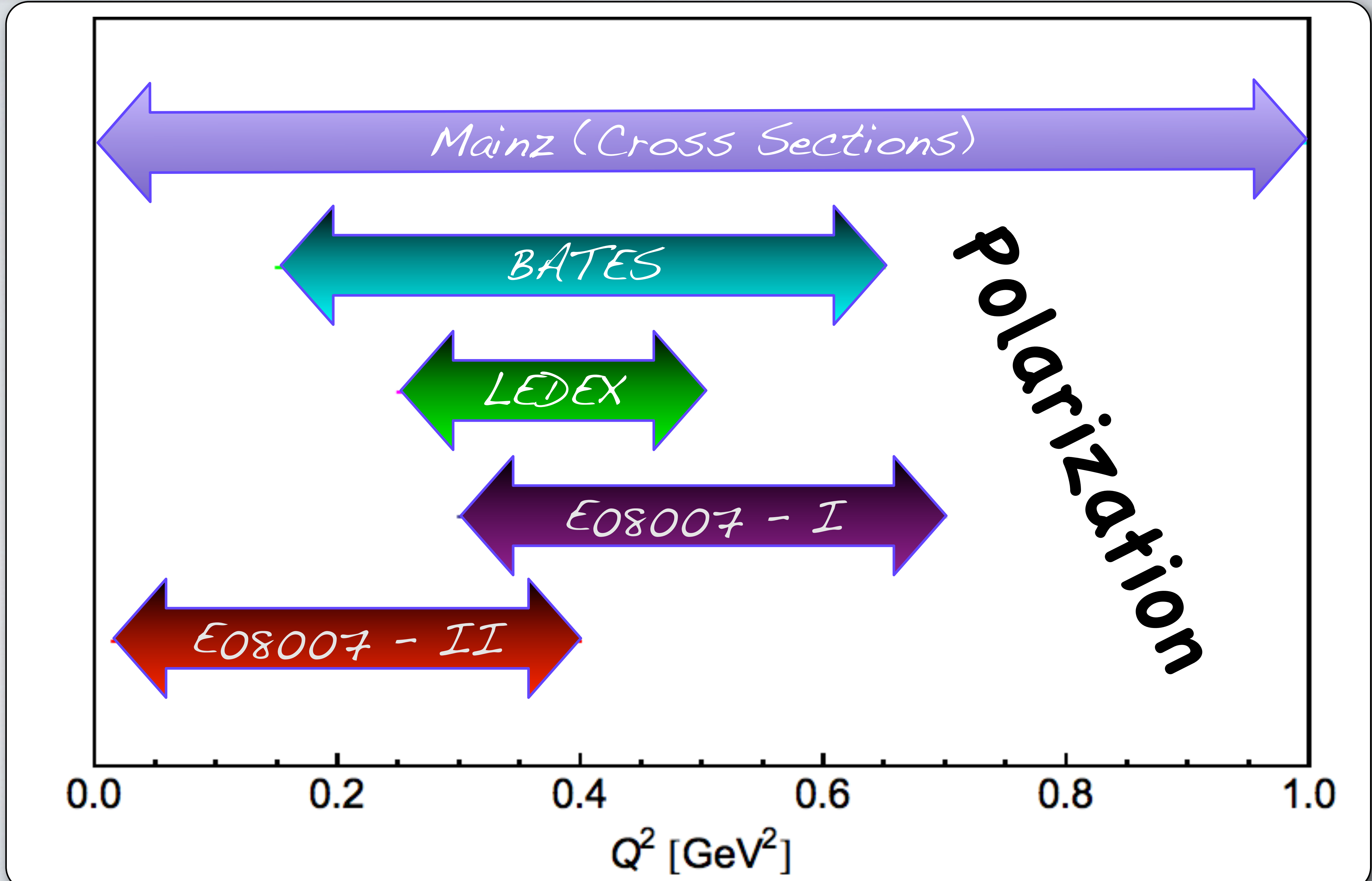


Comparison to other Experiments Coverage



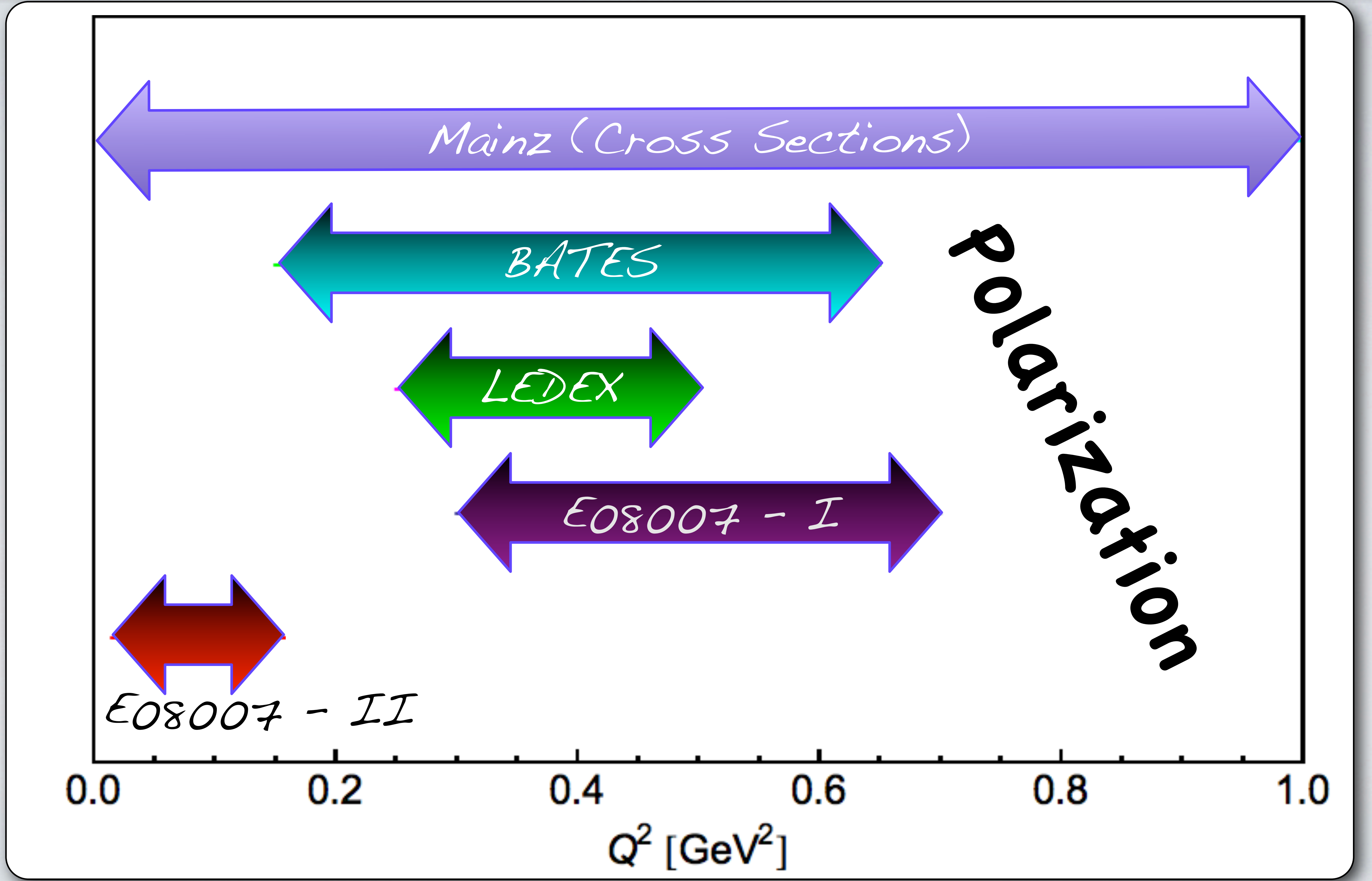
Complements MAINZ

Overlaps LEDEX, E08007-I - Different technique (systematics)



