Experimental Overview of Nucleon Form Factors at High Momentum Transfer

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ECT* Workshop: Transverse Nucleon Structure at High Momentum Transfer

4/18/2016

Outline

- Introduction
- Proton Form Factors: existing data, open questions, experimental challenges
- Neutron Form Factors: existing data, open questions, experimental challenges
- Overview of high-Q^2 FFs at JLab 12 GeV
  - SBS
  - CLAS12 G_{Mn}
  - Hall A HRS G_{Mp} and Hall C G_{En} polarization transfer
- Summary and conclusions

R. Hofstadter
Nobel Prize 1961

"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

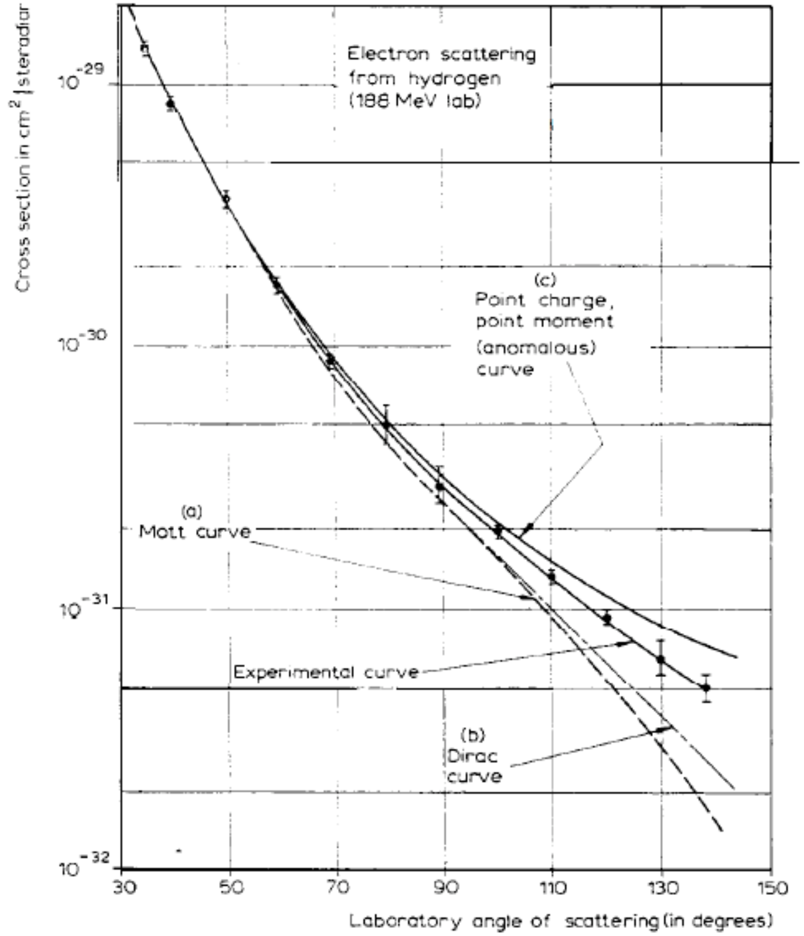
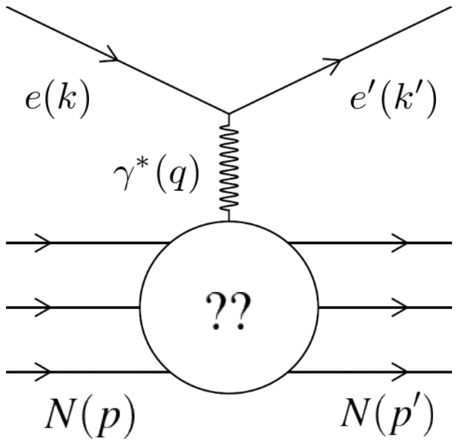


Fig. 9. Electron scattering from the proton at an incident energy of 188 MeV. *Curve (a)* shows the theoretical Mott curve for a spinless point proton. *Curve (b)* shows the theoretical curve for a point proton with a Dirac magnetic moment alone. *Curve (c)* shows the theoretical behavior of a point proton having the anomalous Pauli contribution in addition to the Dirac value of the magnetic moment. The deviation of the experimental curve from the Curve (*c*) represents the effect of form factors for the proton and indicates structure within the proton. The best fit in this figure indicates an rms radius close to $0.7 \cdot 10^{-13}$ cm.

Elastic eN cross section: Rosenbluth formula

$$\mathscr{M} = \frac{4\pi\alpha}{q^2}\bar{u}(k')\gamma^\mu u(k) g_{\mu\nu}\bar{u}(p')\left[F_1(q^2)\gamma^\nu + F_2(q^2)\frac{i\sigma^{\nu\alpha}q_\alpha}{2M}\right]u(p)$$

Invariant amplitude for elastic eN scattering in the one-photon-exchange approximation



- The most general possible form of the nucleon current consistent with Lorentz invariance, parity conservation and gauge invariance is described by two form factors F_1 (Dirac) and F_2 (Pauli):
  - F_1 describes the helicity-conserving amplitude
  - F_2 describes the helicity-flip amplitude (anomalous magnetic moment)

$$G_E \equiv F_1 - \tau F_2$$
$$G_M \equiv F_1 + F_2$$
$$\tau \equiv \frac{Q^2}{4M^2}$$

$$\frac{d\sigma}{d\Omega_e} = \frac{\alpha^2}{Q^2}\left(\frac{E'_e}{E_e}\right)^2 \cot^2\frac{\theta_e}{2}\left[\frac{G_E^2 + \frac{\tau}{\varepsilon}G_M^2}{(1+\tau)}\right],$$

$$\varepsilon^{-1} \equiv 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}$$

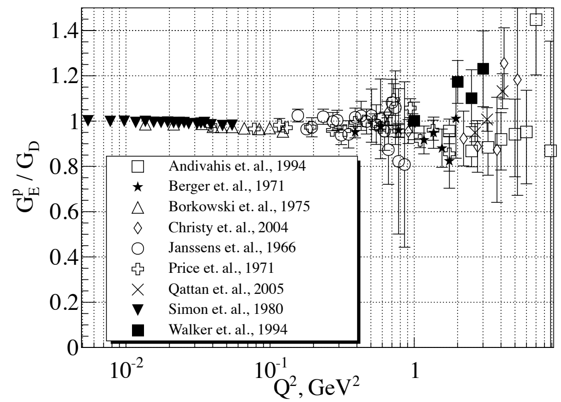
Differential cross section in the nucleon rest frame: ***Rosenbluth formula***

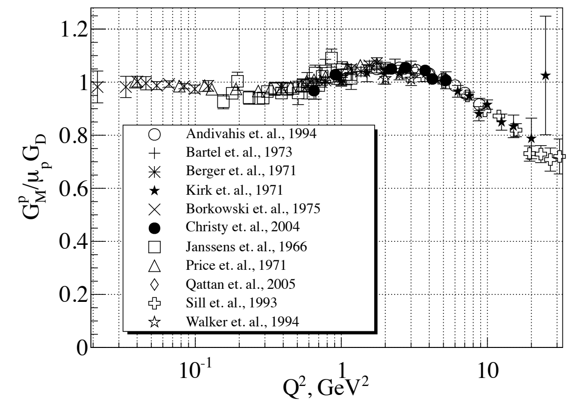
- *Sachs Form Factors* G_E (electric) and G_M (magnetic), are experimentally convenient linearly independent combinations of F_1, F_2

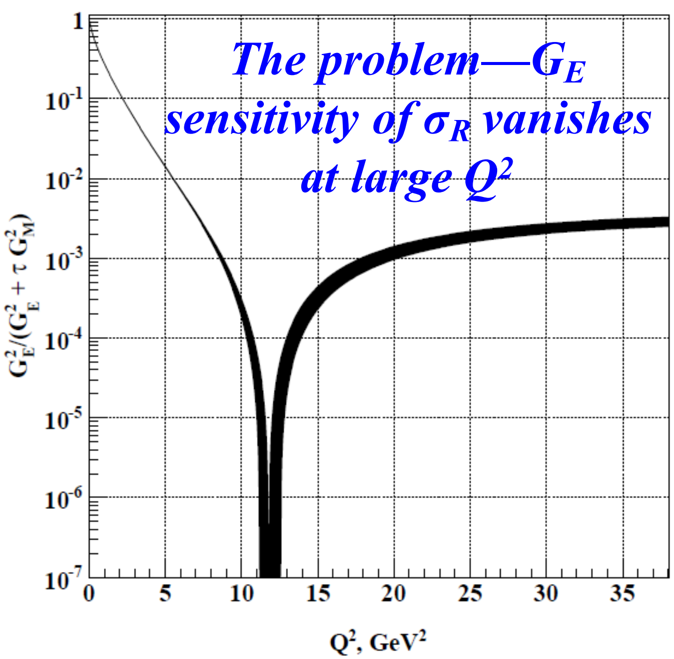
The Proton Form Factors—Cross Section Data

$$\sigma_R \equiv \frac{\varepsilon(1+\tau)\sigma}{\sigma_{Mott}} = \varepsilon G_E^2 + \tau G_M^2$$

Rosenbluth Separation Method: Separate G_E^2, G_M^2 by measuring the ε-dependence of the ep→ep cross section at fixed Q^2







G_{Ep} and G_{Mp} Rosenbluth Data: $G_E \sim G_M/\mu \sim G_D$

$$G_D \equiv \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-2}$$

$$\Lambda^2 \approx 0.71 \text{ GeV}^2$$

- ep→ep cross section data have been used to extract G_E from ~0.005-9 GeV^2 and G_M from ~0.01-31 GeV^2
- Data roughly follow "dipole" form
- In the non-relativistic limit, G_E, G_M are Fourier transforms of proton charge, magnetization distributions
- Dipole FF → Exponential radial charge density

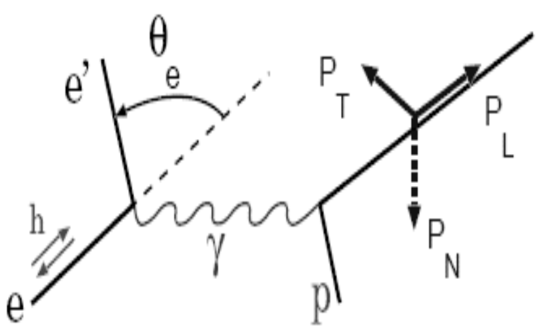
Proton FFs—Polarization Transfer Method

$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\frac{r}{1+\frac{\varepsilon}{\tau}r^2}$$

$$P_\ell = \frac{\sqrt{1-\varepsilon^2}}{1+\frac{\varepsilon}{\tau}r^2}$$

$$P_n = 0$$

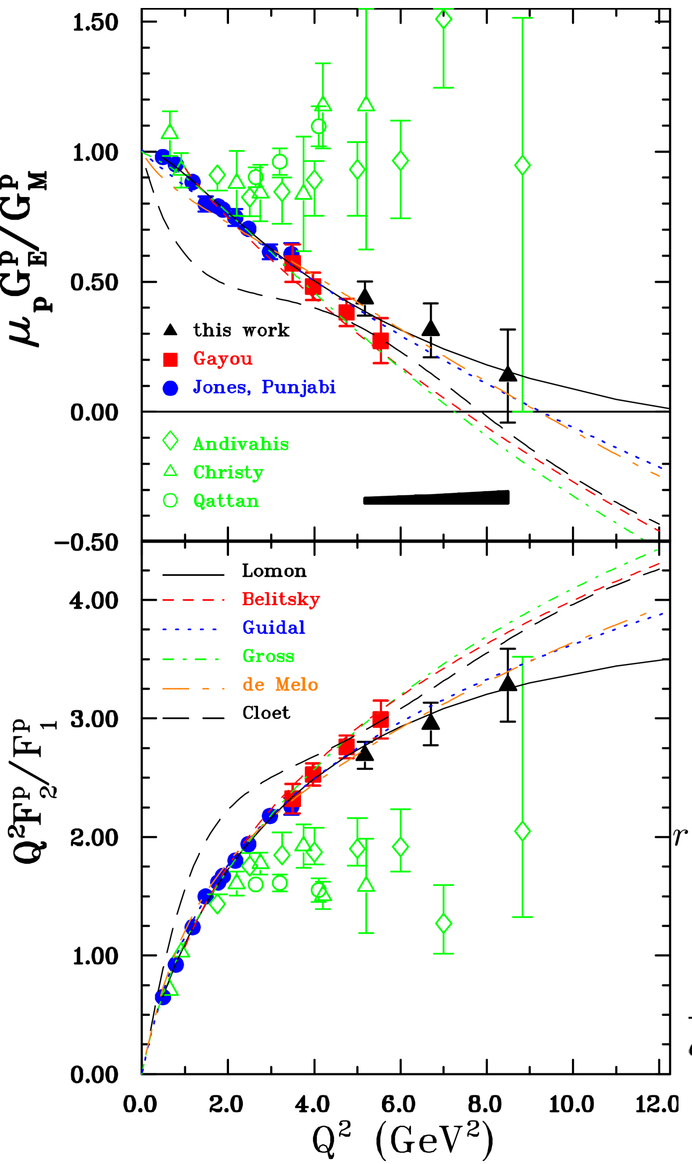
$$r \equiv \frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}} \equiv \frac{R}{\mu_p}$$



$$p(\vec{e}, e'\vec{p})$$

- Akhiezer and Rekalo (1968) + Arnold, Carlson, Gross (1981):
  - ***Derived relations between transferred polarization components in elastic eN scattering and the ratio of electromagnetic FFs $R = \mu G_E/G_M$***
- Perdrisat + Punjabi, 1993 proposal to CEBAF PAC: A ***simultaneous*** measurement of the two recoil polarization components in a polarimeter determines the FF ratio while cancelling many systematic uncertainties (beam polarization, analyzing power)
- ***The ratio of polarization components is directly proportional to G_E/G_M, and therefore much more sensitive to G_E at large Q^2 than the Rosenbluth method***
- Experiments E93-027/GEp-I (1998) and E99-007/GEp-II (2000), carried out in JLab's Hall A, and E04-108/GEp-III (2008) measured the proton FF ratio using this method for Q^2 = 0.5-8.5 GeV^2

Results of Polarization Transfer Experiments at “large” Q^2



- GEp-I: Phys. Rev. Lett. 84, 1398 (2000)
  - **766 INSPIRE-HEP citations (4/17/2016)**
- GEp-II: Phys. Rev. Lett. 88, 092301 (2002)
  - **696 INSPIRE-HEP citations (4/17/2016)**
- GEp-III: Phys. Rev. Lett. 104, 242301 (2010)
  - **178 INSPIRE-HEP citations (4/17/2016)**
- ***Extraction of the same physical quantity from different experimental observables with different results!***
- ***Among the most widely cited results from JLab***

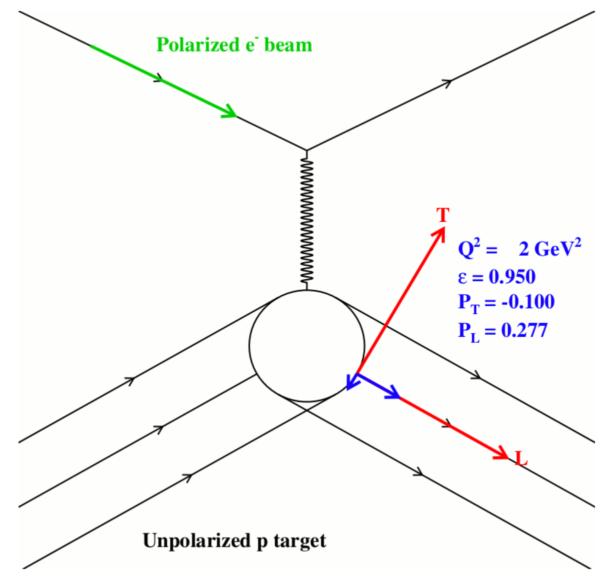
$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\frac{r}{1+\frac{\varepsilon}{\tau}r^2}$$

$$P_\ell = \frac{\sqrt{1-\varepsilon^2}}{1+\frac{\varepsilon}{\tau}r^2}$$

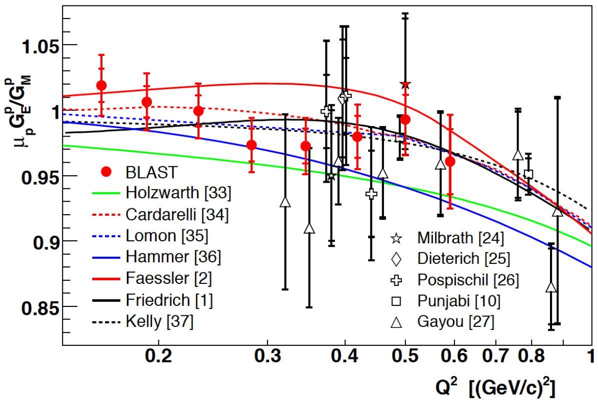
$$P_n = 0$$

$$r \equiv \frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}} \equiv \frac{R}{\mu_p}$$

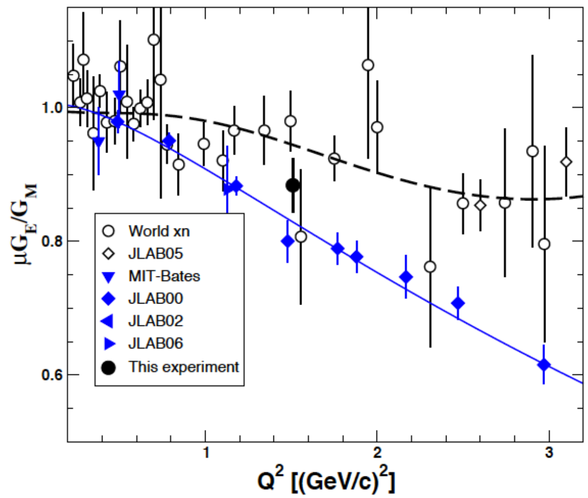
$$\frac{d\sigma}{dQ^2} = \frac{\pi\alpha^2}{Q^2 E_e^2 \tan^2\left(\frac{\theta_e}{2}\right)}\left[\frac{\varepsilon G_E^2 + \tau G_M^2}{\varepsilon(1+\tau)}\right]$$



