Jefferson Lab
Thomas Jefferson National Accelerator Facility

High Q^2 L/T separation in H(e,e'p)

Bogdan Wojtsekhowski

Electro-Magnetic Form Factors

Rosenbluth (1950)

One-photon approximation, α_{em} = 1/137, hadron current

$$\mathcal{J}^{\mu}_{hadronic} = ie\overline{N}(p')\left[\gamma^{\mu}F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M}F_2(Q^2)\right]N(p)$$

At large Q^2, study of G_E requires use of polarization observables – FFs at JLab

Akhiezer (1958)
Arnold, Carlson and Gross (1981)

$1\gamma+2\gamma$ expression for M has three complex functions, F_1, F_2, F_3

$$\mathcal{M} = \frac{4\pi\alpha}{Q^2}\bar{u}'\gamma_{\mu}u \cdot \bar{N}'\left(\tilde{F}_1\gamma^{\mu} - \tilde{F}_2[\gamma^{\mu},\gamma^{\nu}]\frac{q_{\nu}}{4M} + \tilde{F}_3K_{\nu}\gamma^{\nu}\frac{P^{\mu}}{M^2}\right)N$$

Guichon & Vanderhaeghen

$$\tilde{G}_M = \tilde{F}_1 + \tilde{F}_2 \qquad \tilde{G}_E = \tilde{F}_1 - \tau\tilde{F}_2$$

$\tilde{F}_i$ are functions of $(s-u)$ and t

$$d\sigma = d\sigma_{NS}\left\{\varepsilon(\tilde{G}_E + \frac{s-u}{4M^2}\tilde{F}_3)^2 + \tau(\tilde{G}_M + \varepsilon\frac{s-u}{4M^2}\tilde{F}_3)^2\right\}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2 +$$
$$+2\tau G_M \mathcal{R}e\left(\delta\tilde{G}_M + \varepsilon\tfrac{s-u}{M^2}\tilde{F}_3\right) + 2\varepsilon G_E \mathcal{R}e\left(\delta\tilde{G}_E + \tfrac{s-u}{M^2}\tilde{F}_3\right)$$