Complements MAINZ

Does NOT Overlap LEDEX, E08007-I



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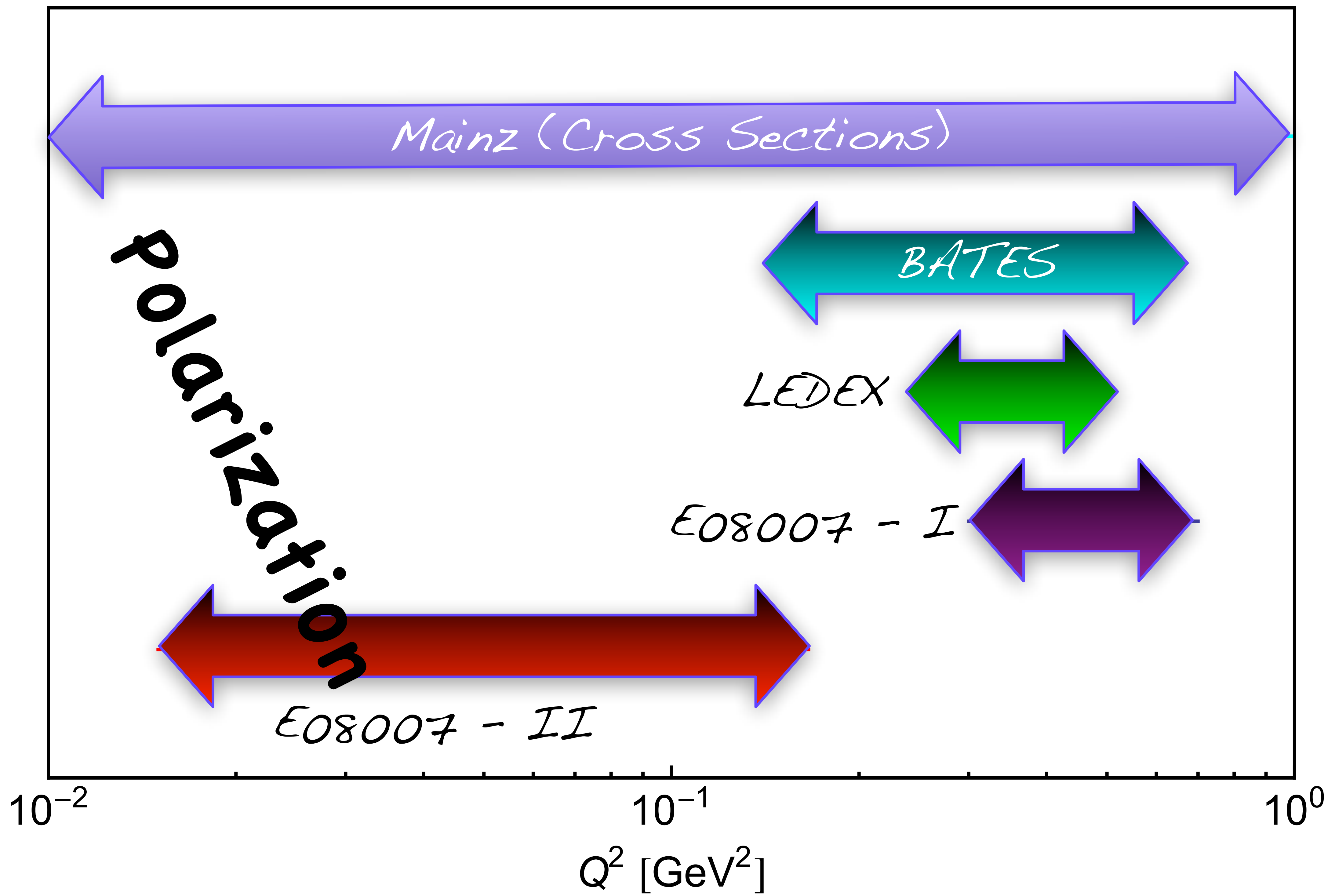
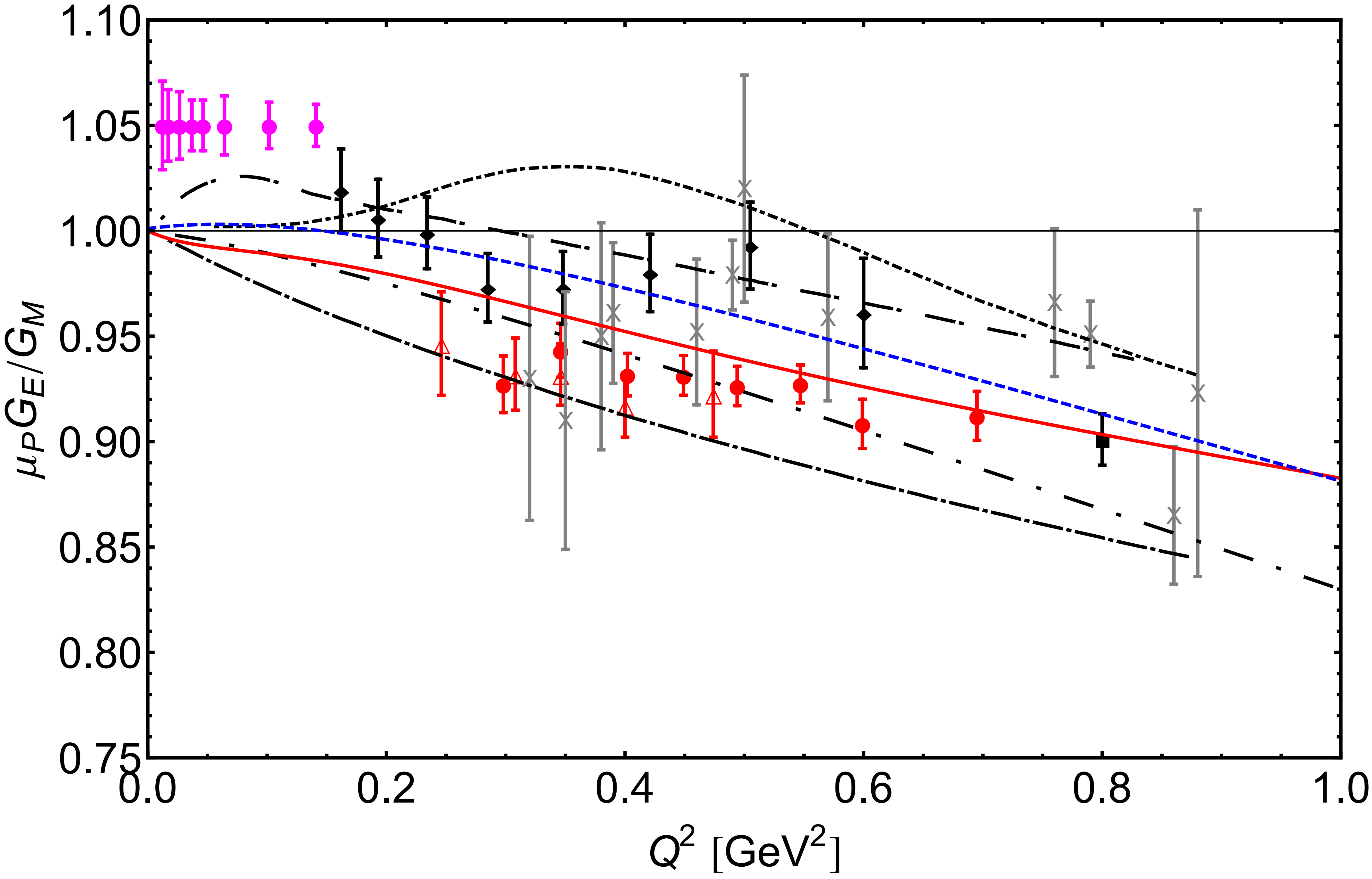