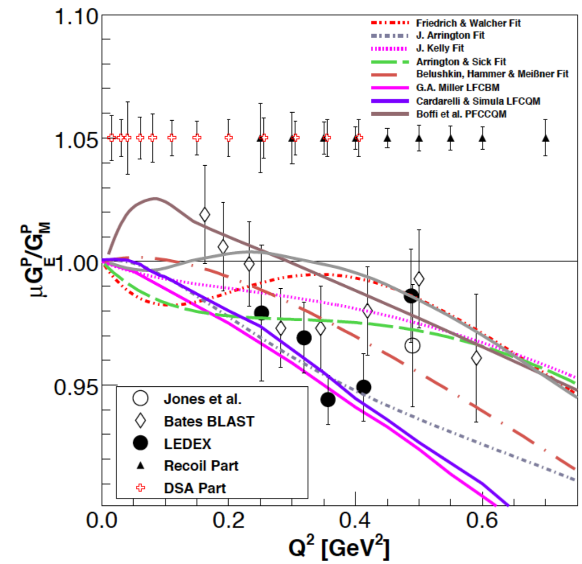
Proton FFs—G_E/G_M from beam-target double-spin asymmetry



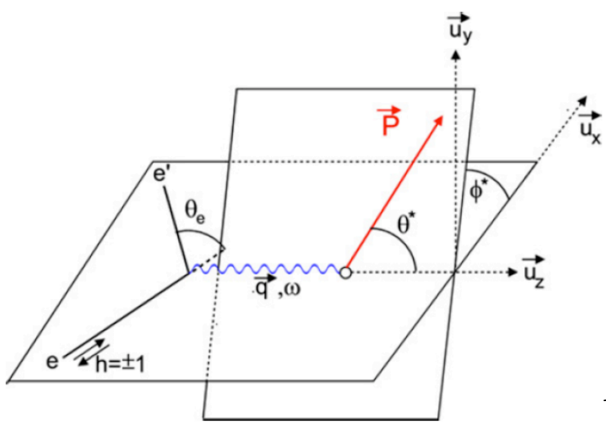
Crawford *et al.* (BLAST collaboration): Phys. Rev. Lett., 98, 052301 (2007)



Jones *et al.*, Phys.Rev.C74:035201,2006

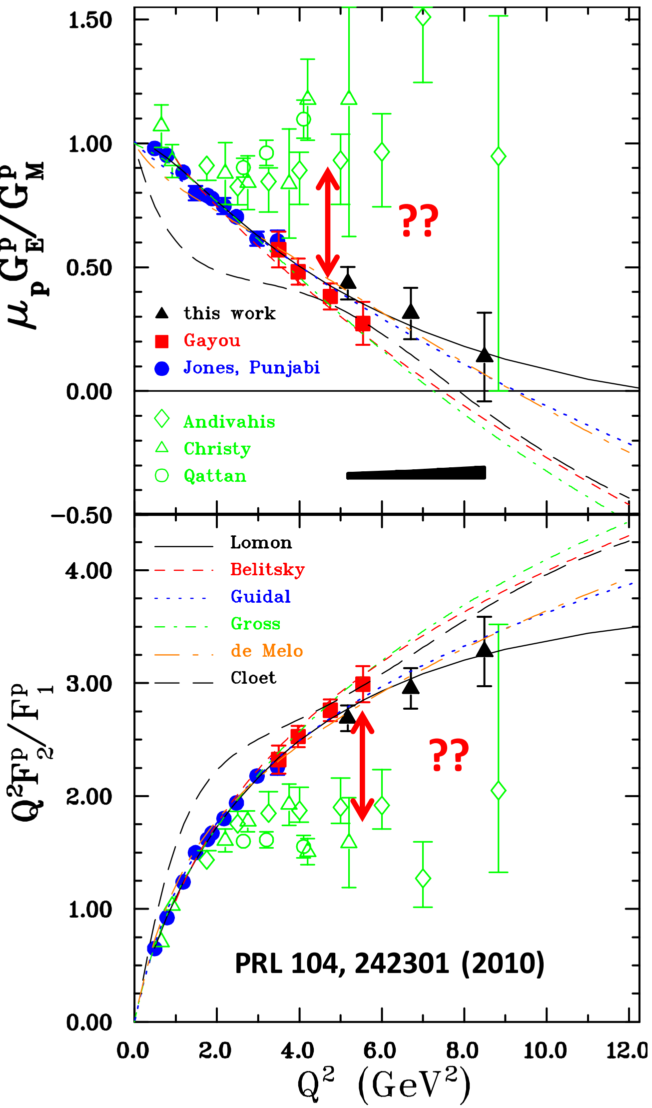


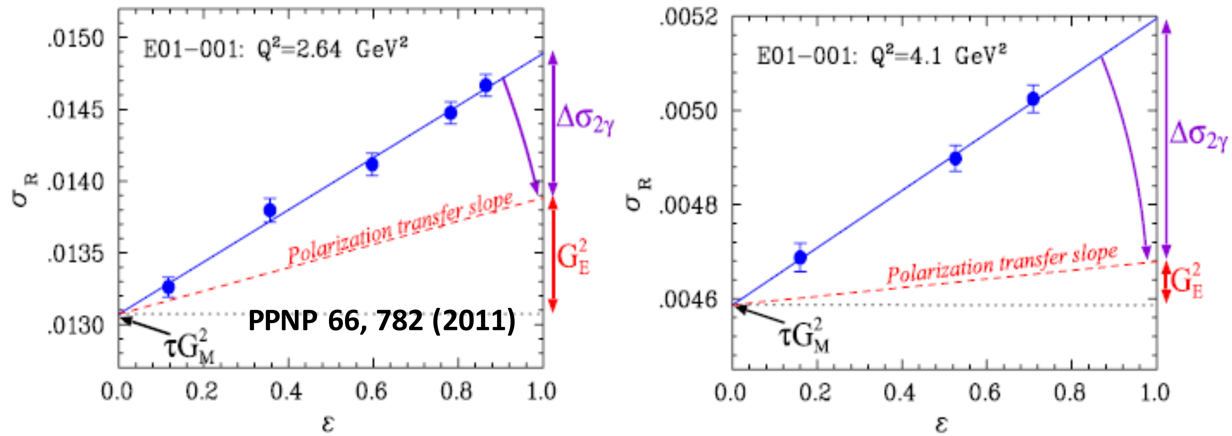
JLab E08-007: low-Q^2 G_E/G_M: recoil polarization part published, X. Zhan *et al.*, Phys.Lett. B705 (2011) 59-64, polarized target data collected 2012



$$A_{ep} = -\frac{P_B P_T}{1+\frac{\varepsilon r^2}{\tau}}\left[\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\sin\theta^*\cos\phi^* r + \sqrt{1-\varepsilon^2}\cos\theta^*\right]$$

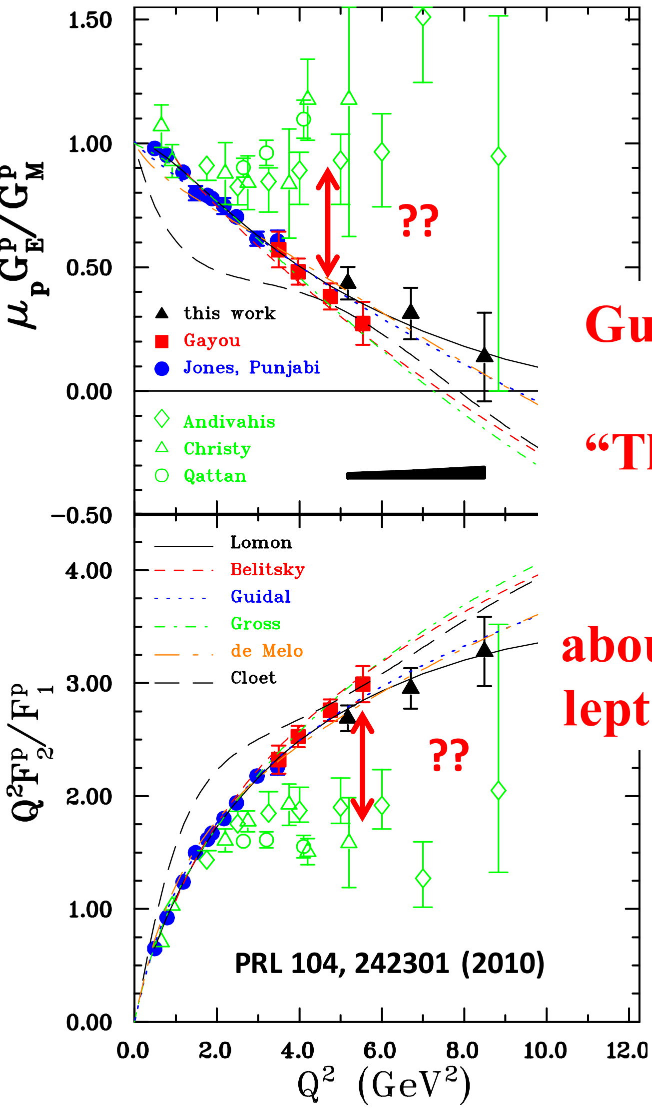
The G_{Ep} "Crisis"

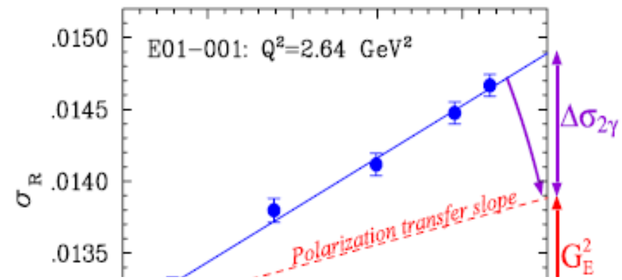


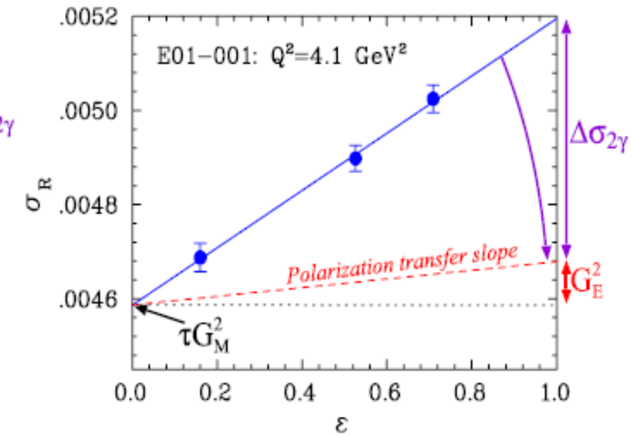


- ***Two methods of measuring the same physical quantity yield radically different results!!***
- A general consensus has emerged that polarization data most reliably determine G_{Ep}—vanishing sensitivity of the cross section to G_{Ep} as Q^2 increases
- Discrepancy still not completely understood:
  - Attributed to previously-neglected two-photon-exchange (TPEX) and higher-order contributions
  - ***TPEX cannot presently be calculated model-independently!!!***

The G_{Ep} "Crisis"







Guichon and Vanderhaeghen, PRL 91, 142303 (2003): "This discrepancy is a serious problem as it generates confusion and doubt about the whole methodology of lepton scattering experiments."

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fferent results!!

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- Discrepancy still not completely understood:
  - Attributed to previously-neglected two-photon-exchange (TPEX) and higher-order contributions
  - *TPEX cannot presently be calculated model-independently!!!*

Born Approximation + "Standard" Radiative Corrections

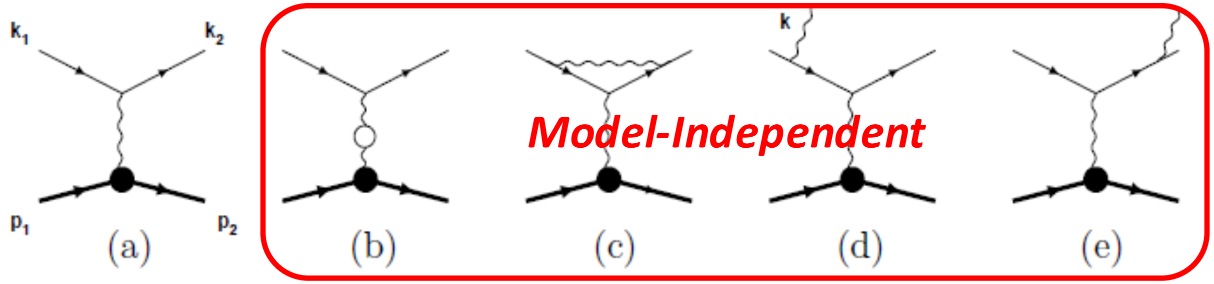


Figure: PRD 64, 113009 (2001)

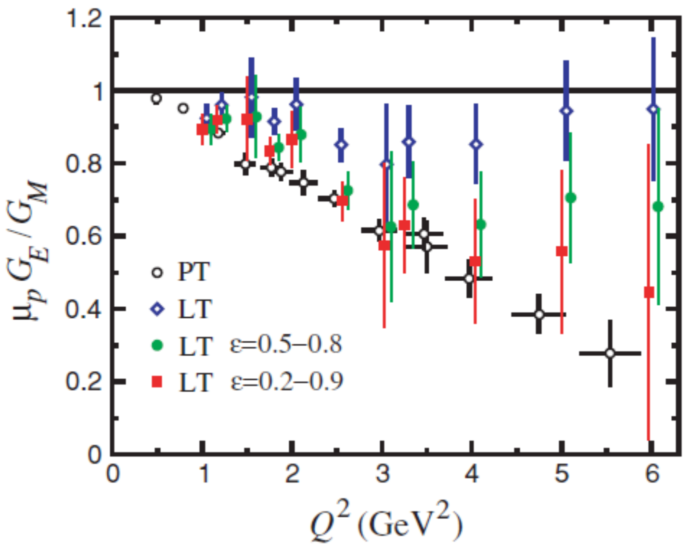
Fig. 1. *Feynman graphs contributing to radiatively corrected cross sections of elastic lepton-nucleus scattering: Born (a), additional virtual particles (b,c) and real photon emission (d,e) contributions.*

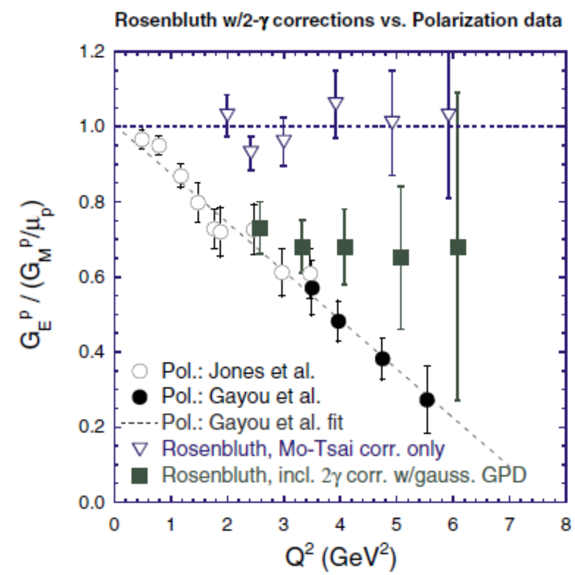
$$\begin{aligned}
\mathcal{J}^\mu(0) &= \bar{u}(P')\left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M}\right]u(P) \\
G_E &= F_1 - \tau F_2 \\
G_M &= F_1 + F_2 \\
\frac{d\sigma}{d\Omega_e} &= \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2\left[\frac{G_E^2+\tau G_M^2}{1+\tau}\cot^2\frac{\theta_e}{2} + 2\tau G_M^2\right] \\
&= \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} \times \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)} \\
\tau &= \frac{Q^2}{4M^2}, \epsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}
\end{aligned}$$

Born approximation dσ and asymmetries

$$\begin{aligned}
P_t &= -\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\frac{r}{1+\frac{\epsilon}{\tau}r^2} \\
P_\ell &= \frac{\sqrt{1-\epsilon^2}}{1+\frac{\epsilon}{\tau}r^2} \\
r \equiv \frac{G_E}{G_M} &= -\frac{P_t}{P_\ell}\sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}} \equiv \frac{R}{\mu} \\
A &= -\frac{1}{1+\frac{\epsilon}{\tau}r^2}\left[\sqrt{\frac{2\epsilon(1-\epsilon)}{\tau}}\sin\theta^*\cos\phi^* r + \right. \\
&\left. \sqrt{1-\epsilon^2}\cos\theta^*\right]
\end{aligned}$$

TPEX—Different Theoretical Approaches





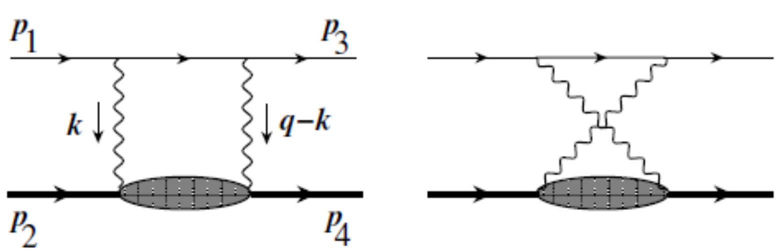
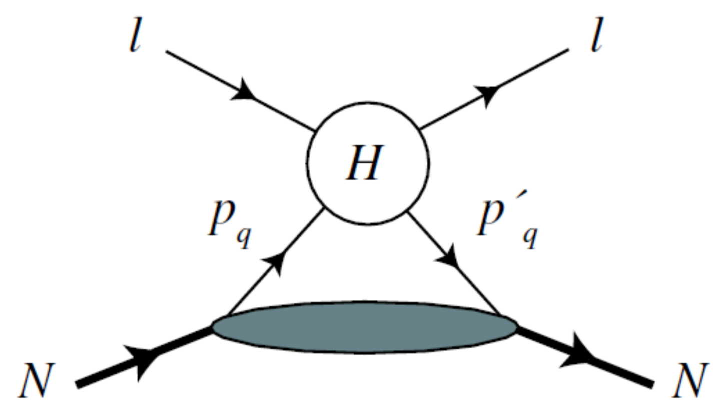


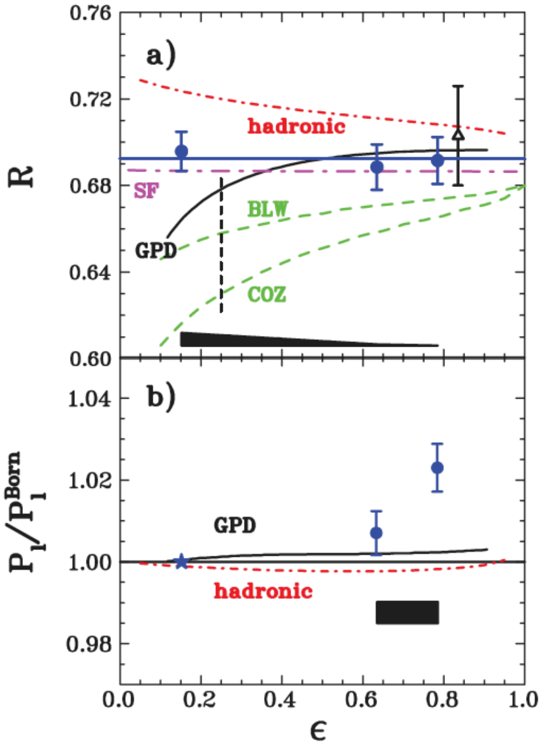
FIG. 1. Two-photon exchange box and crossed box diagrams for elastic electron-proton scattering.