SLAC results for the proton Form Factors

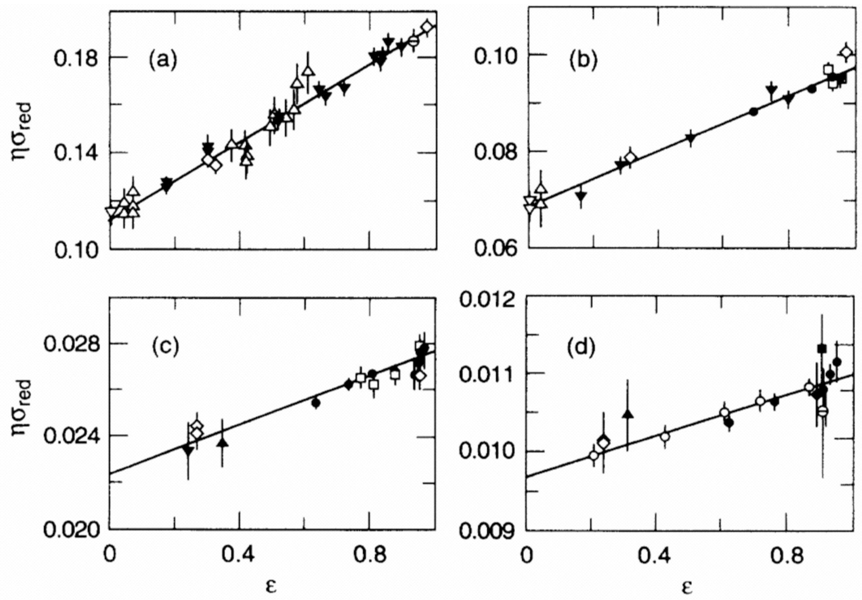
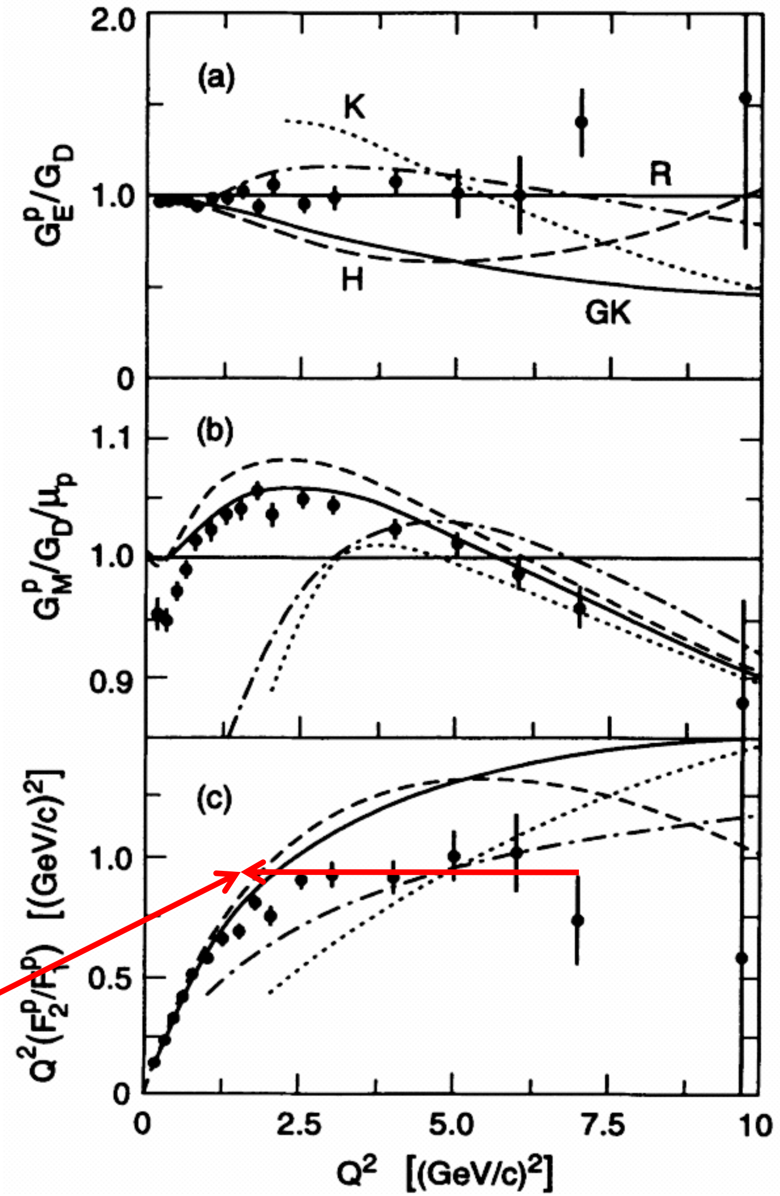


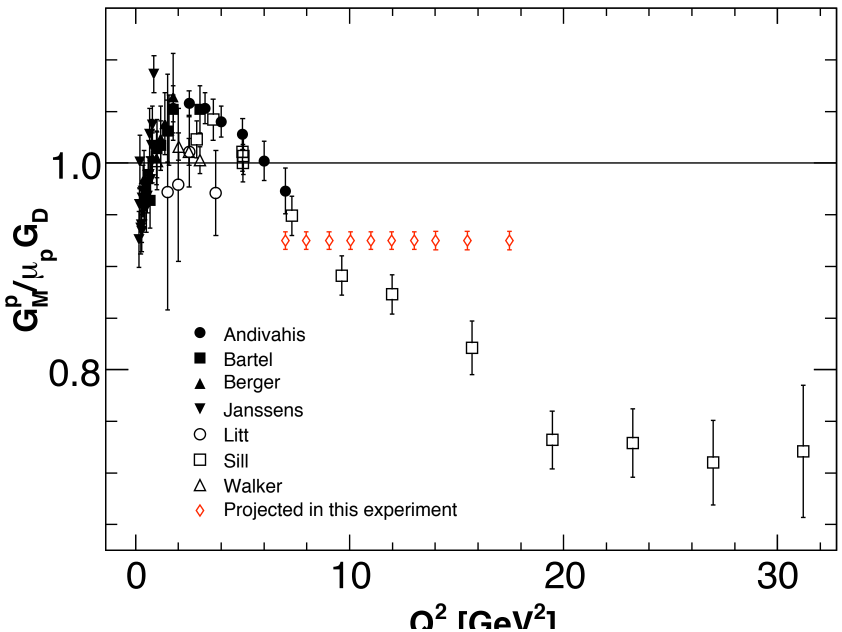
FIG. 9. Four typical Rosenbluth fits for the form factor extraction from the global data set at (a) $Q^2 = 0.6$, (b) $Q^2 = 1.0$, (c) $Q^2 = 2.0$, and (d) $Q^2 = 3.0$ $(\mathrm{GeV}/c)^2$.