E08007 - Part II
Projected uncertainties



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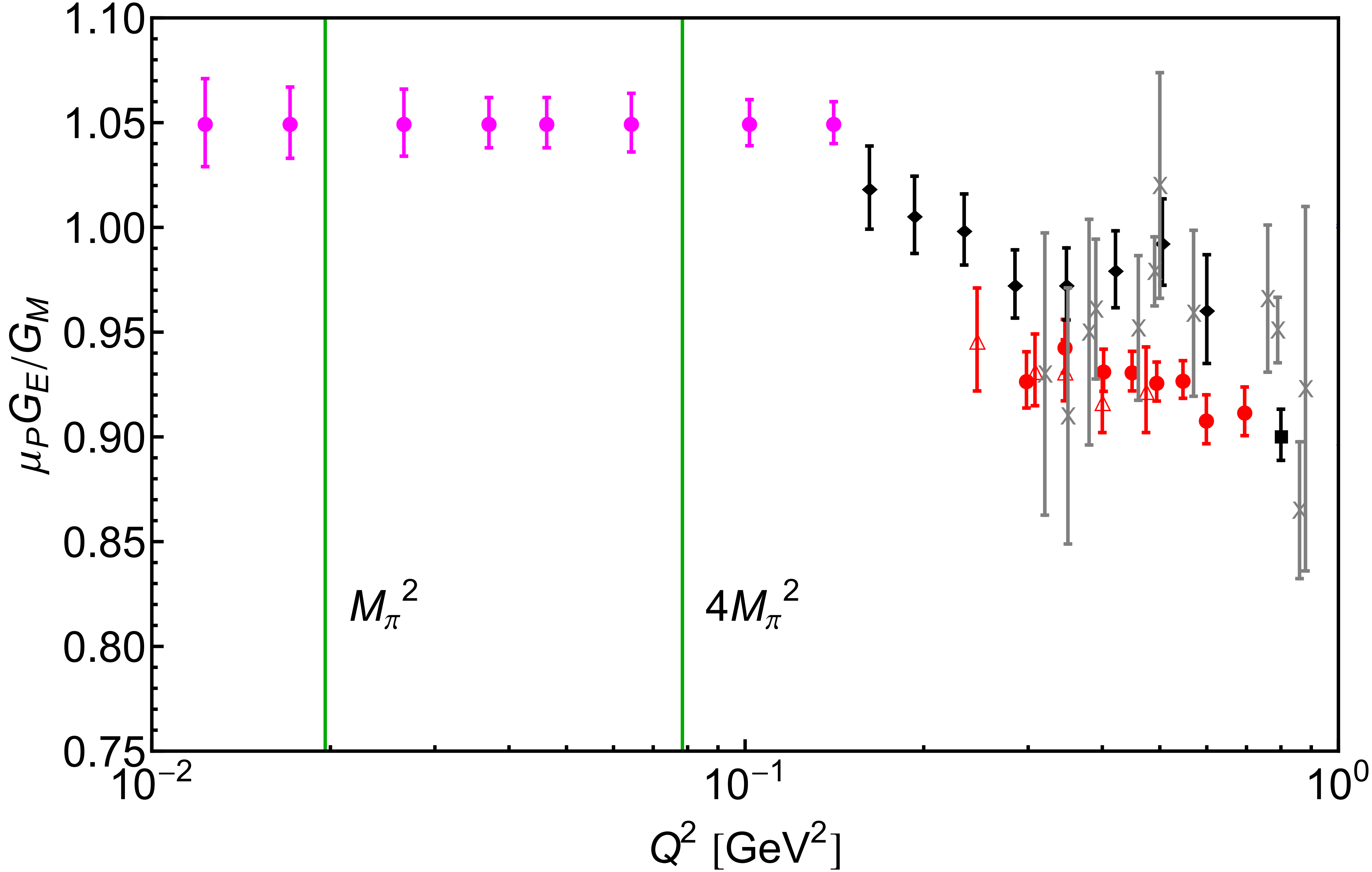