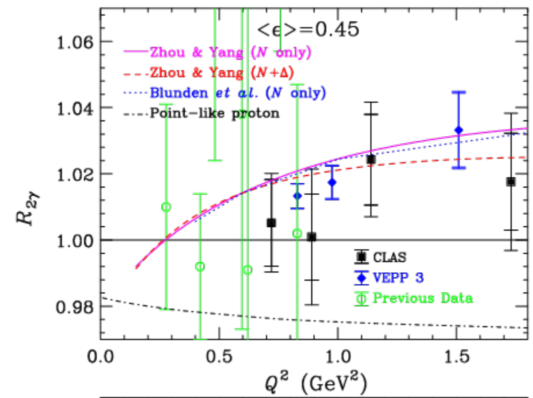
"Hadronic": PRC 72, 034612 (2005)

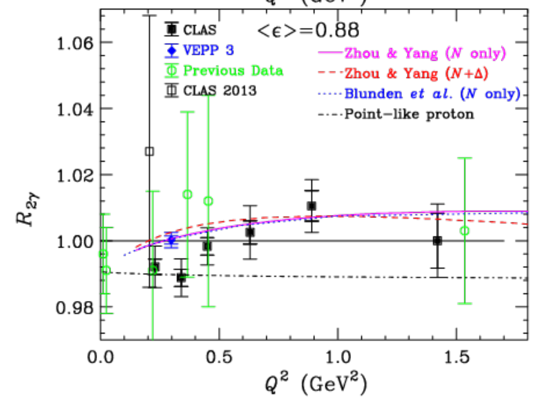
"GPD": PRD 72, 013008 (2005)

TPEX—Experimental Signatures (see M. Kohl talk Tuesday afternoon for more detail)

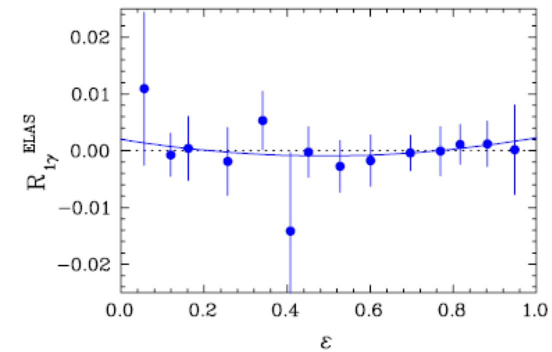


- Angular dependence of polarization transfer observables at fixed Q^2: PRL 106, 132501 (2011)

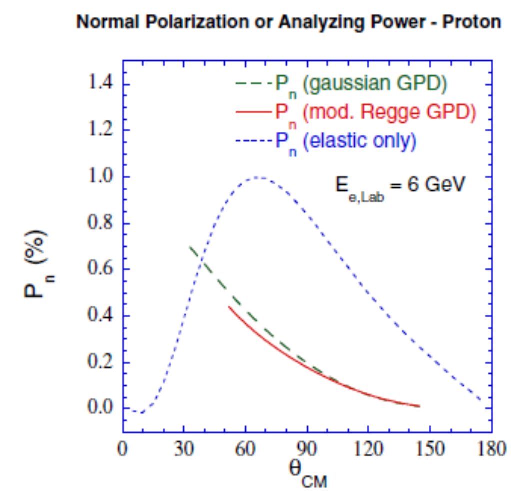




- e^+/e^- cross section ratio: CLAS, VEPP 3, OLYMPUS

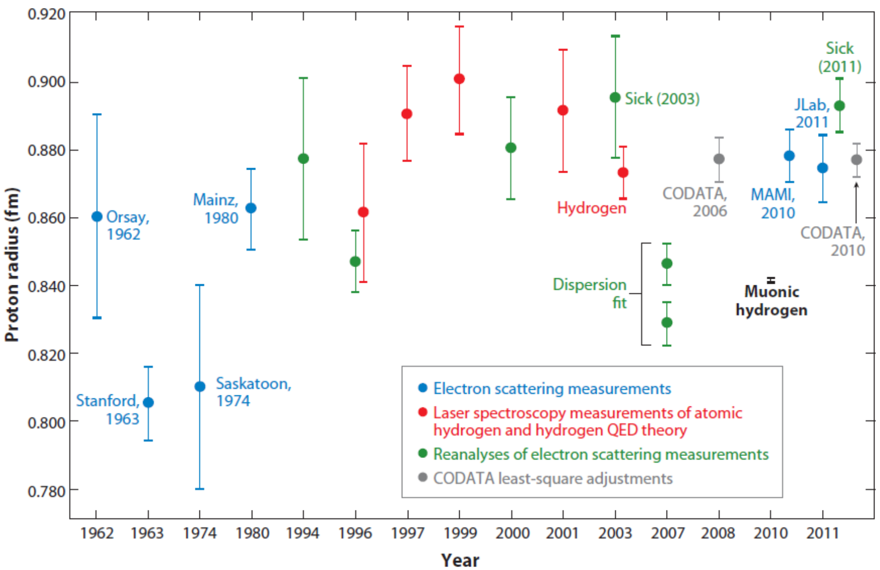


- Non-linearity of the Rosenbluth plot: Hall C 2007 data

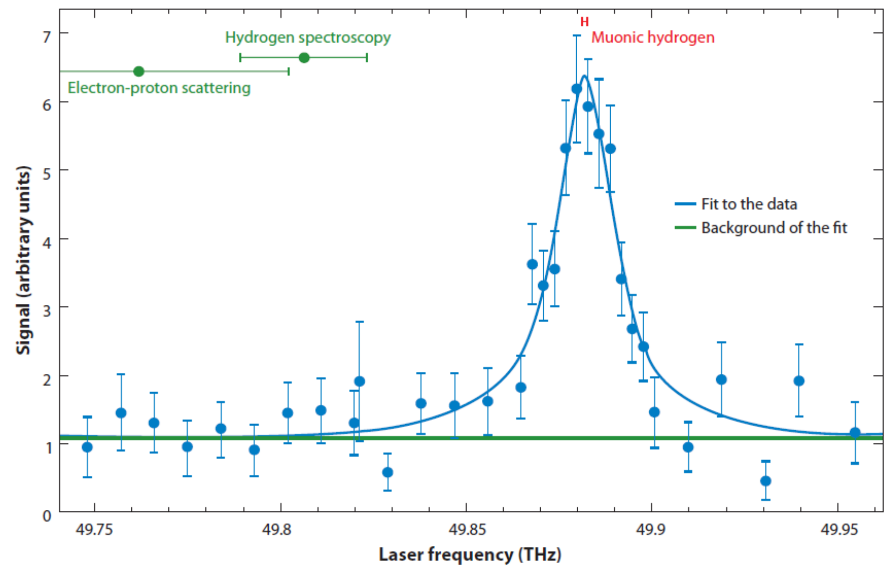


- $A_N = P_N$ (0 in Born): Virtually no data exist!

The low-Q^2 regime and the proton radius puzzle



Pohl, Gilman, Miller, Pachucki: Ann. Rev. Nucl. Part. Sci. 63 (2013) 175-204



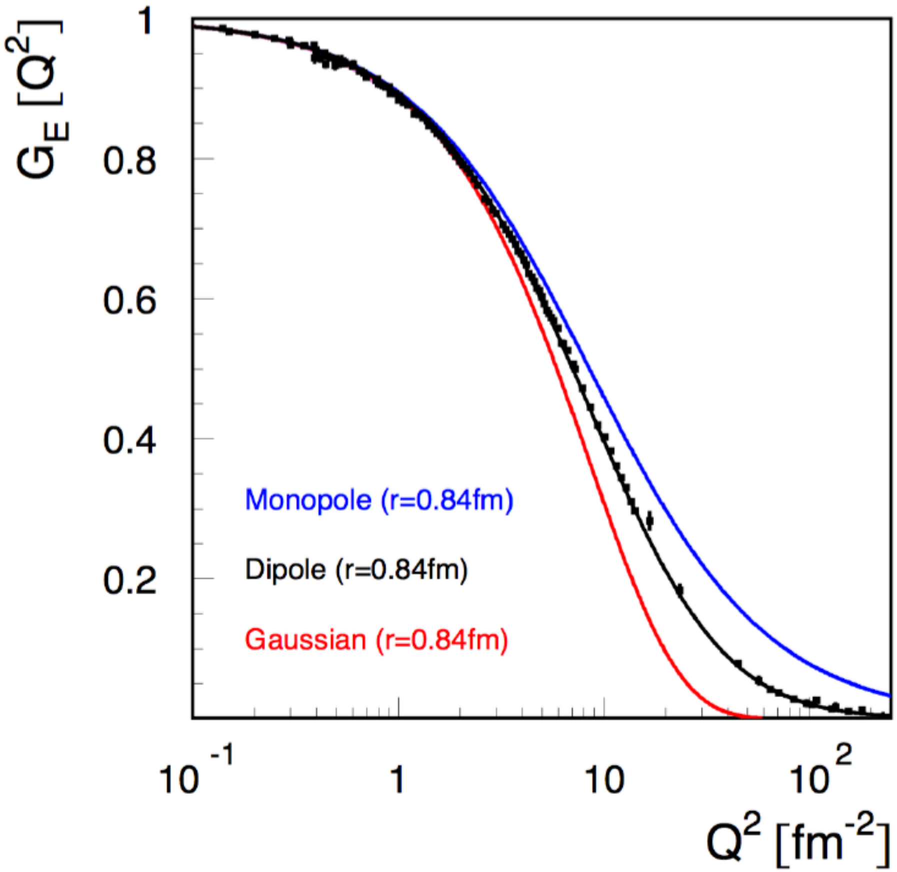
Pohl R, et al. (CREMA Collab.) *Nature* 466:213 (2010)

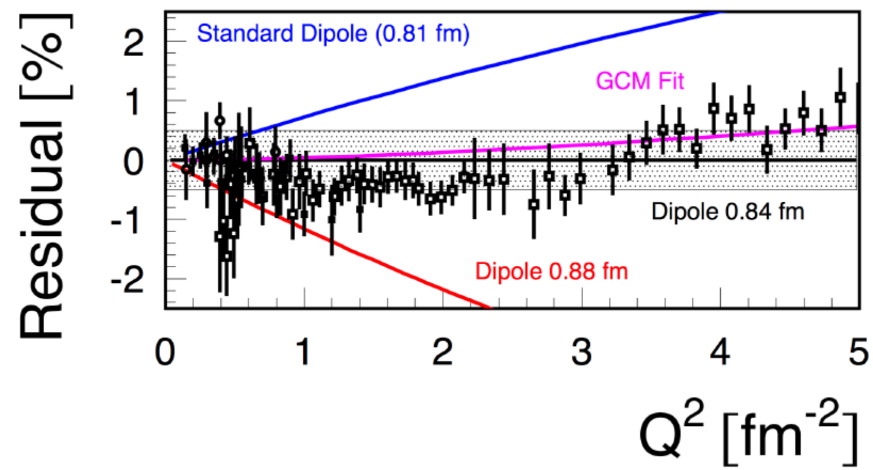
- Charge radius of the proton: extractions from electronic hydrogen spectroscopy and elastic electron scattering agree on a value $r_p \sim 0.88$ fm
- Lamb shift in muonic hydrogen atom has much higher ($\sim 10^7$) sensitivity to proton radius because muon is much heavier than electron, spends more time "inside" the proton:

$$a_{\mu H} = a_{eH}\left(\frac{m_e}{m_\mu}\right) \approx 256 \text{ fm}$$

- New experiments planned:
  - ep scattering at ultra-low Q^2
  - μp elastic scattering

Is r_p from electron scattering consistent with muonic hydrogen results after all?

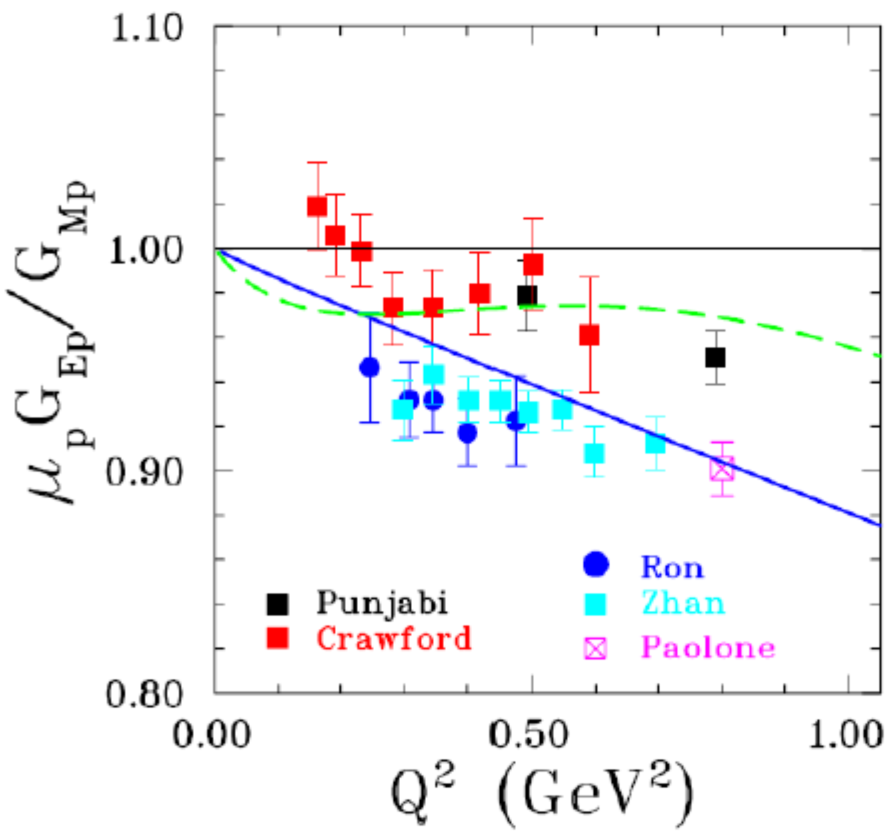




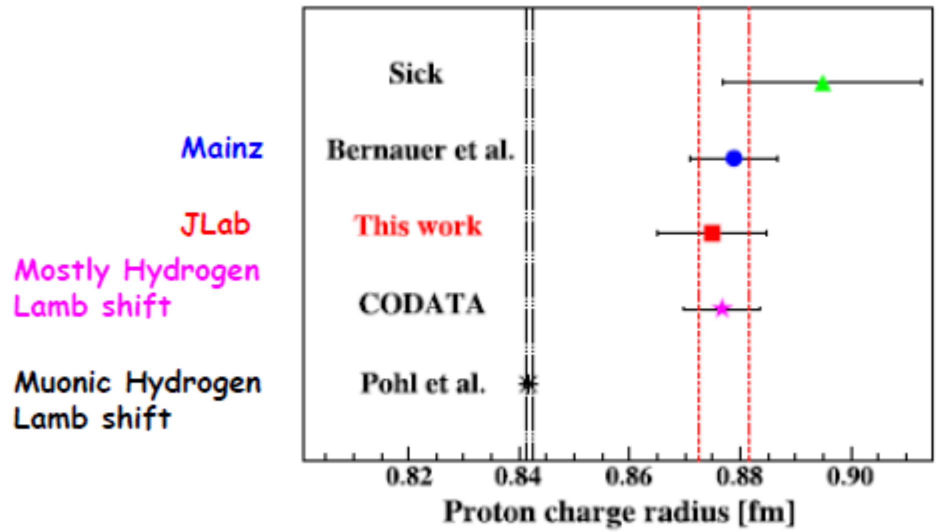
D. Higinbotham *et al.*, arXiv:1510.01293v2 [nucl-ex] 31 Mar 2016

- New statistical analysis of elastic *ep* scattering data suggests that electron scattering data are consistent with the muonic hydrogen determination of the proton charge radius, and that "the electronic hydrogen spectroscopy data are the outliers"
- Extension of modified dipole fit with r_p = 0.84 fm to large Q^2 describes cross section data rather well, but does not (and cannot) describe the observed falloff of the polarization data. The range of data described is notable nonetheless (and the conclusion of a smaller r_p compared to some other analyses does not depend on the dipole assumption).