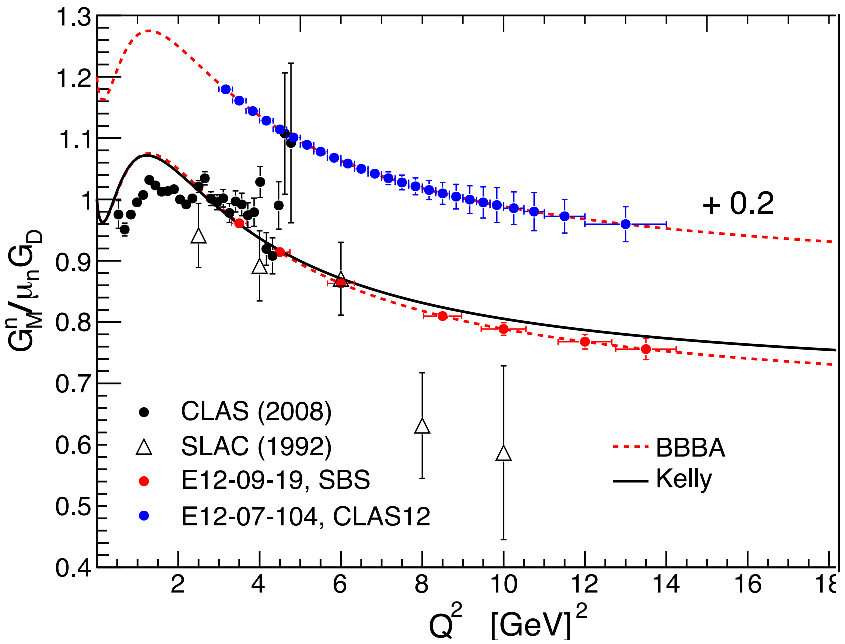
Walker et al,1993

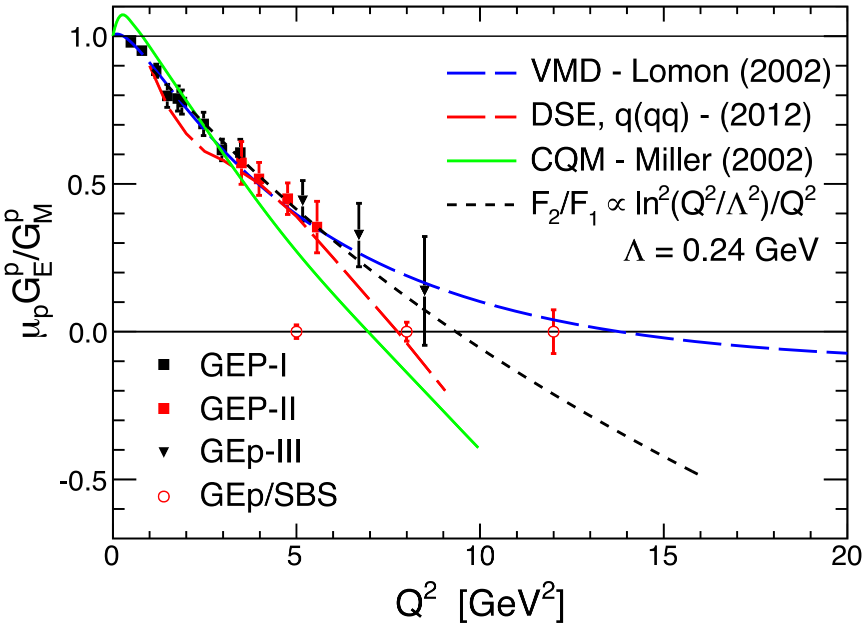


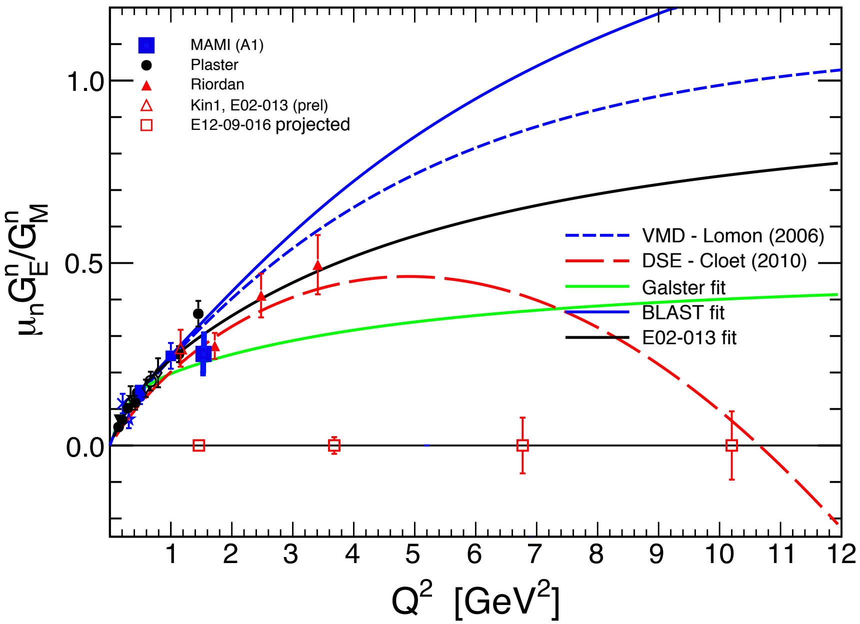
The onset of the pQCD scaling?