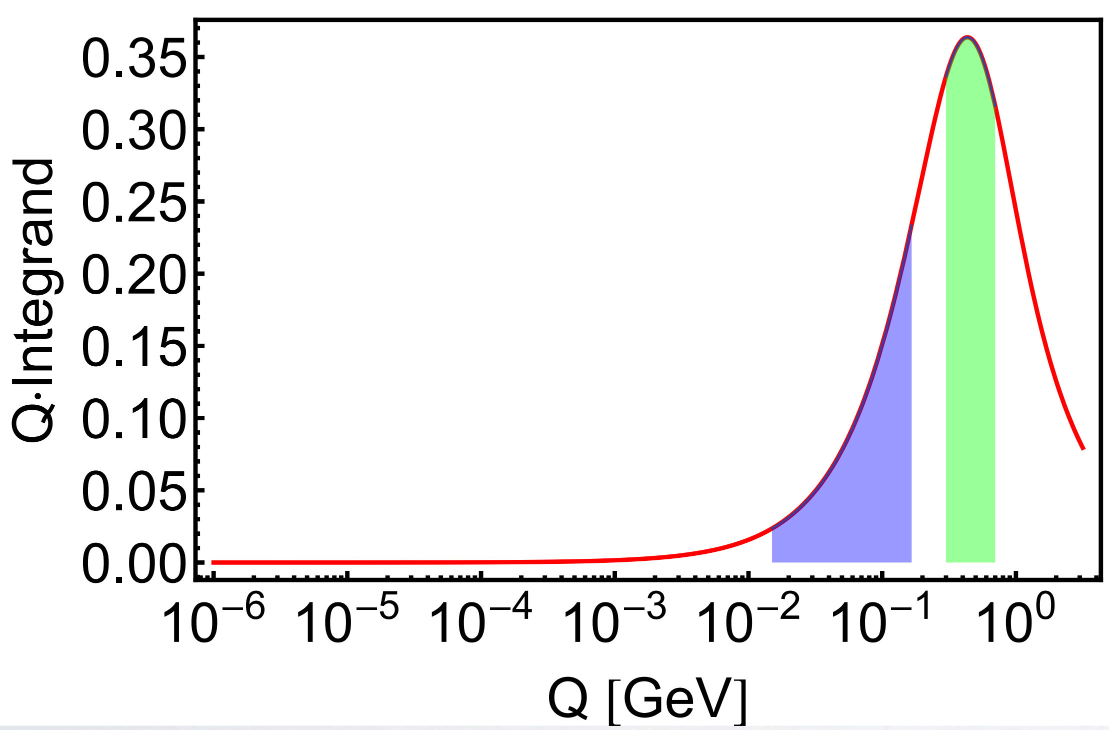
Zemach Radius

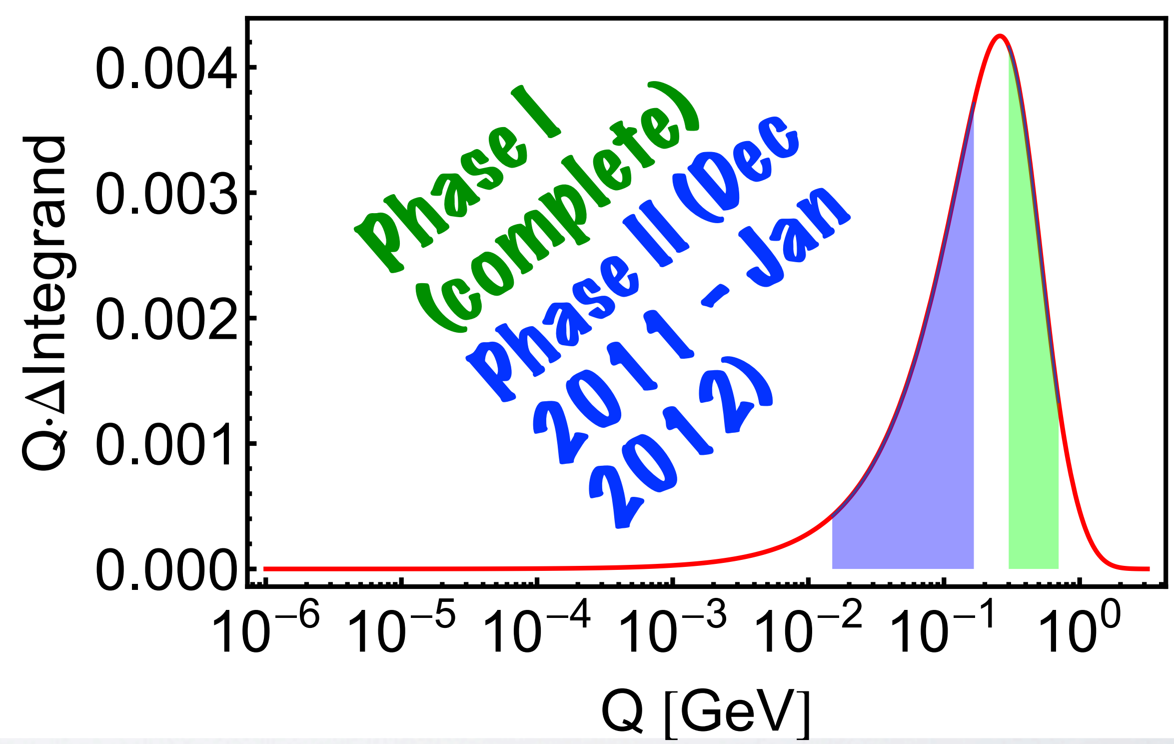
$$E_{hfs} = (1 + \Delta_{QED} + \Delta^p_{hvp} + \Delta^p_{\mu vp} + \Delta^p_{weak} + \Delta_S) E^p_F$$

$$\Delta_S = \underline{\Delta_Z} + \Delta^p_R + \Delta_{pol}, \quad \Delta_Z = -2\alpha Z \frac{m_e m_p}{m_e + m_p} r_Z$$

$$r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{\underline{Q^2}}\left[G_E(Q^2)G_M(Q^2)/(1+\kappa_p) - 1\right]$$

- $1/Q^2$ term suppresses high Q^2
- $[1-G_E(Q^2)G_M(Q^2)/\mu_p]$ suppresses lowest Q^2.
- As G_E, G_M become small, $[1-G_E(Q^2)G_M(Q^2)/\mu_p] \rightarrow 1$, and the form factor uncertainty has almost no impact on Zemach moment