Systematic issues with low-Q^2 G_{Ep} polarization data!



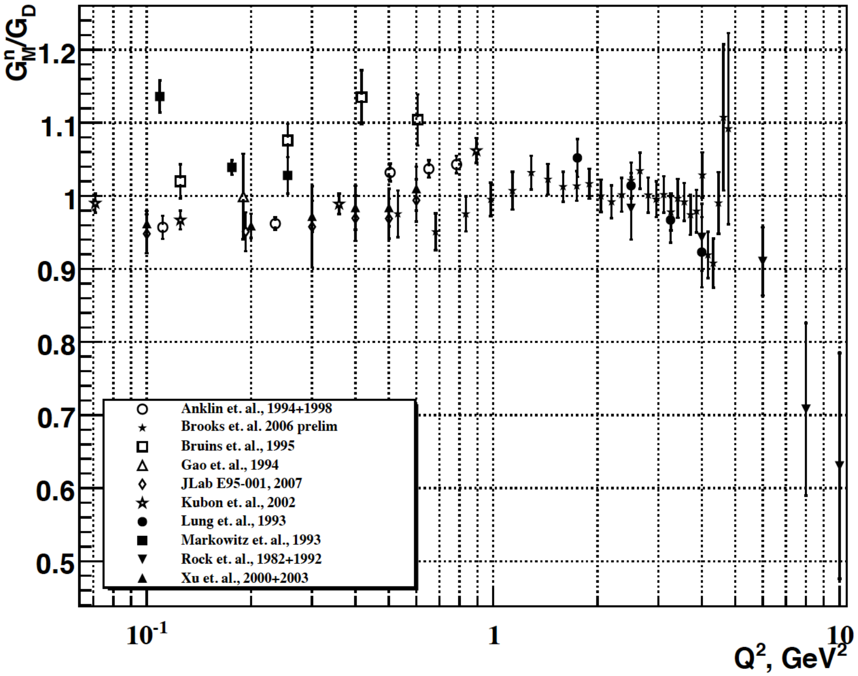
Beam-target asymmetry and recoil polarization data disagree at low Q^2!

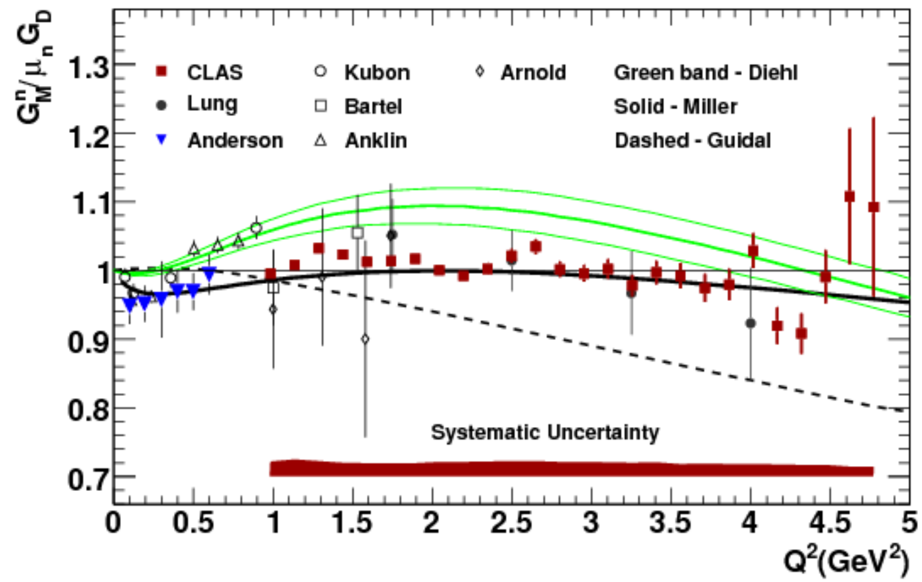


r_p from muonic hydrogen Lamb shift disagrees with ep scattering and electronic hydrogen Lamb shift determinations

Tension among low-Q^2 G_E/G_M ratios from polarization observables not yet understood, but at least one of these experiments has to have an unaccounted-for source of systematic error!

Neutron form factors—G_{Mn} existing data



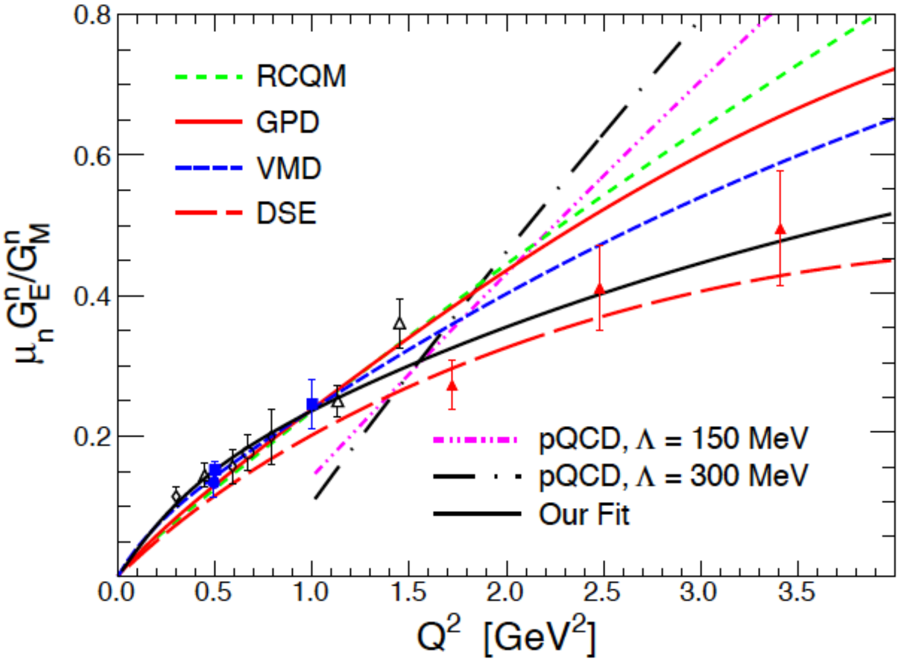


Lachniet *et al.*, CLAS Collaboration, Phys.Rev.Lett. 102 (2009) 192001

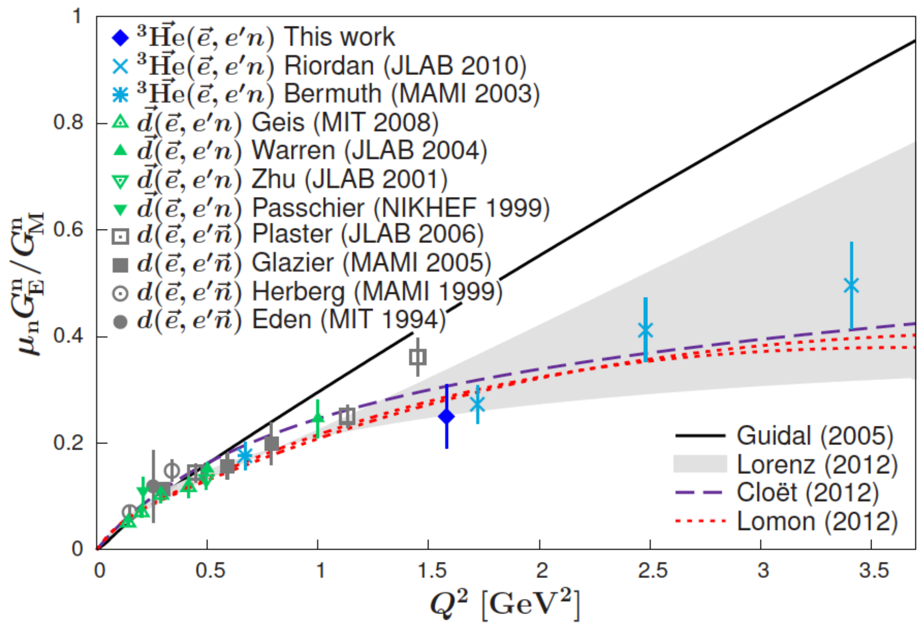
- Three main methods have been used to measure G_{Mn}:
  - "Ratio" method: measure cross section ratio of d(e,e'n)p/d(e,e'p)n in quasi-elastic kinematics
  - Absolute d(e,e'n)p quasi-elastic cross section measurement
  - Beam-target double-spin asymmetry* in inclusive quasi-elastic ^{3}He(e,e')

- **Note: double-spin asymmetry method for G_{Mn} would not work for a free neutron target, as the free nucleon asymmetry depends only on the ratio G_E/G_M, and not G_E or G_M independently.*
- Widest combined Q^2 coverage and precision from recent CLAS 6 GeV data from $1 < Q^2 < 5$ GeV^2—consistent with "standard" dipole
- Consistency issues in low-Q^2 data

Neutron form factors—G_{En} existing data



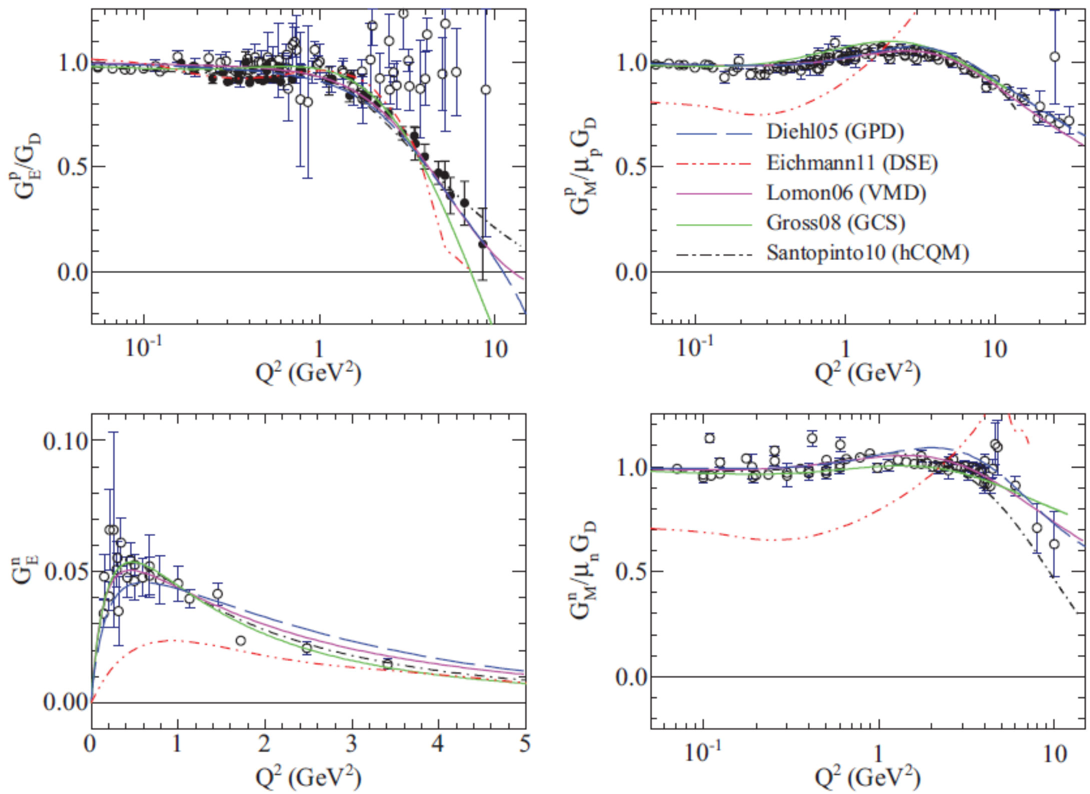
Riordan *et al.*, Phys. Rev. Lett. 105, 262302 (2010)



Schlimme *et al.*, Phys.Rev.Lett. 111 (2013), 132504

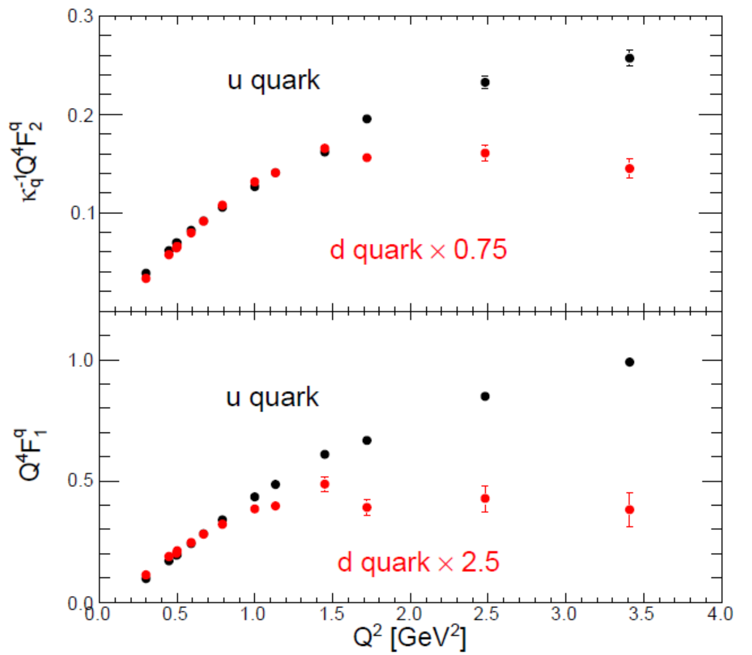
- G_{En} is the least well-known and most difficult to measure of the nucleon EMFFs:
  - Goes to zero at low Q^2 and cross-section contribution is small at large Q^2
- Existing knowledge is based on polarization observables:
  - Beam-target double-spin asymmetry in semi-exclusive quasi-elastic ^{3}**He**(**e**,e'n)pp
  - Beam-target double-spin asymmetry in semi-exclusive quasi-elastic ^{2}**H**(**e**,e'n)p
  - Neutron recoil polarimetery: d(**e**,e'**n**)p

Taking stock of nucleon FF data at the start of JLab 12 GeV



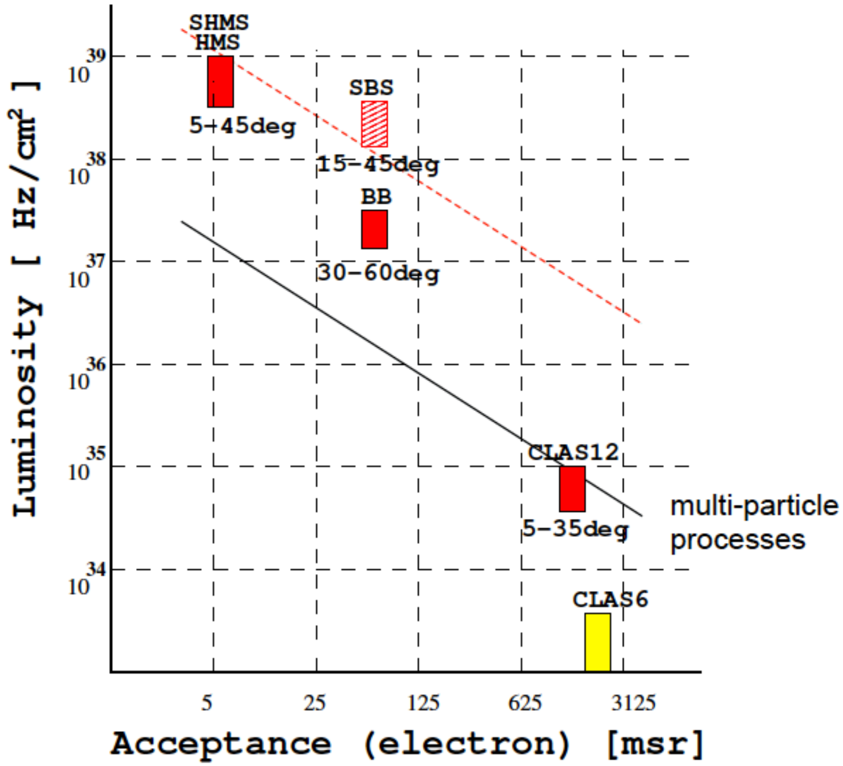
World data for G_{Ep}, G_{Mp}, G_{En}, G_{Mn} compared to selected theory/model calculations from **Puckett *et al.*, Phys. Rev. C, 85, 045203 (2012)**

$$G_D = \left(1 + \frac{Q^2}{\Lambda^2}\right)^{-2}, \Lambda^2 = 0.71 \text{ GeV}^2$$



- Flavor decomposition of nucleon FFs: **Cates *et al.*, Phys. Rev. Lett., 106, 252003 (2011)**
- Different behavior of u and d quark contributions to FFs can be interpreted as a probe/signature of diquark correlations

JLab detector landscape



A range of 10^4 in luminosity.

A big range in solid angle:
from 5 msr (SHMS)
to about 1000 msr (CLAS12).
=========================
The SBS is in the middle:
for solid angle (up to 70 msr)
and high luminosity capability.

In several A-rated experiments
SBS was found to be the best
match to the physics.