The nucleon FFs by 2014

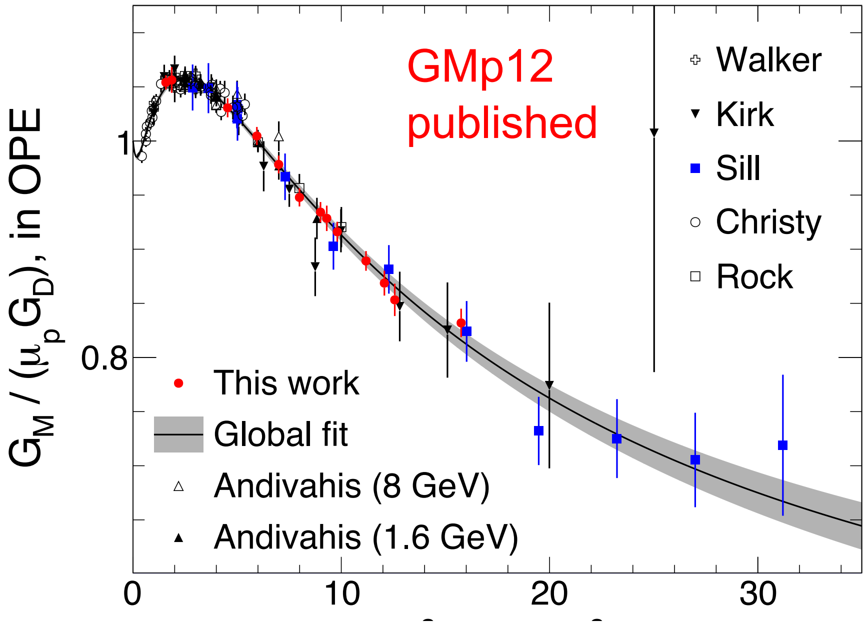


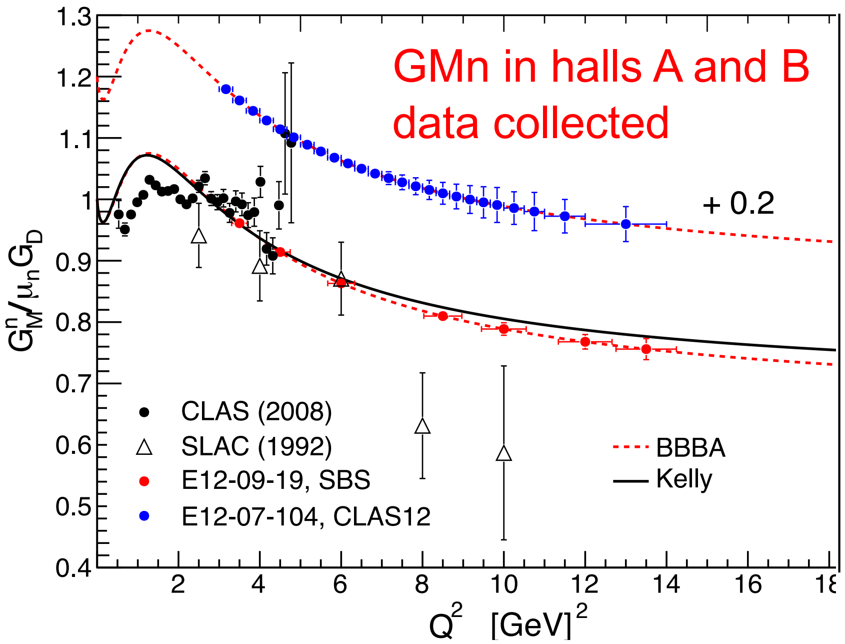