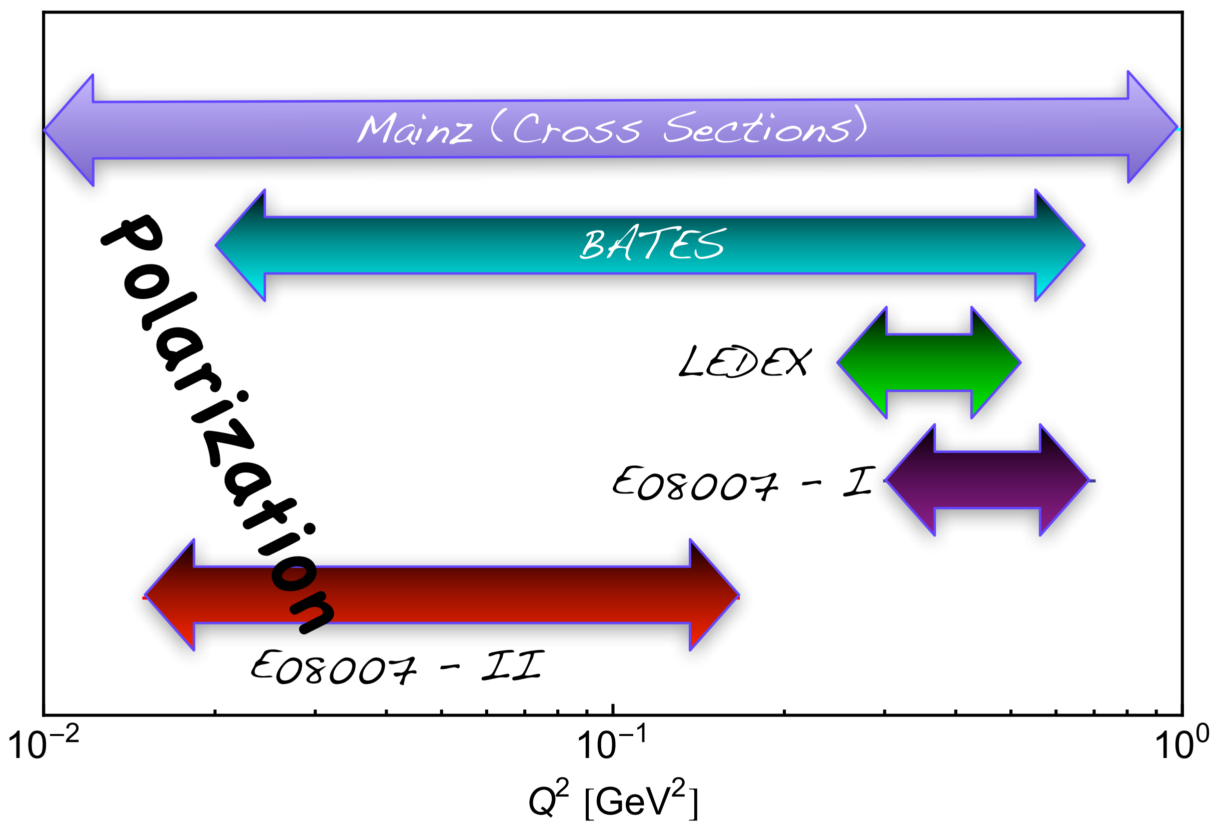


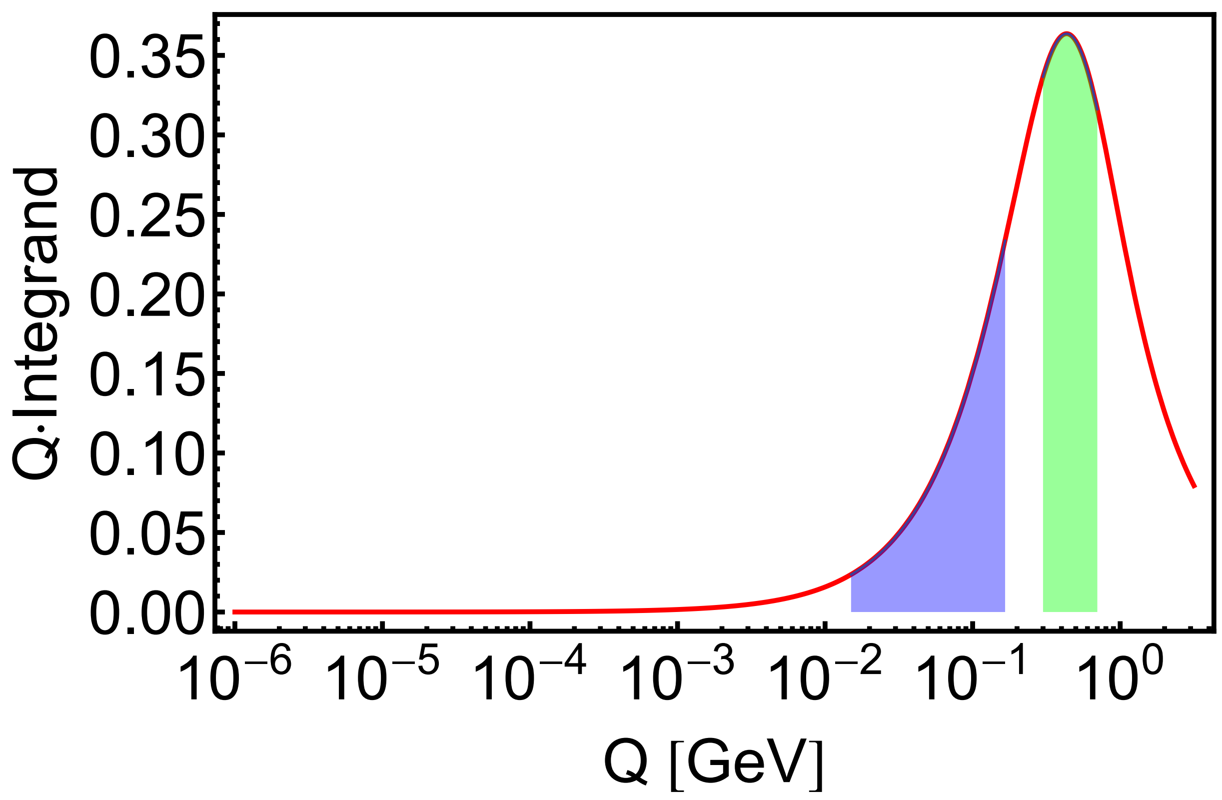


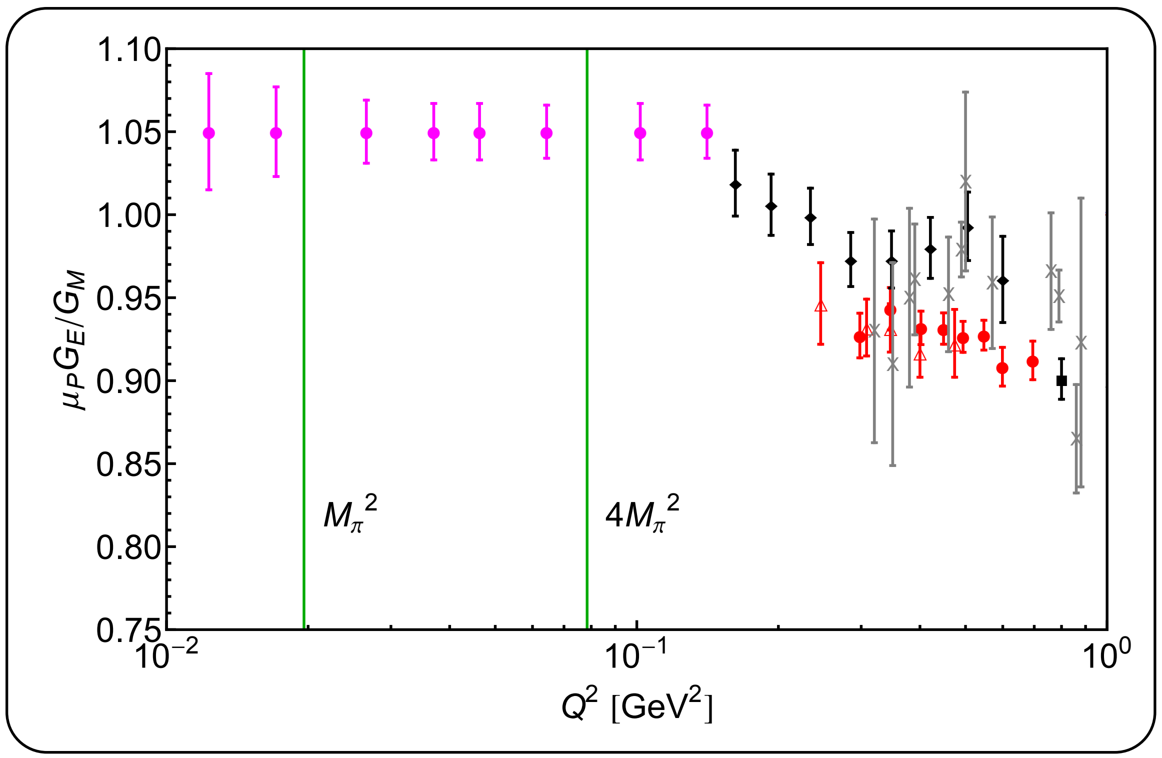
Significant contribution to integral above Q^2=1 GeV^2 and below Q^2=0.01 GeV^2