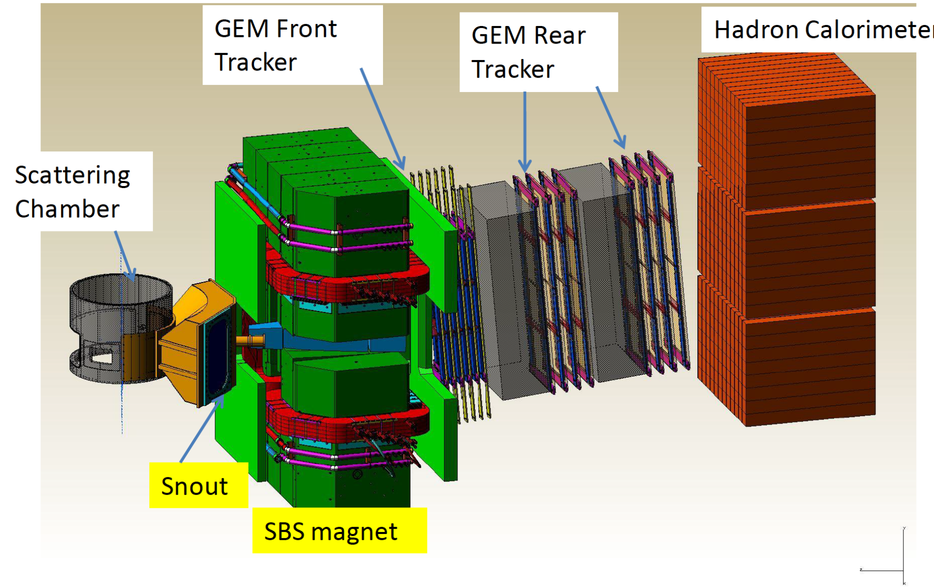
GEM allows a spectrometer
with open geometry (->large
acceptance) at high L.

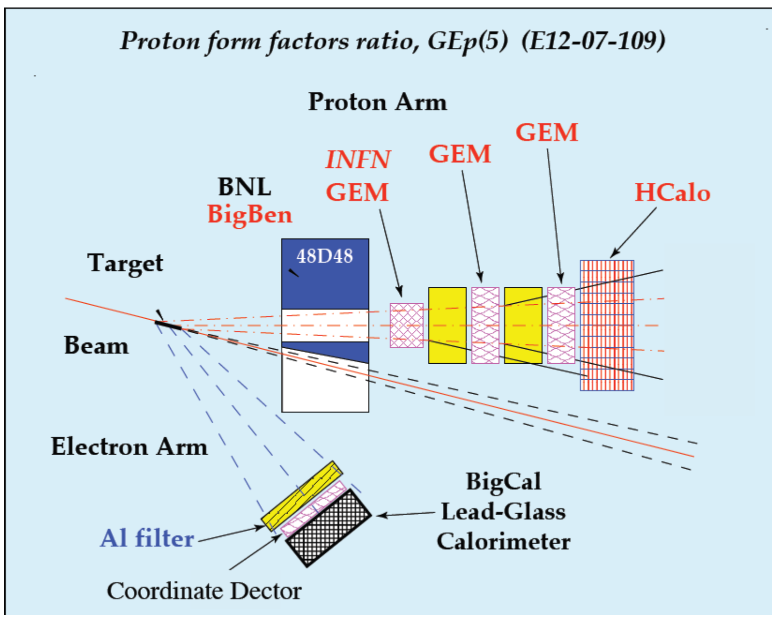
11/16/15 Super Bigbite Spectrometer Review slide 9

Acknowledgements to B. Wojtsekhowski for this figure

How to reach higher Q^2?

- Elastic ep cross section scales as $\sigma \approx E^2/Q^{12}$
- FPP efficiency is roughly Q^2-independent
- FPP analyzing power scales roughly as $1/p_p \sim M/Q^2$
- Statistical FOM scales as $NA_y^2 \sim E^2/Q^{16}$
- Increase beam polarization? 80%→100% would only increase FOM by 1.6
- Increase luminosity? Best possible at JLab 12 GeV ~ 10^{39} cm^{-2} s^{-1}; ~factor of 2 above 6 GeV expt's.
- Most room for growth? →***Increase solid angle/Q^2 acceptance!***
  - **2X increase in target thickness and solid angle from 6→35 msr leads to ~30X gain in figure-of-merit**
- JLab PAC-approved G_E^p experiment: E12-07-109; 45 days in Hall A
  - $\Delta(\mu G_E/G_M) \sim 0.07$ @$Q^2 = 12$ GeV^2

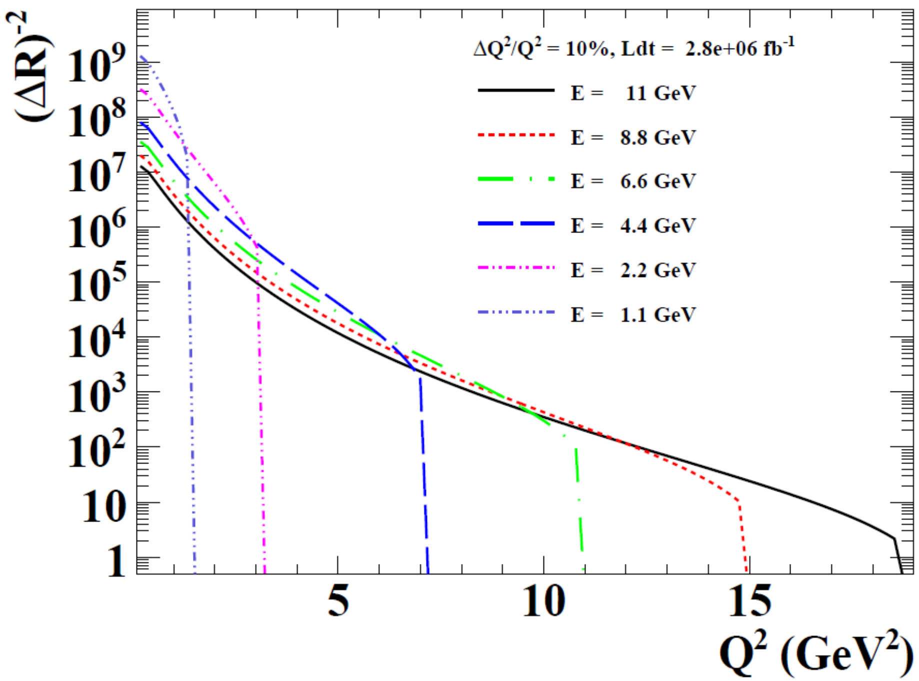




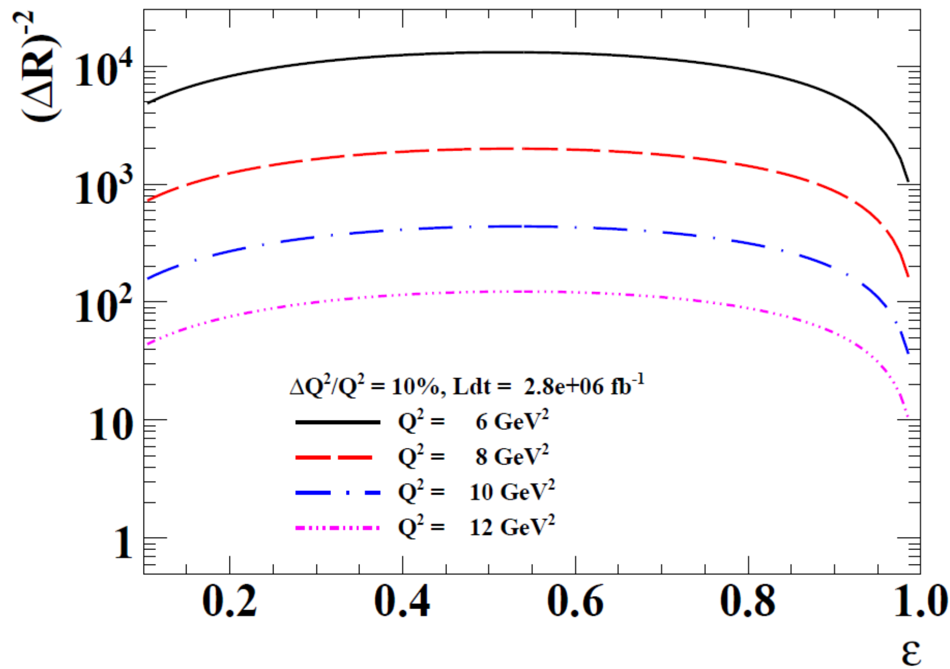
Statistical FOM of polarization transfer expt.'s

Experiment	Q^2 $(\mathrm{GeV/c})^2$	E_e (GeV)	$\Delta\Omega_p$ (msr)	P_e (%)	$\Delta\,(\mu_p G_E^p/G_M^p)$	Reference
GEp-I	0.5-3.5	0.9-4.1	6.5	40-60	0.01-0.05	PRL **84**, 1398 (2000), PRC **71**, 055202 (2005)
GEp-II	3.5-5.6	4.6	6.5	70	0.05-0.09	PRL **88**, 092301 (2002) PRC **85**, 045203 (2012)
GEp-III	5.2-8.5	4.0, 5.7	7	80-85	0.07-0.18	PRL **104**, 242301 (2010)

Previous PT experiments: focusing magnetic spectrometers, small proton solid angle/ΔQ²

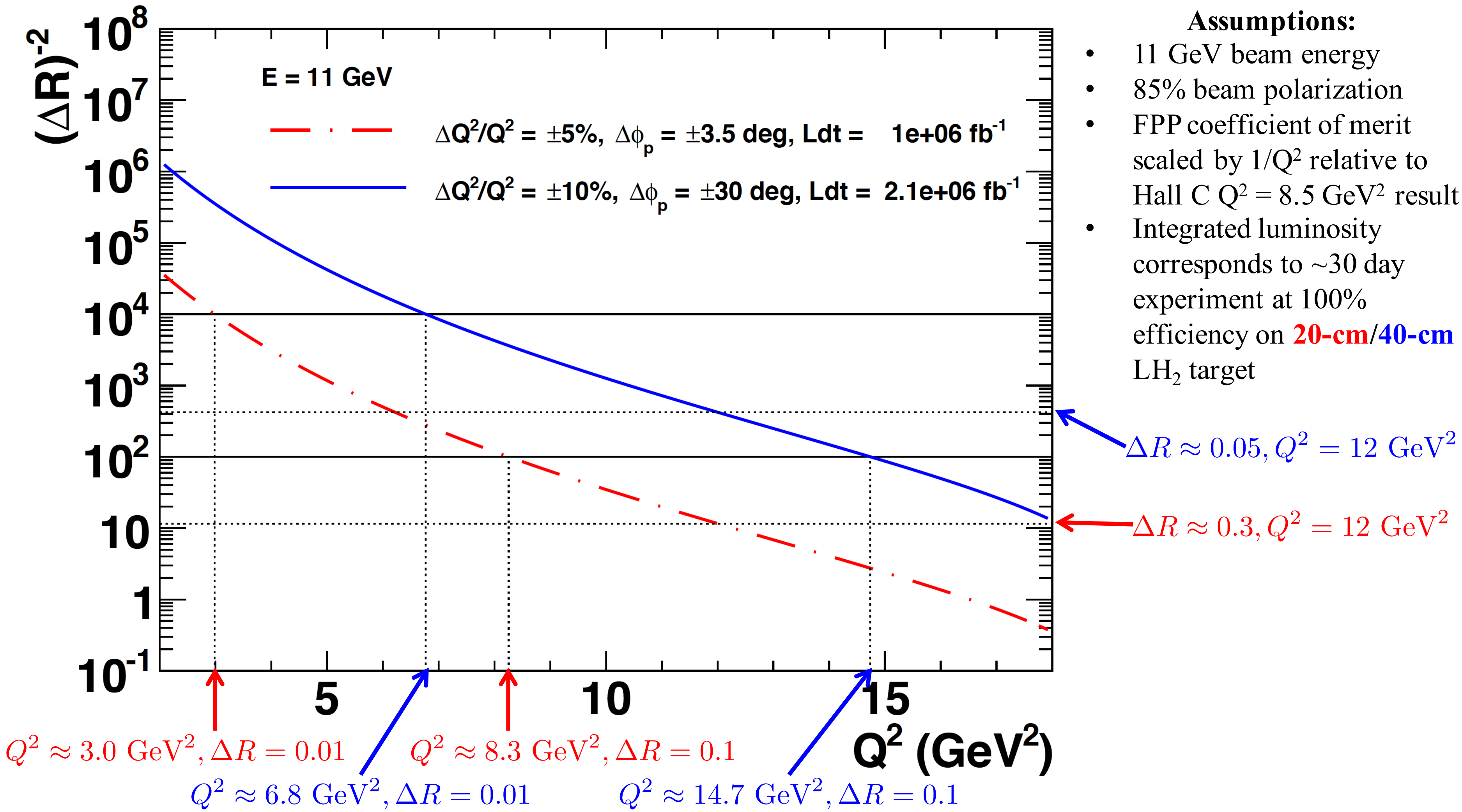


Theoretical PT FOM vs. Q^2 for different beam energies



Theoretical PT FOM vs. ε at various Q^2 values

Polarization Transfer FOM vs. Q^2: HMS/HRS vs SBS

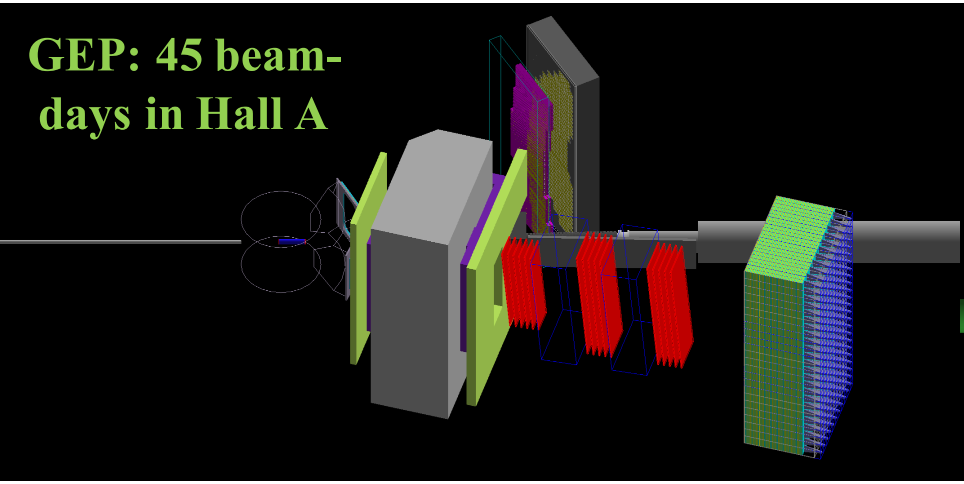


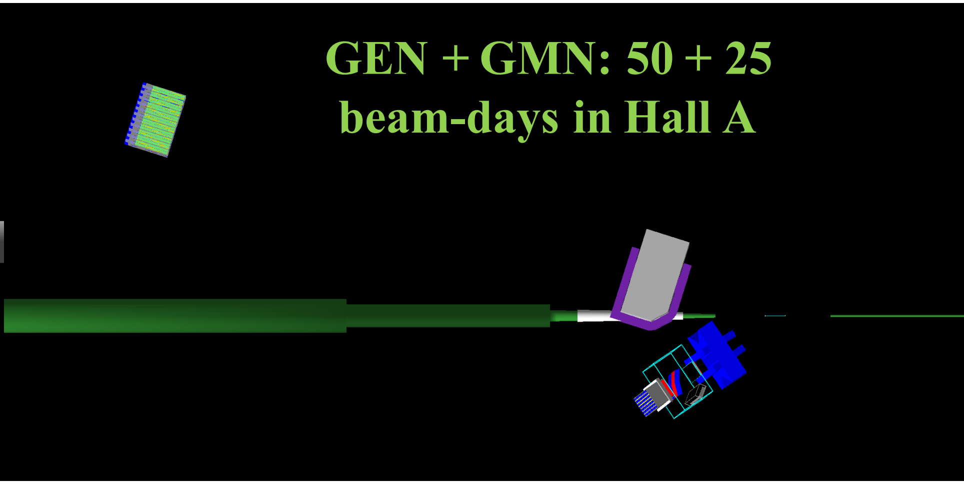
Assumptions:

- 11 GeV beam energy
- 85% beam polarization
- FPP coefficient of merit scaled by $1/Q^2$ relative to Hall C $Q^2 = 8.5$ GeV^2 result
- Integrated luminosity corresponds to ~30 day experiment at 100% efficiency on **20-cm**/**40-cm** LH_2 target

Increase in proton solid angle from 6→35 msr and ~2X increase in luminosity leads to *doubling* of Q^2 range for which absolute $\Delta(\mu G_E/G_M) \leq 0.1$

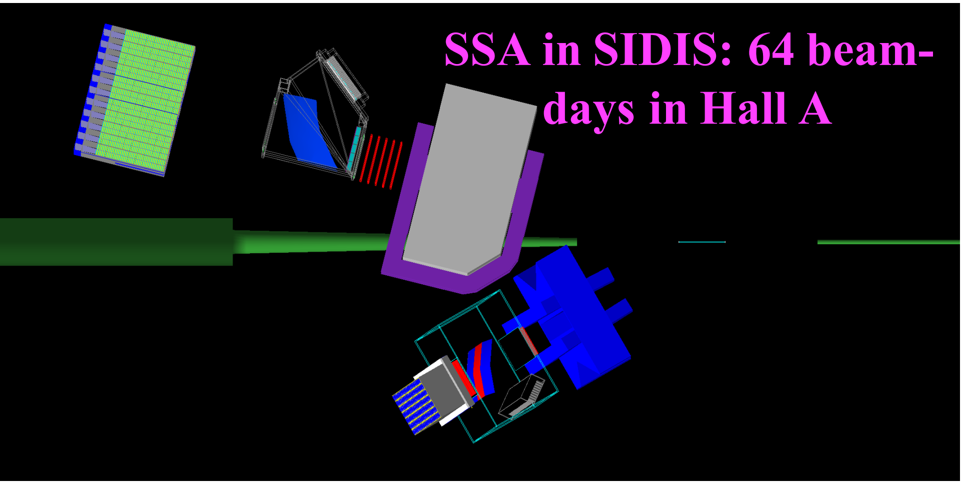
The Super BigBite Spectrometer (SBS) in Hall A