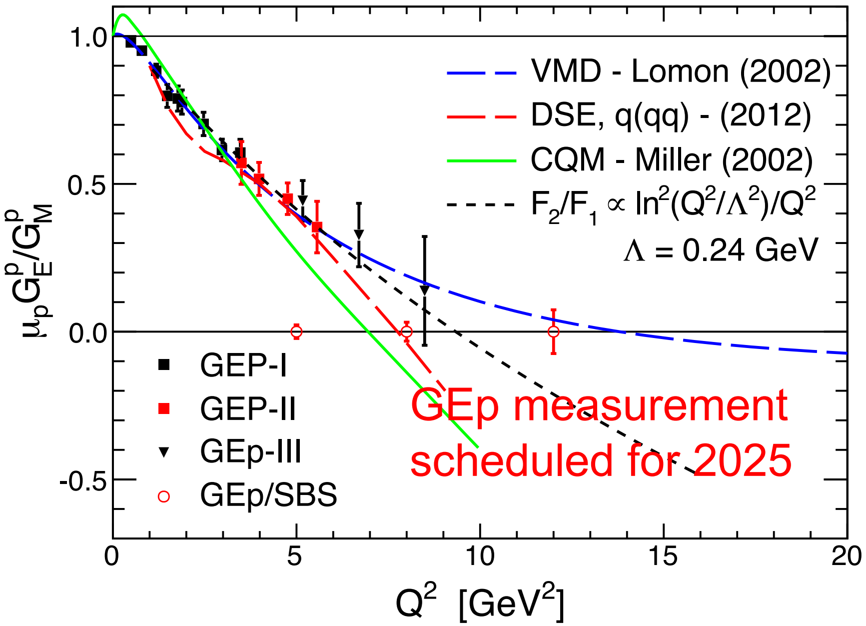


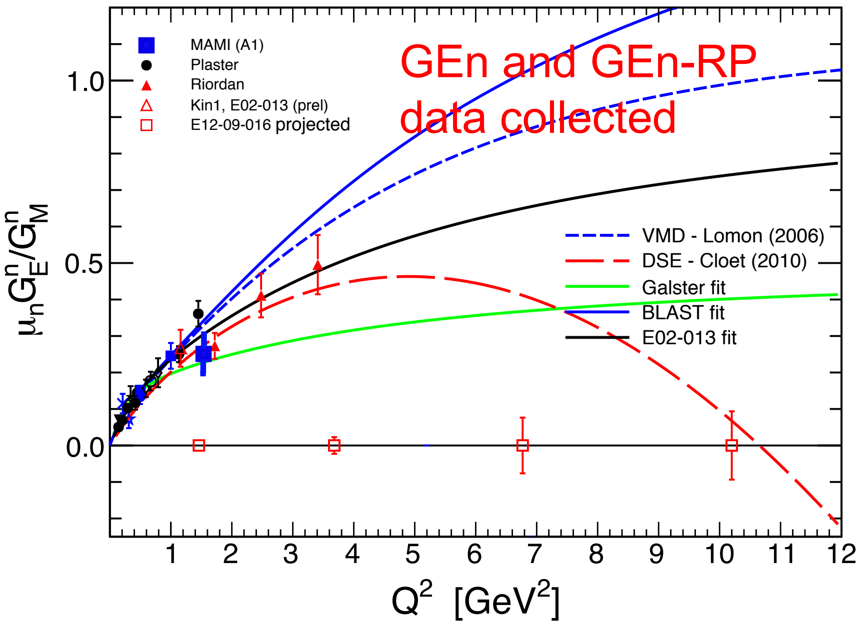


Sachs Form Factors today