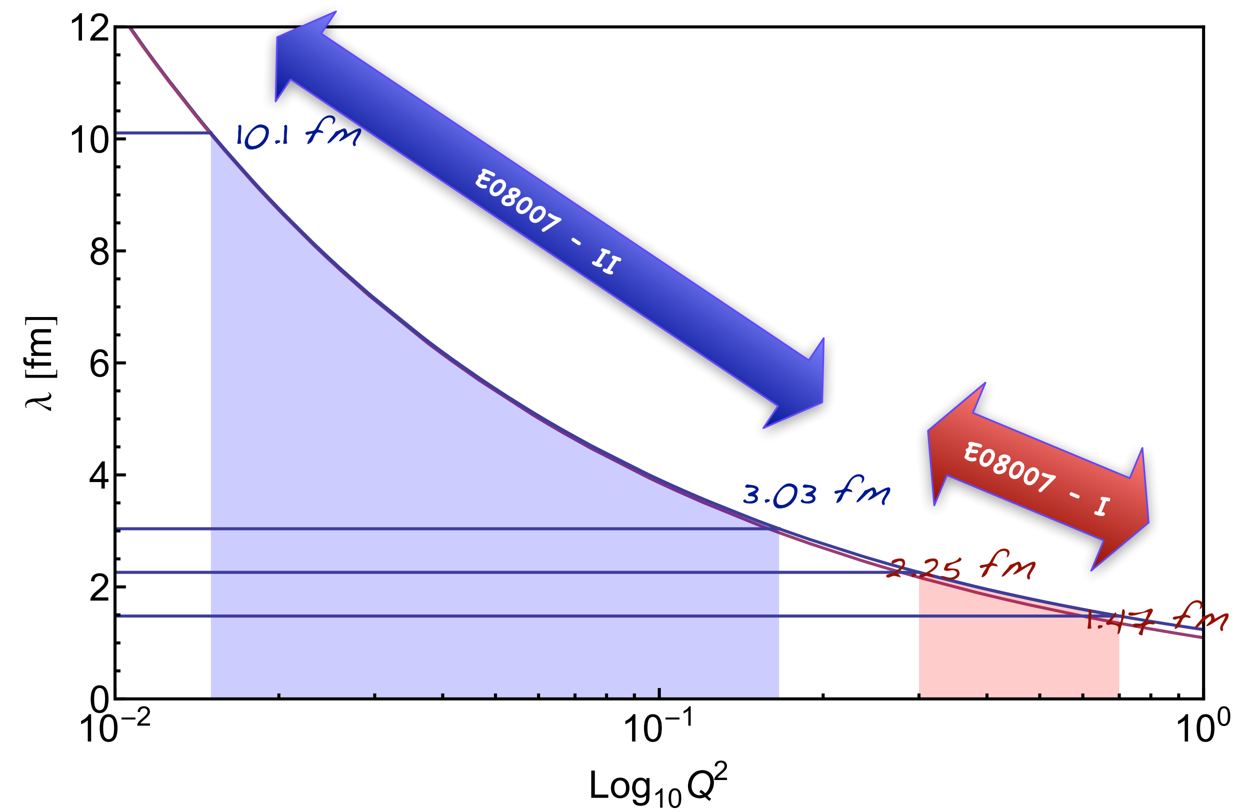
Negligible contribution to uncertainty above Q^2=1 GeV^2

E08007 Coverage









Summary

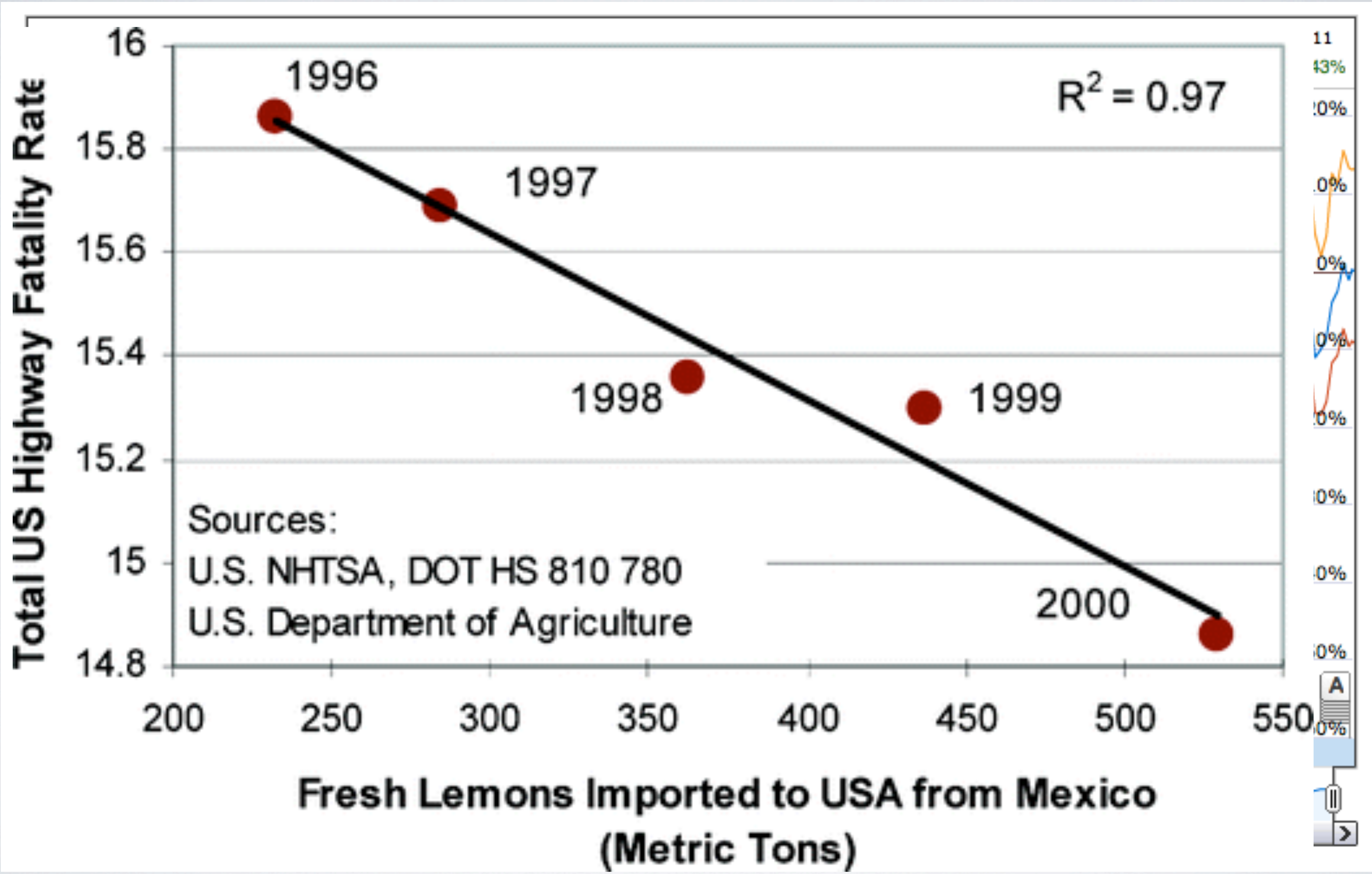
- Form factors are physical, model-independent, observable of the nucleon.
- Many discoveries over the years have changed our understanding of one of the basic constituents of matter and still new issues keep popping up.
- While high energy (and Q^2) are, of course, important, there is great significance 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.

And Finally

And Finally

Zoom: 1d 5d 1m 3m 6m YTD 1y 5y 10y All
Mar 09, 2007 - Nov 15, 2011
.DJI -0.15%
.INX -9.33%
.IXIC +13.43%
20%
10%
0%
-10%
-20%
-30%
-40%
-50%
-60%
2007
2008
2009
2010
2011
Link to this view