E12-07-109: Proton form factor ratio G_{Ep}/G_{Mp} using polarization transfer

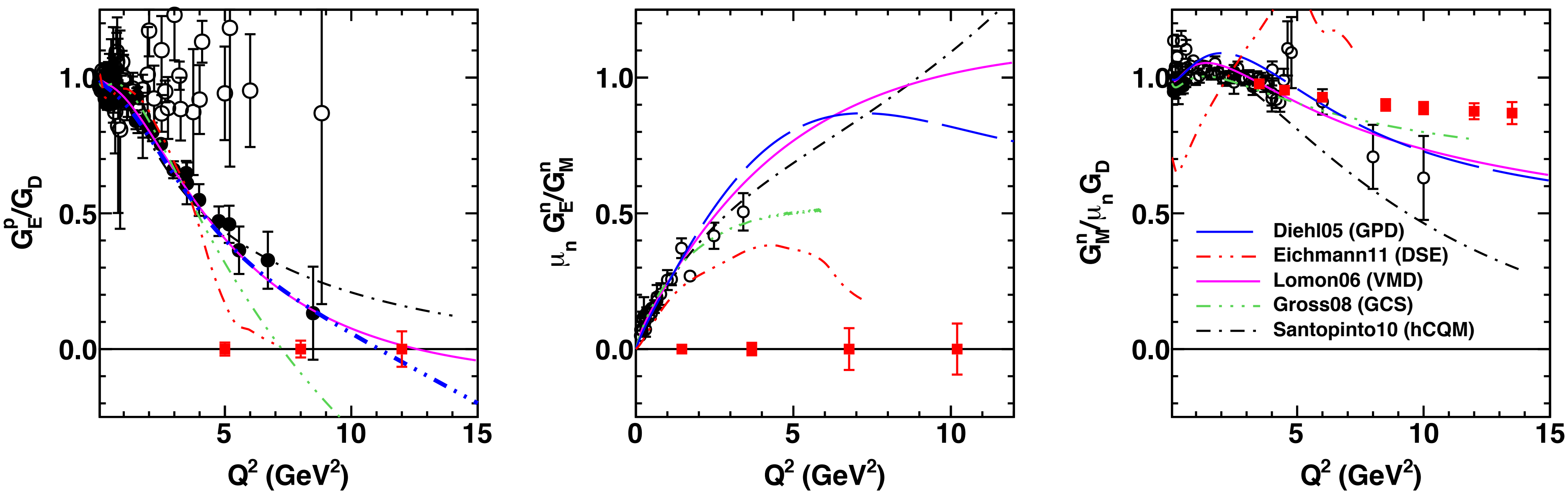
E12-09-016 and E12-09-019: Neutron magnetic form factor G_{Mn} and neutron form factor ratio G_{En}/G_{Mn}



E12-09-018: Transverse target SSA in SIDIS

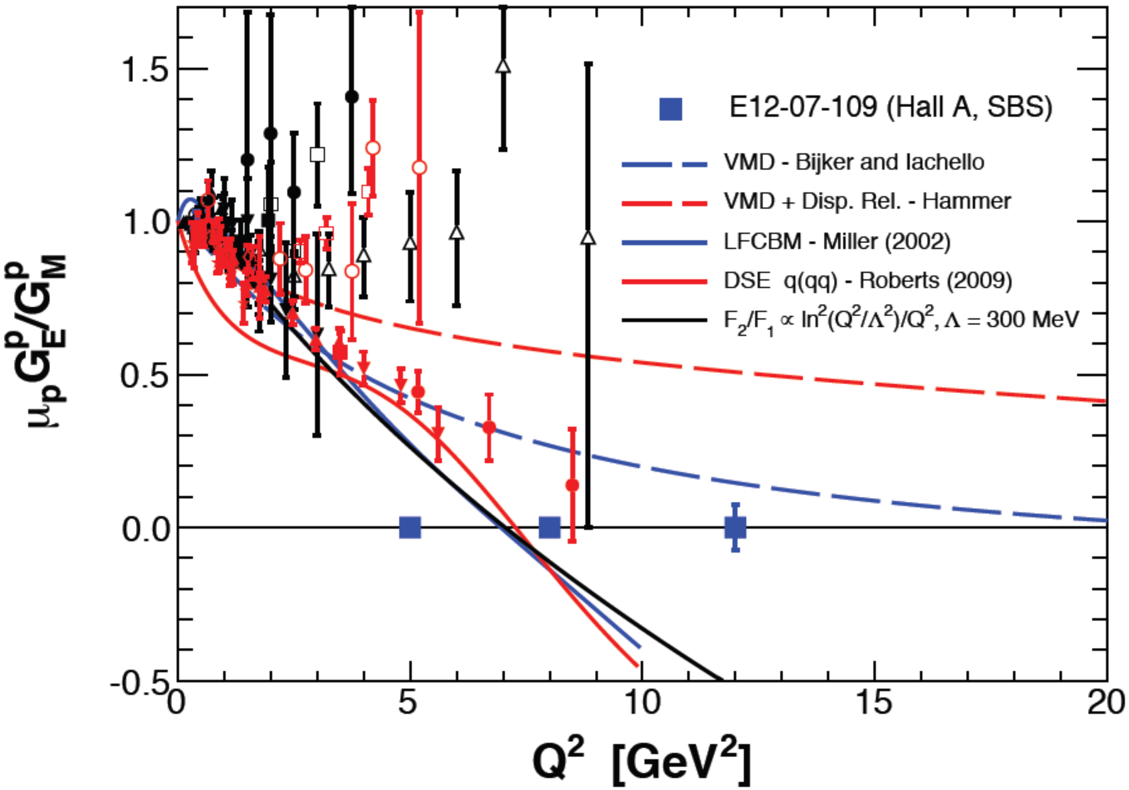
- SBS is a novel magnetic spectrometer based on time-tested "detectors behind a dipole magnet" approach
- Detects forward-going, high-energy particles with medium solid angle acceptance and large momentum bite at highest achievable luminosities of CEBAF
- **Physics program: nucleon EMFFs and SIDIS, 180 beam-days approved in Hall A**
- **Conditionally approved: Pion structure function via tagged DIS, 27 days Hall A**

SBS (Initial?) Form Factor Program



- SBS high-Q^2 form factor program:
  - Map transition to perturbative regime—running of dressed quark mass function
  - Imaging of the nucleon charge and magnetization densities in impact-parameter space in the infinite momentum frame.
  - Precision high-Q^2 form factors have significant impact on GPD extraction from DVCS
- GEP: Proton electric form factor, increase Q^2 range from 8.5 → 12 GeV^2
- GEN: Neutron electric form factor, increase Q^2 range from 3.4 → 10 GeV^2
- GMN: Neutron magnetic form factor, increase Q^2 range from 5 → 13.5 GeV^2

SBS G_E^p Projected Results

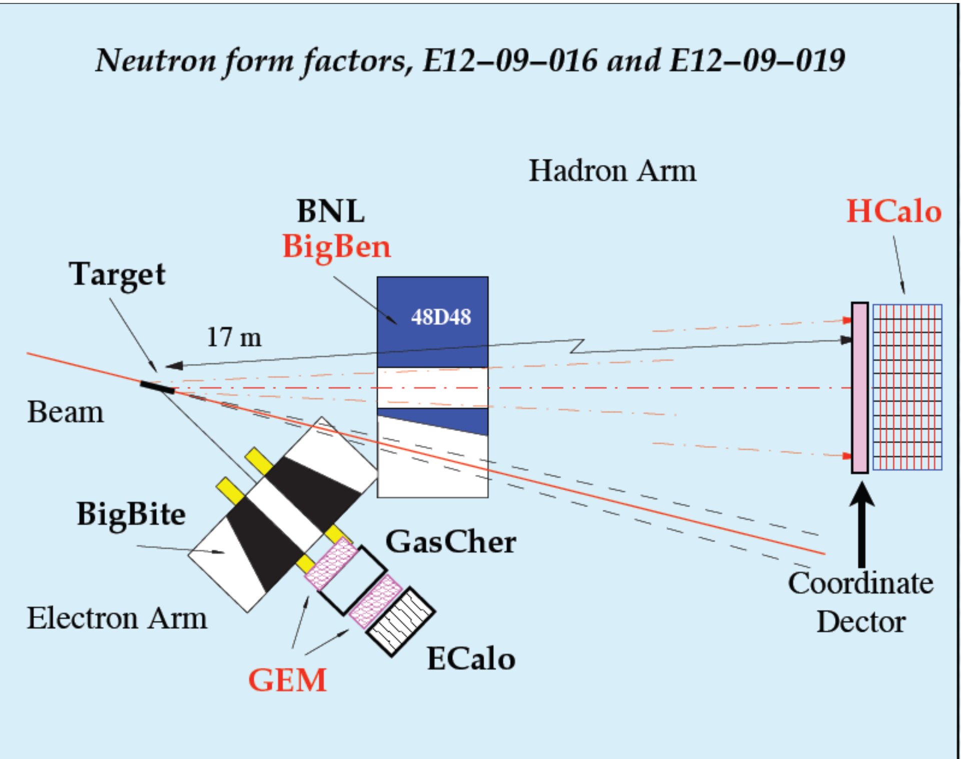


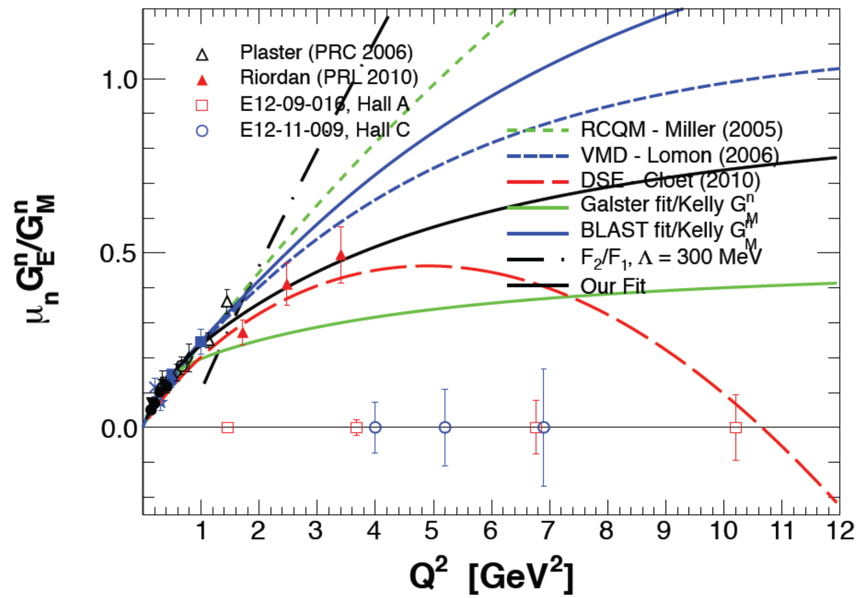
- The SBS GEP experiment in ~11 days running will dramatically improve the statistical precision in $\mu G_E/G_M$ at Q^2 in the range overlapping GEp-II/III, and in 30 days will reach comparable precision at 12 GeV^2 to that of GEp-II/III at 5-6 GeV^2
- Data of such precision carry significant discovery potential and may (or may not) settle the questions of a zero crossing of G_E^p and the onset (or lack thereof) of dimensional scaling.

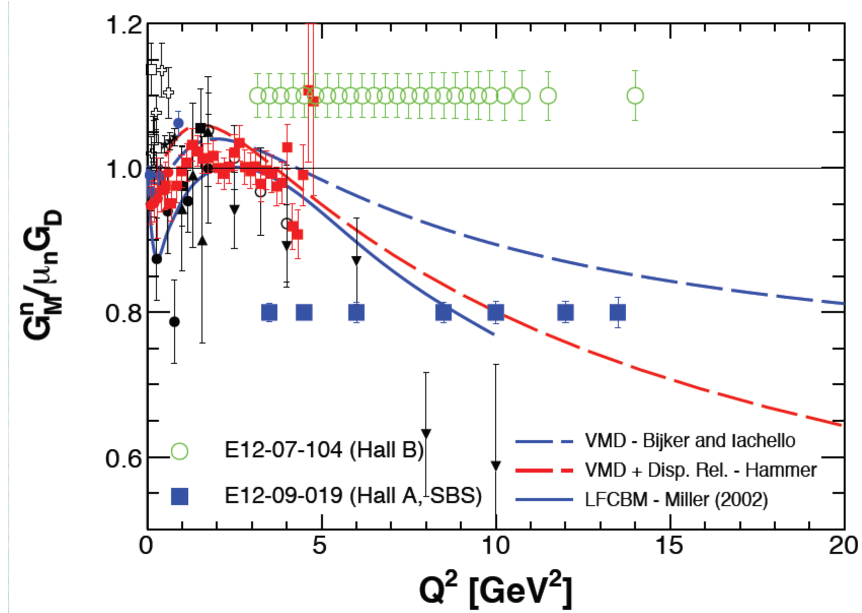
- Combined with GEN, GMN, GMP experiments, full flavor decomposition of F_1 and F_2 becomes possible up to 10 GeV^2

Kinematics and expected accuracy							
E (GeV)	Q^2 (GeV^2)	θ_E (deg)	P_e (GeV)	Θ_p (deg)	P_p (GeV)	Days	$\Delta\mu G_E/G_M$
6.6	5.0	25.3	3.94	29.0	3.48	1	0.023
8.8	8.0	25.9	4.54	22.8	5.12	10	0.032
11.0	12.0	28.2	4.60	17.4	7.27	30	0.074

Neutron form factors: E12-09-016 & E12-09-019

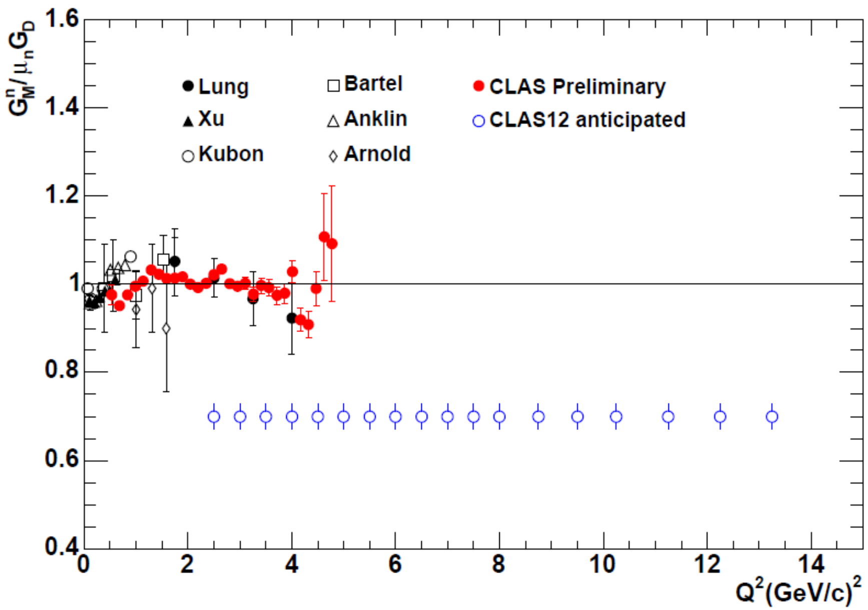






- SBS as neutron arm w/48D48 + HCAL
- Magnet sweeps charged particles out of acceptance, limiting backgrounds and ”CDet” acts as proton veto
- BigBite as electron arm w/upgraded 12 GeV detector package (including re-use of GEMs, built for GEP, not otherwise in use during BigBite expt’s.
- High-luminosity polarized Helium-3 for GEN
- Standard LH2/LD2 for GMN

CLAS12 G_{Mn}: E12-07-104



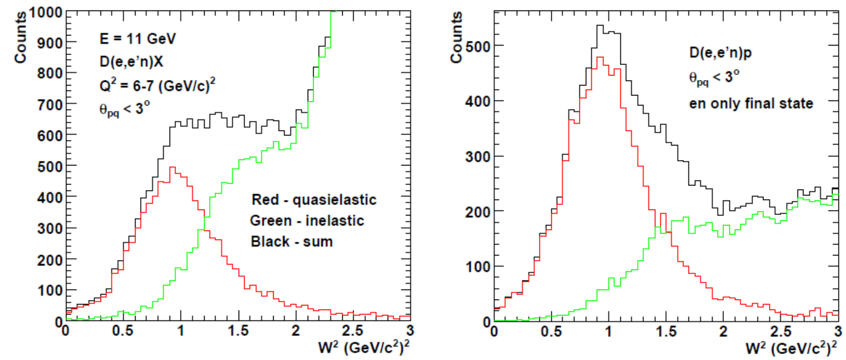
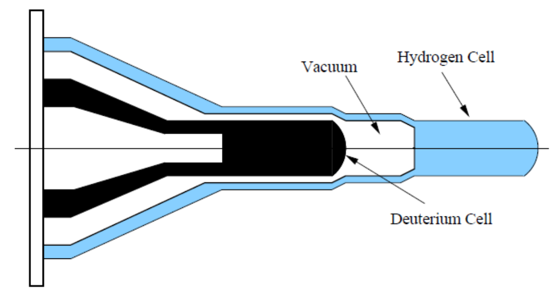


Figure 18: Comparison of the simulated W^2 spectra for the $D(e, e'n)X$ (left-hand panel) and $D(e, e'n)p$ reactions (right-hand panel). Both spectra are for $\theta_{pq} < 3°$.