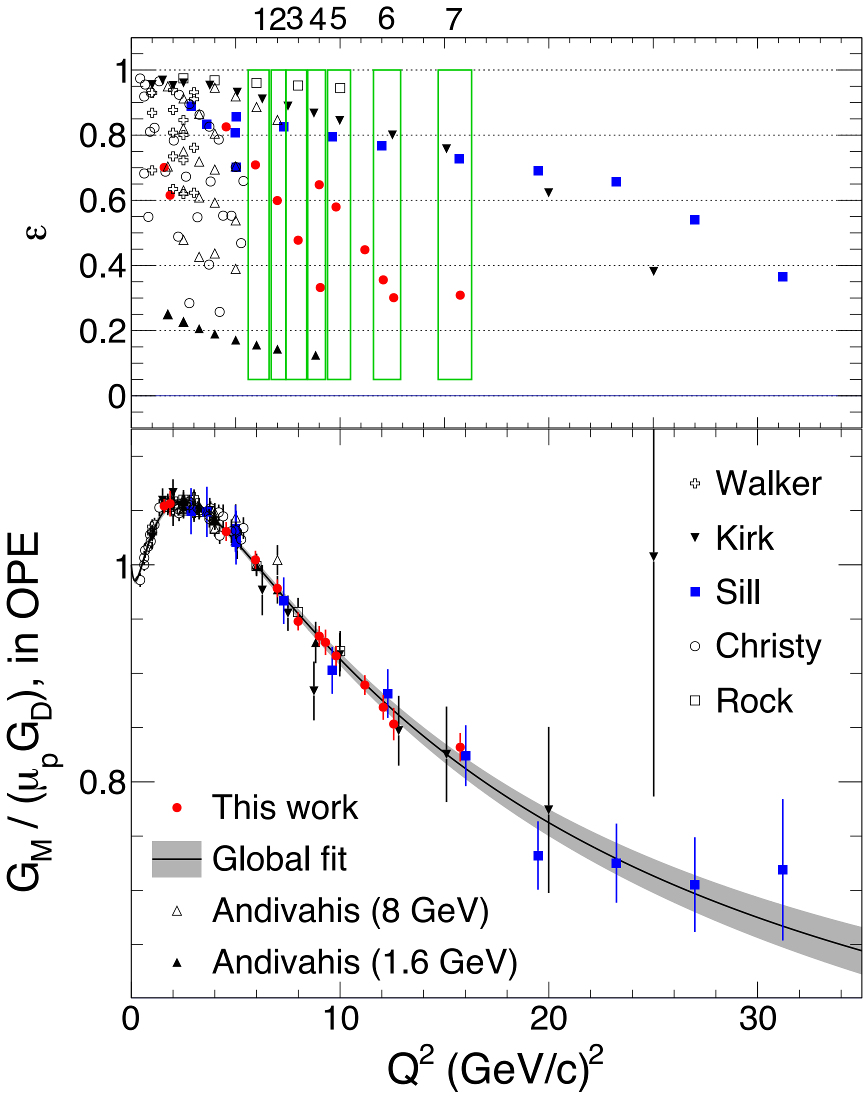


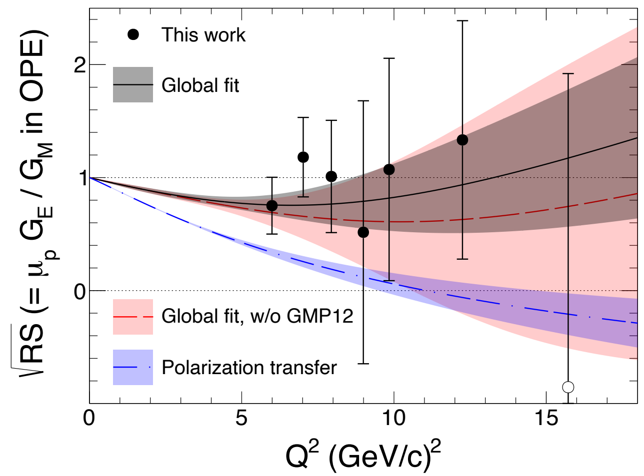




The GMp12 experiment (E12-07-108)