And Finally

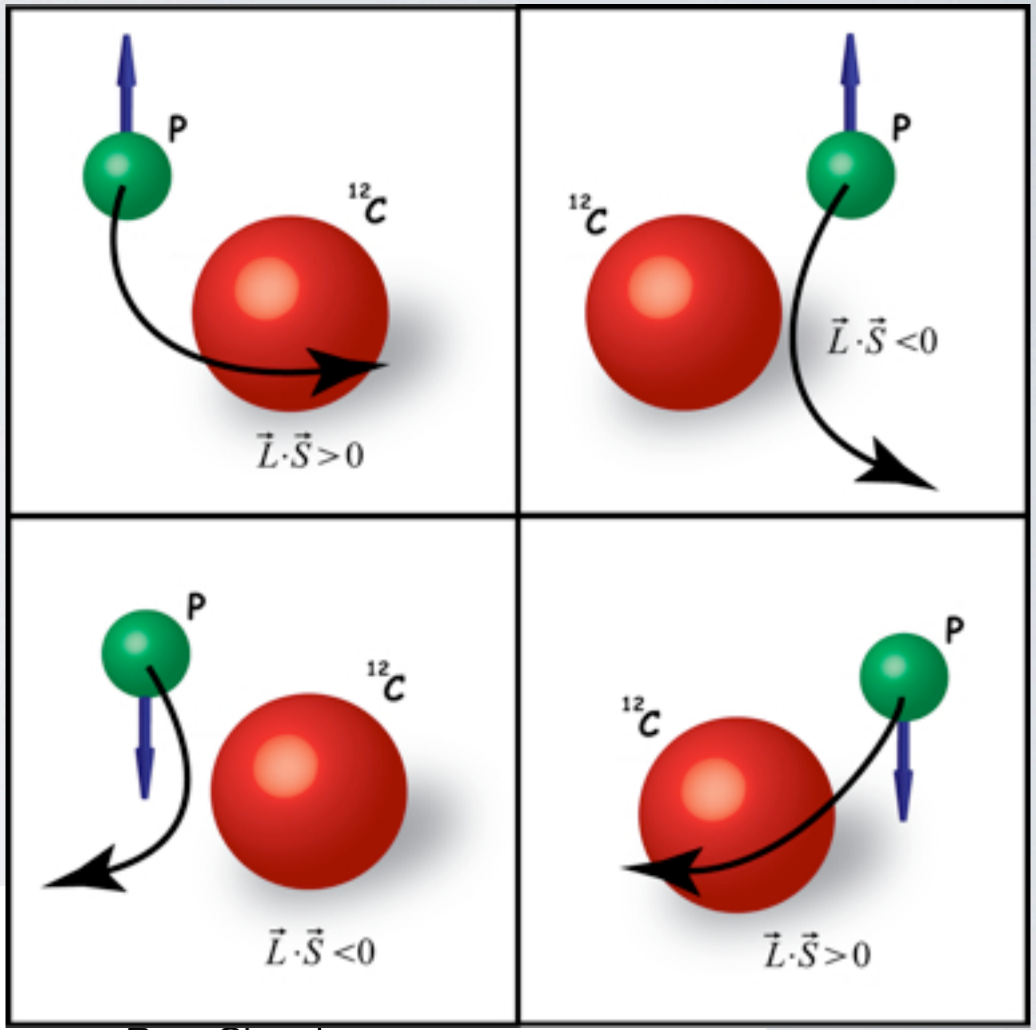


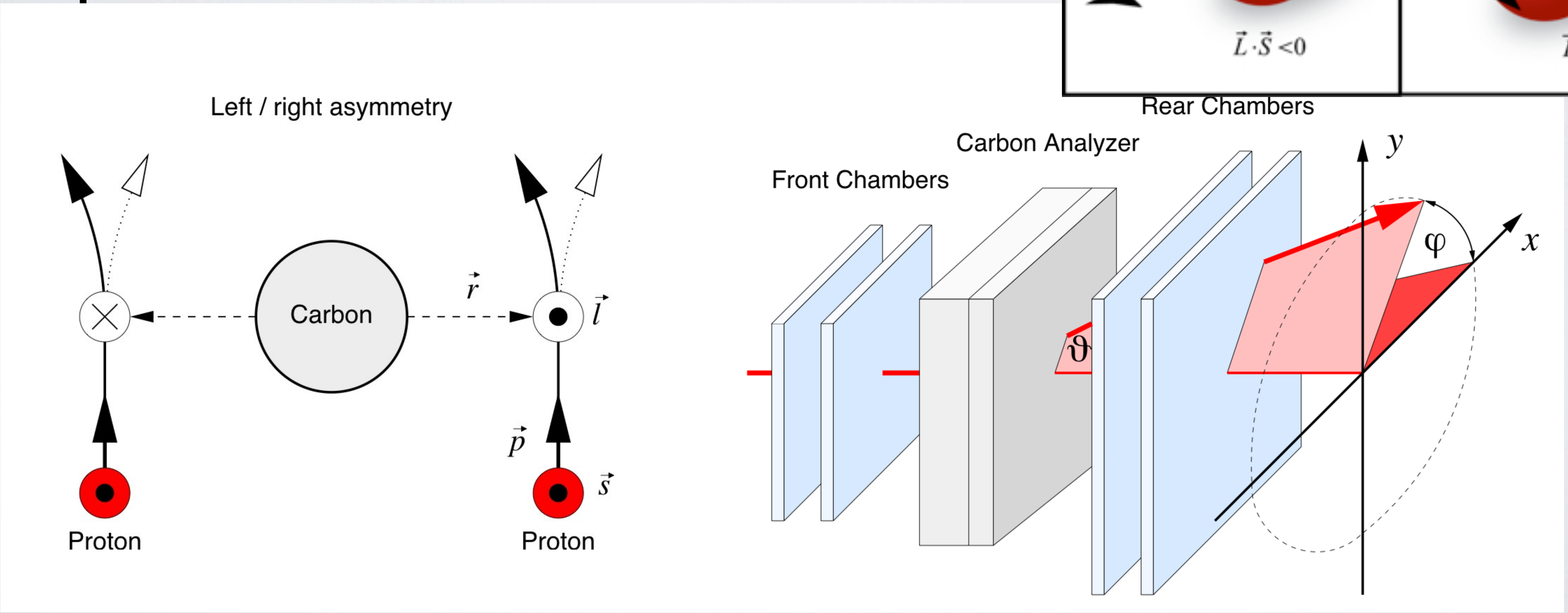
R² = 0.97
1996
1997
1998
1999
2000
Sources:
U.S. NHTSA, DOT HS 810 780
U.S. Department of Agriculture
Total US Highway Fatality Rate
16
15.8
15.6
15.4
15.2
15
14.8
200
250
300
350
400
450
500
550
Fresh Lemons Imported to USA from Mexico
(Metric Tons)

Backup

How to measure the polarization

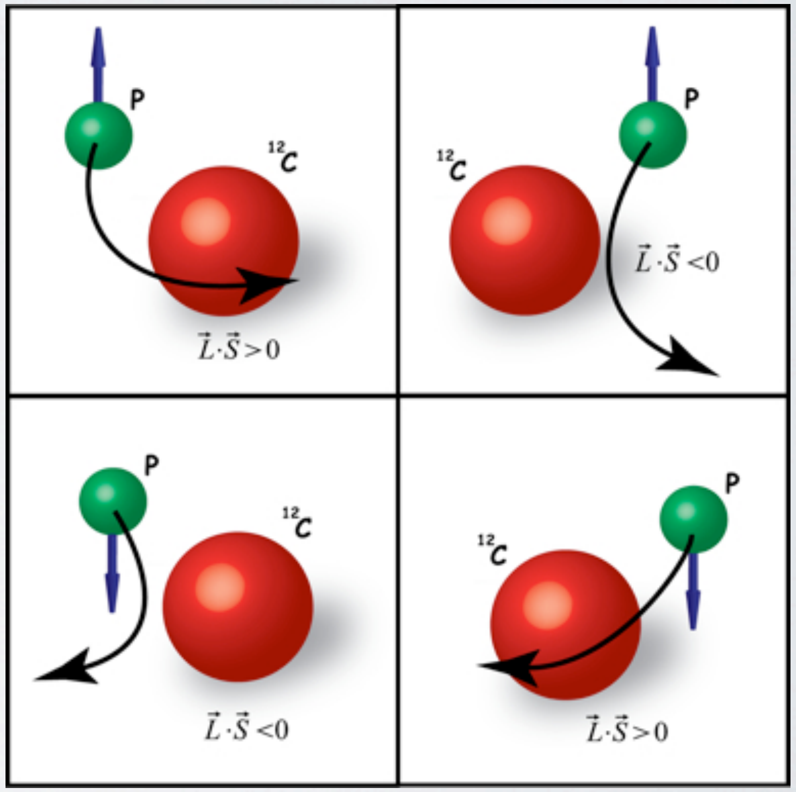
- Scatter recoil nucleons off a nucleus (carbon/hydrogen/...).
- Spin-Orbit coupling causes angular dependence on spin.