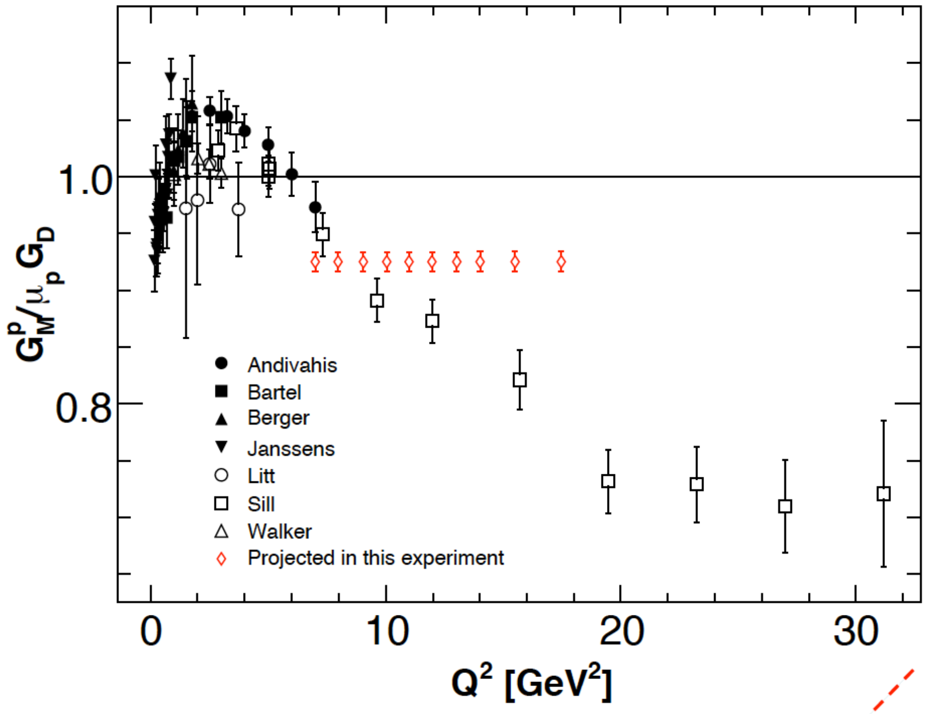


$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))}$$

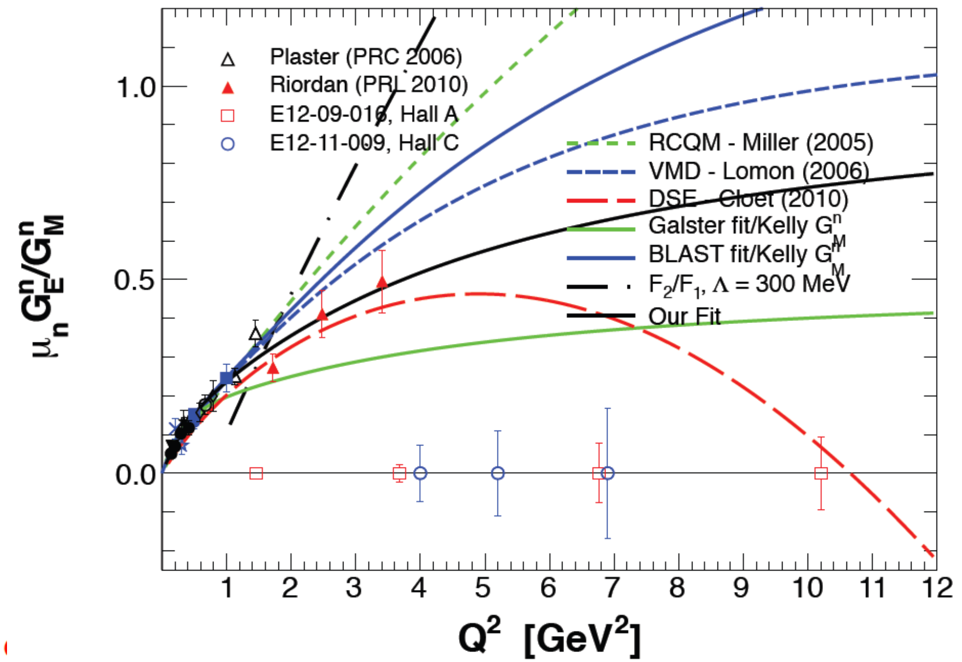
$$R = a(Q^2)\frac{\sigma^n_{mott}({G^n_E}^2 + \frac{\tau_n}{\varepsilon_n}{G^n_M}^2)\left(\frac{1}{1+\tau_n}\right)}{\sigma^p_{mott}({G^p_E}^2 + \frac{\tau_p}{\varepsilon_p}{G^p_M}^2)\left(\frac{1}{1+\tau_p}\right)}$$

- Extract neutron magnetic form factor from the ratio of d(e,e'n)/d(e,e'p) quasielastic cross sections and known form factors of the proton
- Nuclear corrections small at large Q^2
- Important to have independent data (SBS and CLAS12) in high-Q^2 regime to cross-check systematics of G_{Mn}

Hall A GMP and Hall C G_{En} Recoil



Hall A G_{Mp}: a high-precision measurement of the elastic ep cross section at large Q^2 (Currently running in Hall A, in parallel with DVCS)



Hall C G_{En} polarization transfer: independent extraction of G_{En} in Q^2 regime overlapping SBS, with different experimental method

Summary and Conclusions

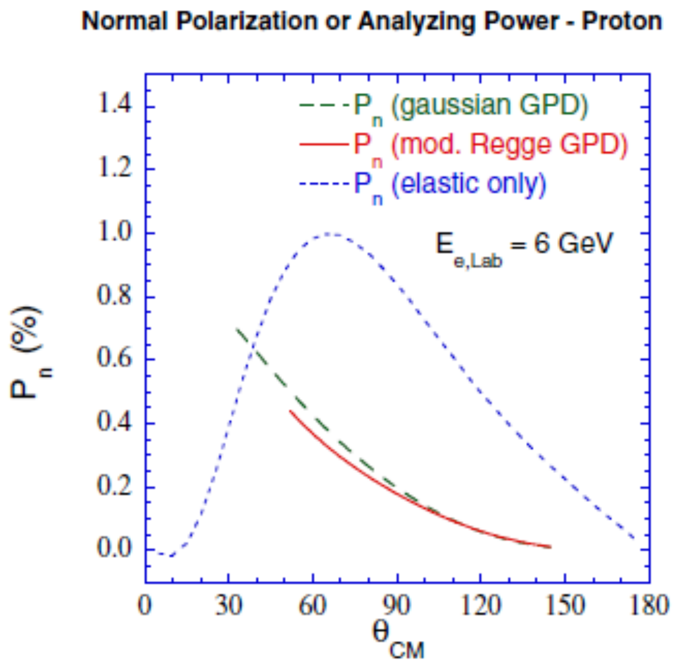
- Electromagnetic FFs are fundamental, Lorentz-invariant properties of the nucleon that are rigorously defined, and provide a benchmark for theoretical models of the nucleon and *ab-initio* approaches in lattice gauge theory and continuum non-perturbative QCD (e.g., DSEs).
- The renewal of interest in the high-Q^2 nucleon EMFFs that started with the surprising JLab 6 GeV polarization transfer results continues unabated, now driven also by surprises at low Q^2 and improved theoretical understanding
- The JLab 12 GeV FF program (including but not limited to SBS) will reach the highest achievable Q^2 with an 11 GeV beam for all four nucleon EMFFs

Acknowledgements

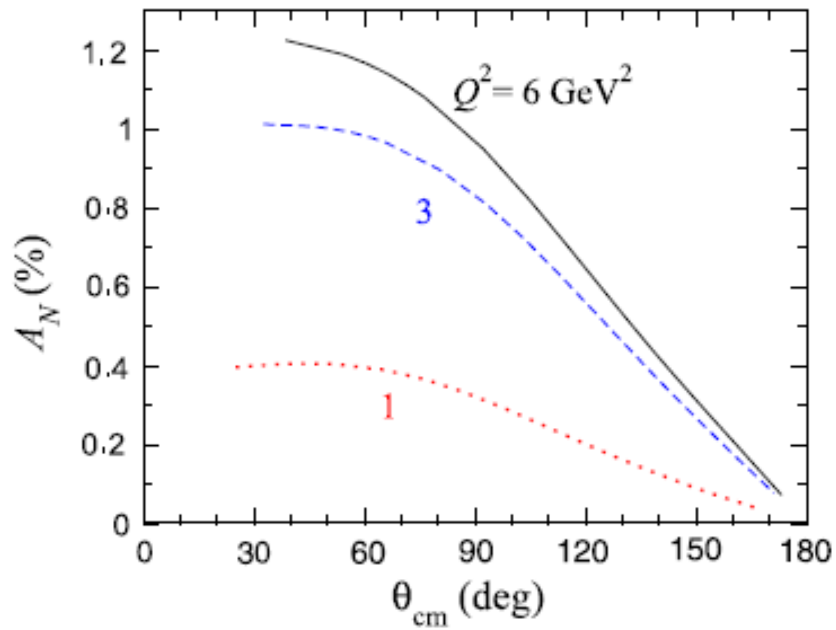
- ECT* for support and hospitality
- Workshop organizers
- This work was supported by the US Department of Energy Office of Science, Award #DE-SC0014230

Another idea for JLab 12 GeV (time permitting): high-Q^2 elastic scattering on transversely polarized protons

Normal Single-Spin Asymmetry in ep→ep with transversely polarized proton target



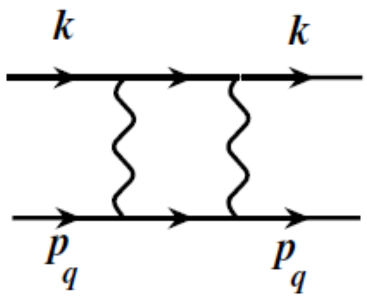
Elastic and GPD A_N vs θ, fixed E

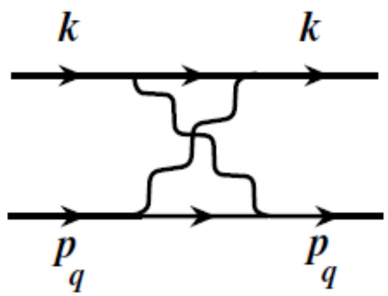


Elastic A_N vs θ, fixed Q^2

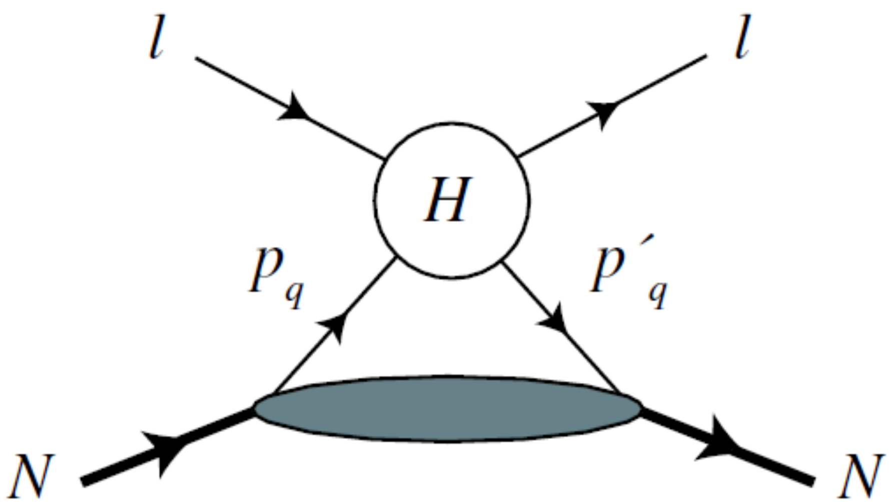
- A_N = single-spin asymmetry in elastic scattering when proton polarization is normal to the scattering plane
- ***Identically zero in one-photon-exchange approximation—clean signal for TPEX***
- Equal to induced normal recoil polarization in unpolarized ep→ep (time reversal)
- No data currently exist (due to challenges of tranversely polarized targets).
- Induced recoil polarization very difficult to measure due to polarimeter false asymmetries

A_N in GPD framework—handbag mechanism





- The TPEX occurs at the parton level in eq → eq box diagram
- Parton process embedded in the nucleon via GPDs:



$$A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}}\frac{1}{\sigma_R}\left\{G_E I(A) - \sqrt{\frac{1+\varepsilon}{2\varepsilon}}G_M I(B)\right\},$$

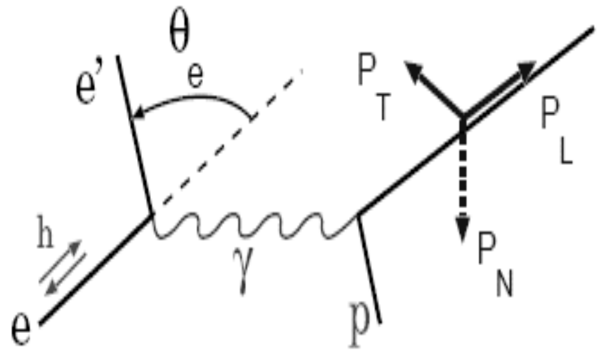
$$A \equiv \int_{-1}^{1}\frac{dx}{x}\frac{[(\hat{s}-\hat{u})\tilde{f}_1^{\text{hard}} - \hat{s}\,\hat{u}\,\tilde{f}_3]}{(s-u)}\sum_q e_q^2(H^q + E^q),$$

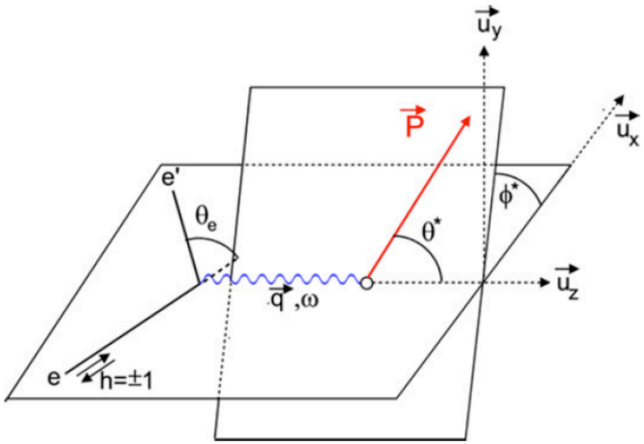
$$B \equiv \int_{-1}^{1}\frac{dx}{x}\frac{[(\hat{s}-\hat{u})\tilde{f}_1^{\text{hard}} - \hat{s}\,\hat{u}\,\tilde{f}_3]}{(s-u)}\sum_q e_q^2(H^q - \tau E^q),$$

$$I\left(\tilde{f}_1^{\text{hard}}\right) = -\frac{e^2}{4\pi}\left\{\frac{Q^2}{2\hat{u}}\ln\left(\frac{\hat{s}}{Q^2}\right) + \frac{1}{2}\right\},$$

$$I\left(\tilde{f}_3\right) = -\frac{e^2}{4\pi}\frac{1}{\hat{u}}\left\{\frac{\hat{s}-\hat{u}}{\hat{u}}\ln\left(\frac{\hat{s}}{Q^2}\right) + 1\right\}.$$

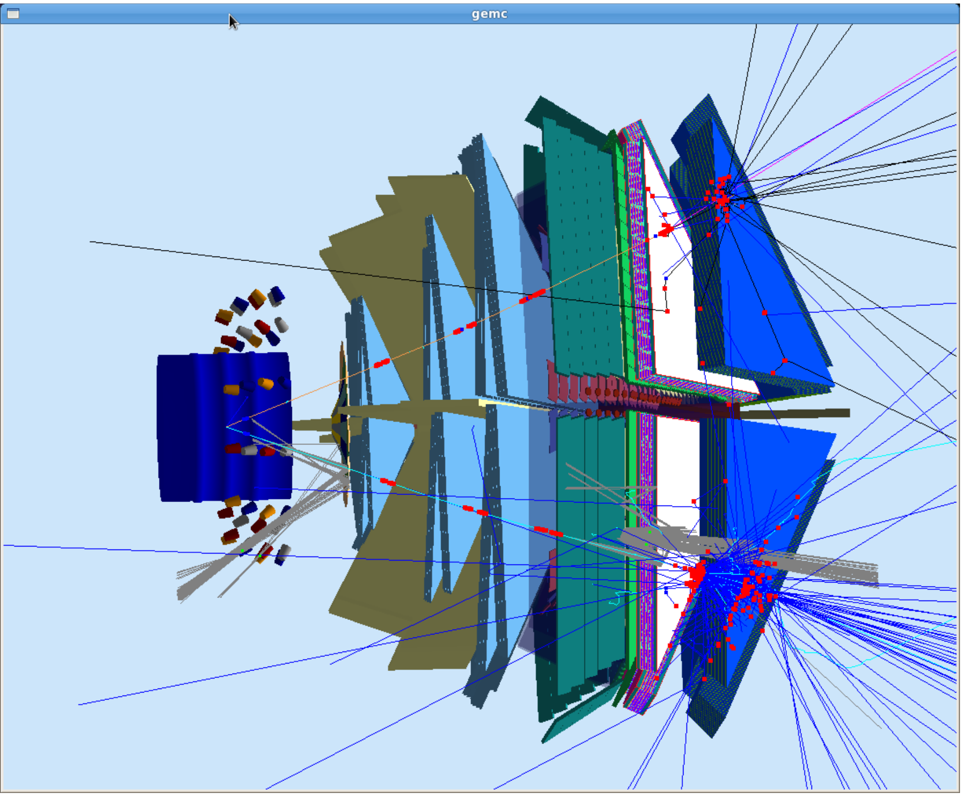
G_E/G_M: Polarization Transfer vs. Polarized Target





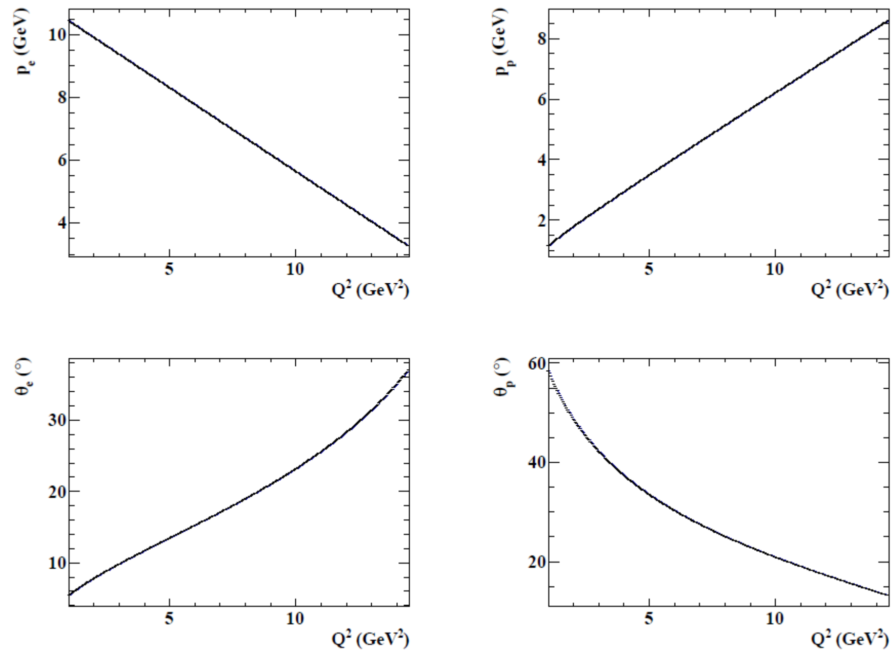
	Polarization Transfer	*Polarized Beam-Target Asymmetry*
Luminosity (Hz/cm^2)	~10^{38}-10^{39}	<~10^{35}
Asymmetry Magnitude	~$P_{beam}\, A_y$ (A_y ~ $1/Q^2$)	~$P_{beam}\, P_{target}$ (or P_{target} for P_N)
Acceptance	Defined by proton arm: ~6 msr (HRS/HMS) or ~40 msr (SBS)	~4π (e.g., CLAS12 or SoLID)
Polarimeter efficiency	~25%	N/A
Systematics	Spin precession	Polarimetry/relative lumi.
Rad. Corr.	Very small	Small
TPEX Corr.	Small (GEp-2γ expt)	??

ep→ep in CLAS12 @ 11 GeV



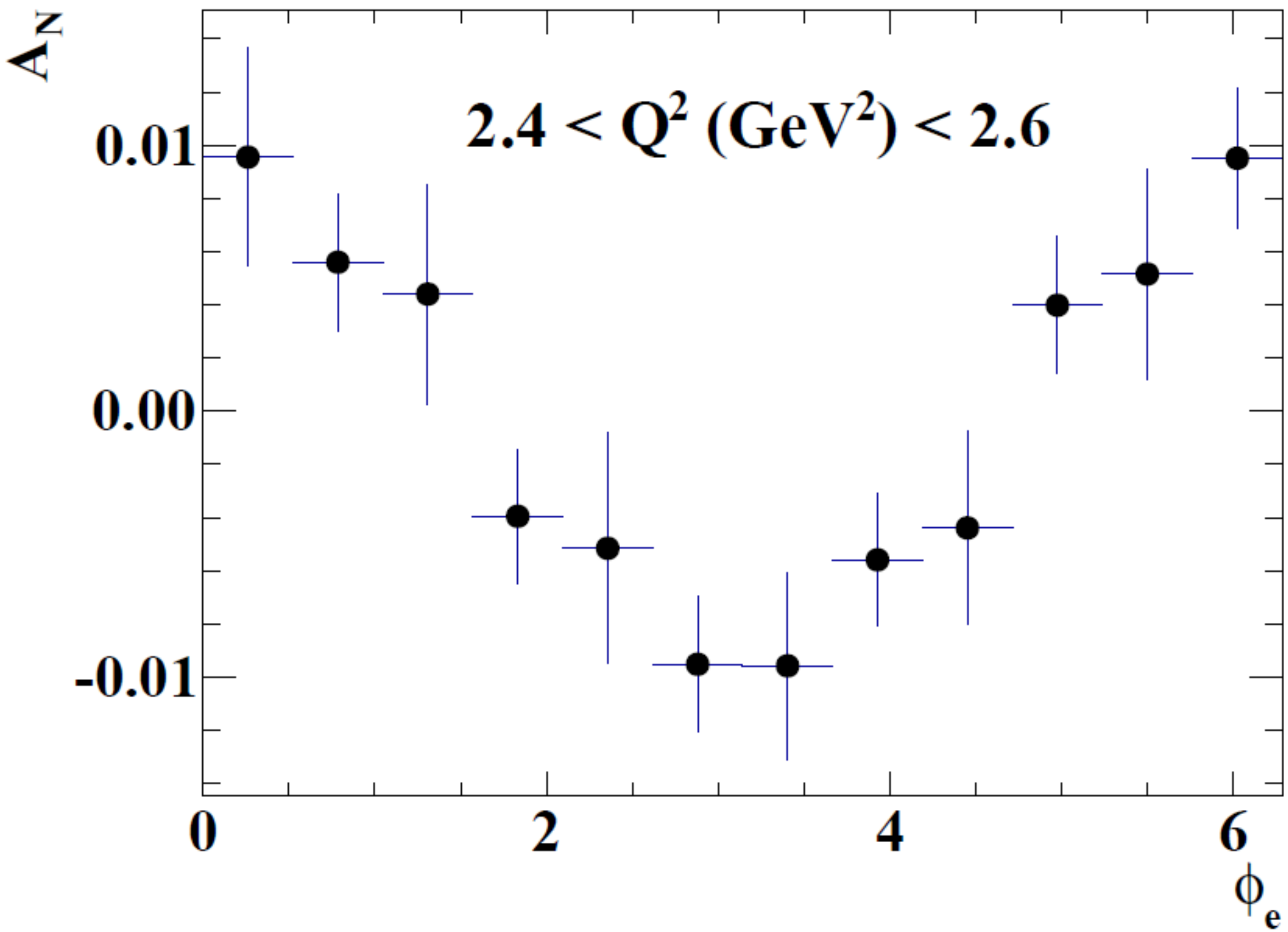
Elastic ep→ep in gemc

- Standard detector/magnetic field configuration (inbending e^-)
- ELRADGEN2.0 rad. corr. (internal only)

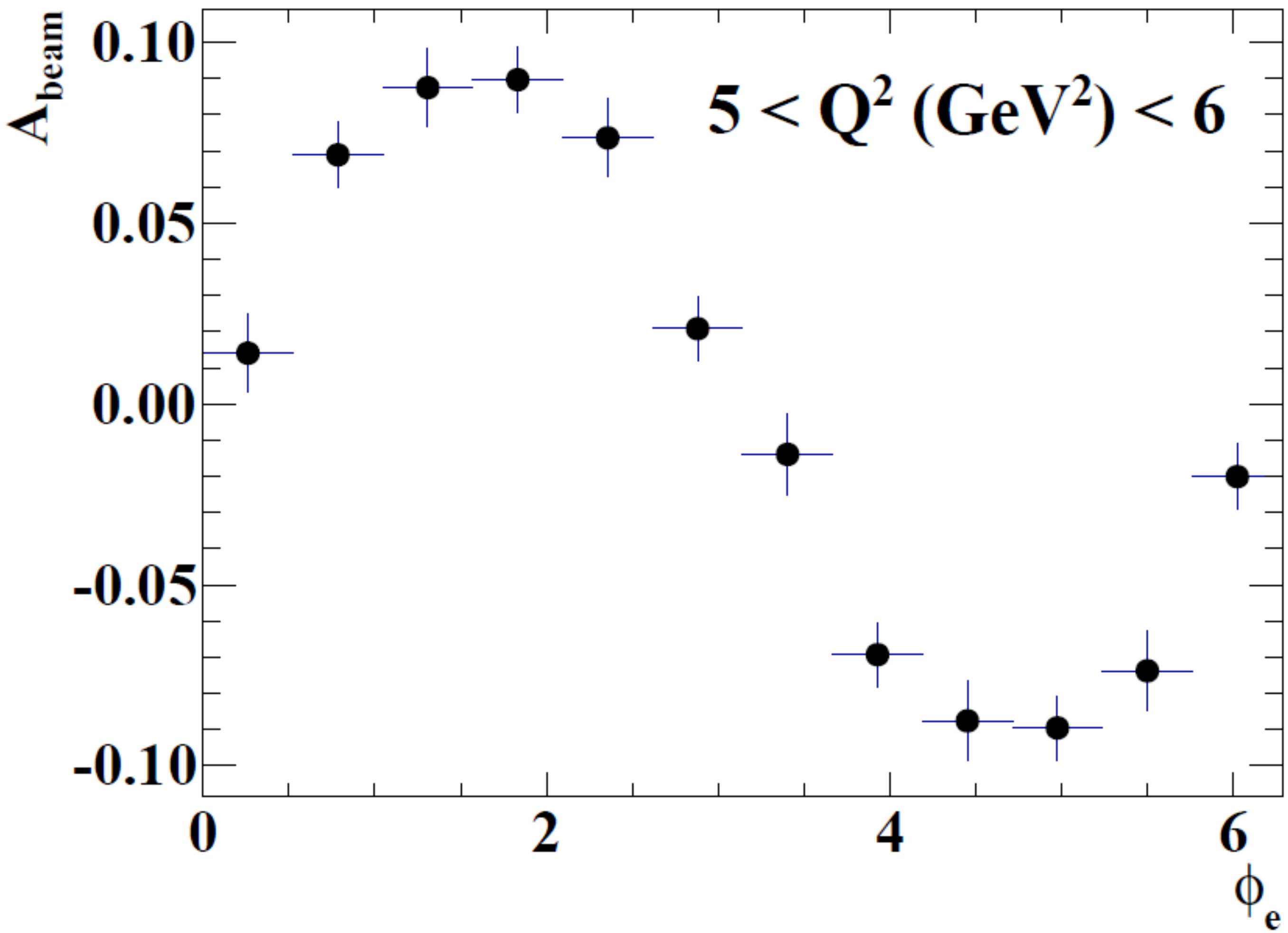


- Scattered electron and proton kinematics vs. Q^2 at E_{beam} = 11 GeV
- Forward CLAS12 acceptance ~2-14 GeV^2 (electrons)

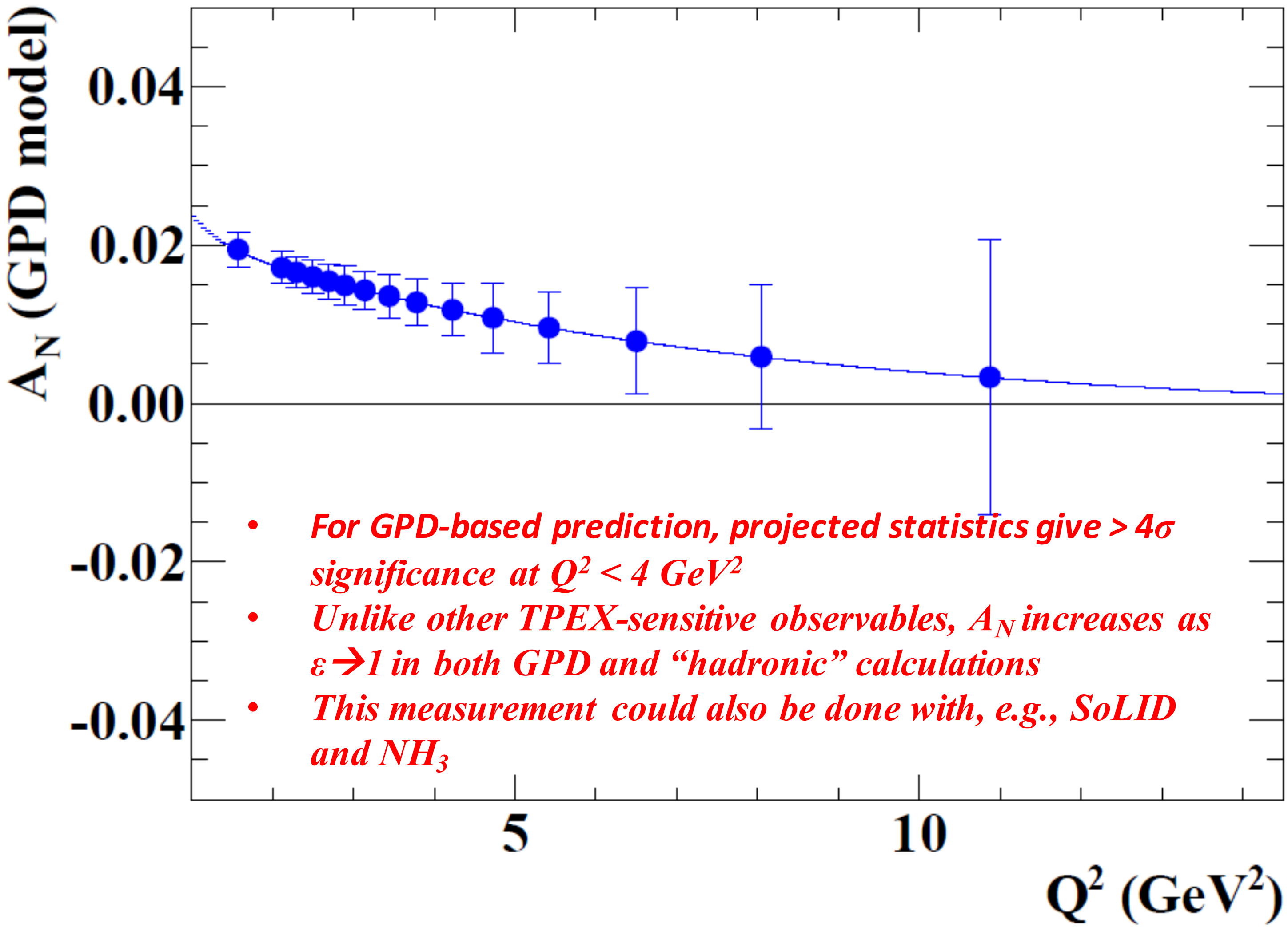
Normal Asymmetry φ Dependence



Beam-target Double-Spin Asymmetry

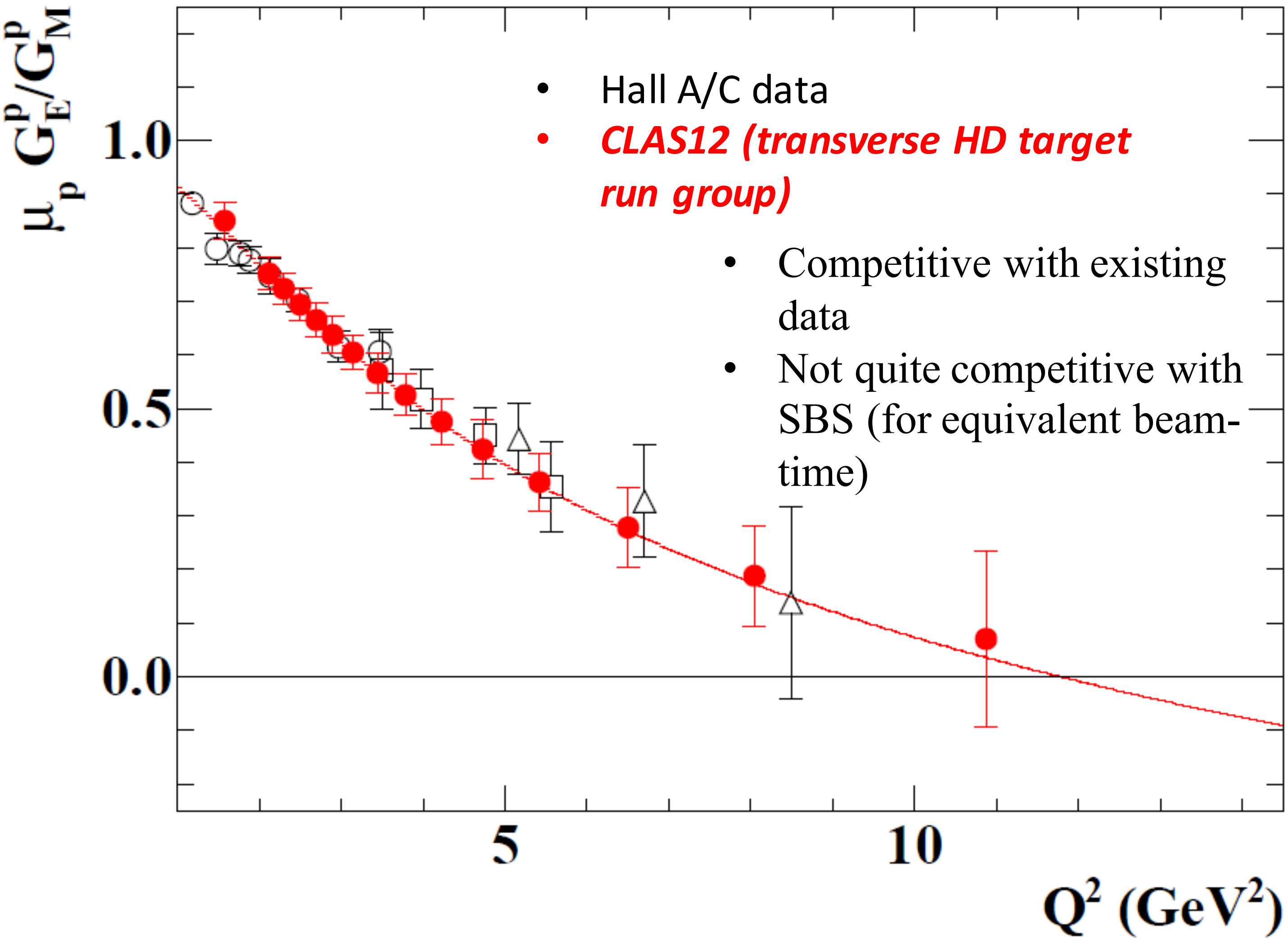


A_N Q^2 Dependence



- *For GPD-based prediction, projected statistics give > 4σ significance at $Q^2 < 4$ GeV^2*
- *Unlike other TPEX-sensitive observables, A_N increases as $\varepsilon \rightarrow 1$ in both GPD and "hadronic" calculations*
- *This measurement could also be done with, e.g., SoLID and NH_3*

G_E/G_M: Projected Sensitivity with transverse target



- Competitive with existing data
- Not quite competitive with SBS (for equivalent beam-time)