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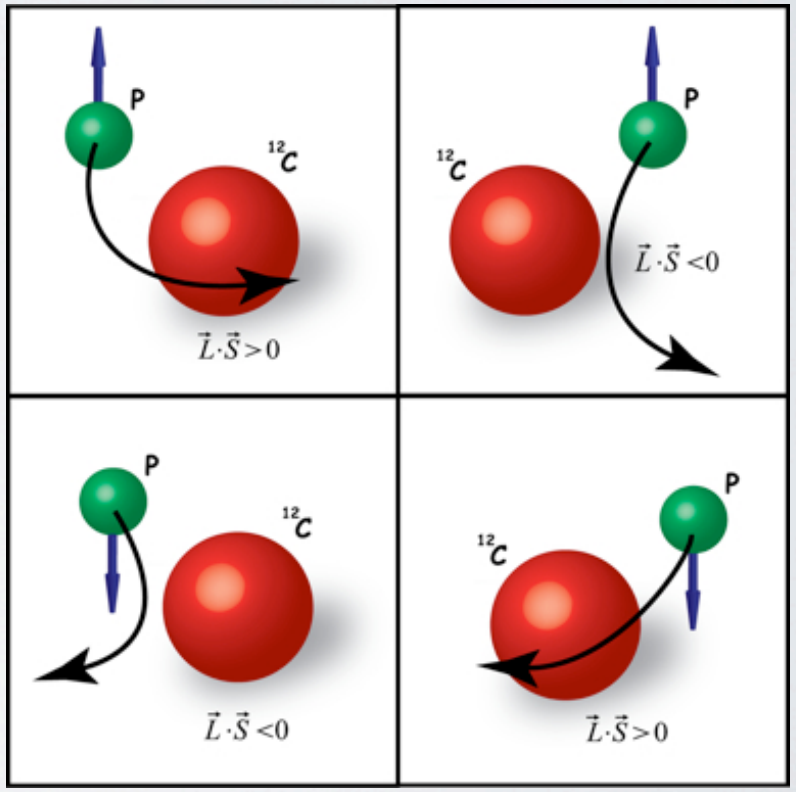
$$N_+ - N_- \quad = \quad N_0(\theta)\varepsilon(\theta) \left\{hA_y(\theta)P_t^{fpp}sin\phi - hA_y(\theta)P_n^{fpp}cos\phi\right\}$$



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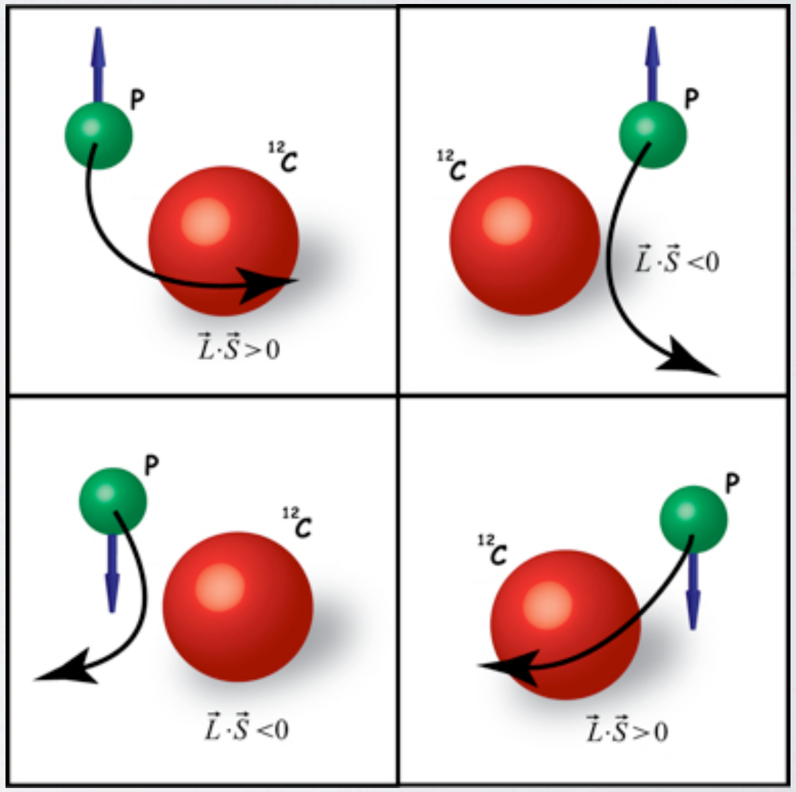
$$\frac{N_0(\theta)\varepsilon(\theta)hA_y(\theta)P_n^{fpp}}{N_0(\theta)\varepsilon(\theta)hA_y(\theta)P_t^{fpp}} = \frac{P_n^{fpp}}{P_t^{fpp}} \propto \frac{G_E}{G_M}$$



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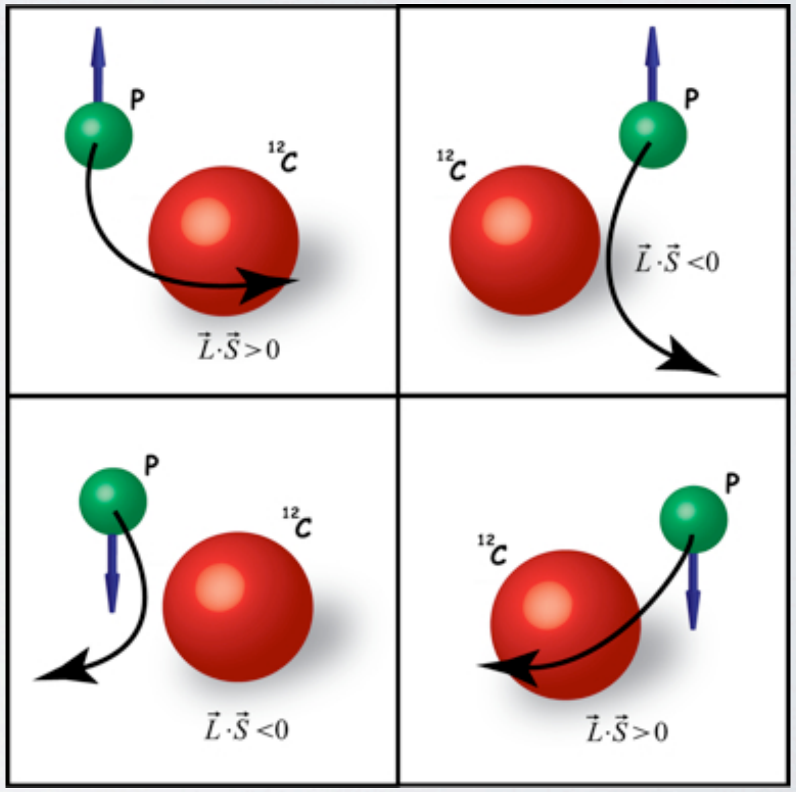

Systematic uncertainties cancel out (to ~0.5%)!

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