Phys.Rev.Lett. 128 (2022) 10, 102002





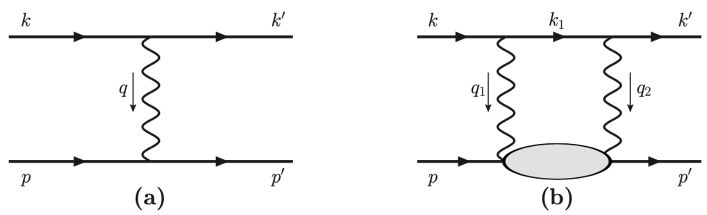
GMp12 fit:

$$G_M = \mu_p (1 + a_1\tau)/(1 + b_1\tau + b_2\tau^2 + b_3\tau^3),$$
$$\mathrm{RS} = 1 + c_1\tau + c_2\tau^2.$$

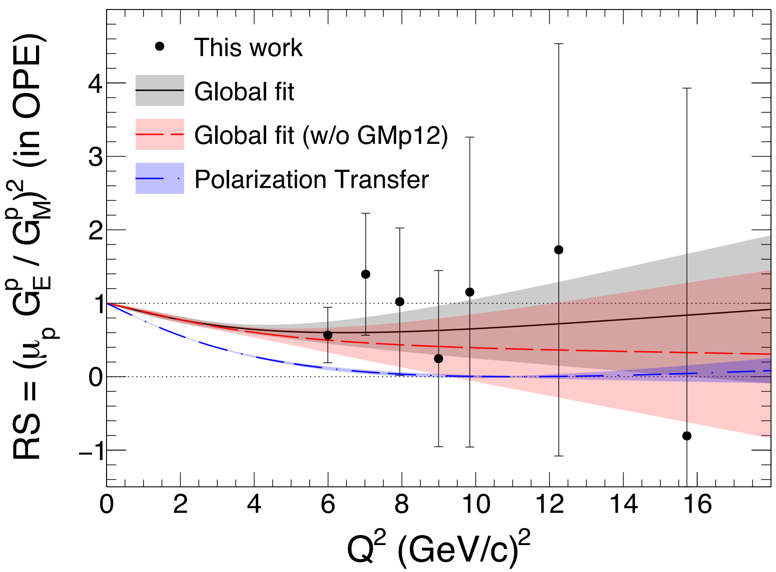
a_1	b_1	b_2	b_3	c_1	c_2
0.072(22)	10.73(11)	19.81(17)	4.75(65)	-0.46(12)	0.12(10)

courtesy of A. Gramolin and A. Puckett

Proton E/M from cross section



$$\sigma_R = \tau\, G_M^2(Q^2) + \varepsilon\, G_E^2(Q^2) = \sigma_T + \varepsilon\, \sigma_L$$
$$= G_M^2(Q^2)(\tau + \varepsilon\, RS(Q^2)/\mu_p^2),$$



$$d\sigma/d\Omega \propto E_e^2/Q^4 \times 1/(Q^2)^4$$

TABLE III. Rosenbluth separation results for the data groupings shown in the top panel of Fig. 1, after centering to the average Q_c^2. The quoted values of σ_L and σ_T as defined in Eq. (2), and $G_M/(\mu_p G_D)$ and $\mu_p G_E/G_M$ are obtained assuming validity of the OPE approximation. For the largest Q^2, where $\sigma_L < 0$, we quote $-\sqrt{|RS|}$.

Q_c^2 $(\mathrm{GeV}/c)^2$	$\sigma_T \times 10^5$	$\sigma_L \times 10^5$	$G_M/(\mu_p G_D)$ (OPE)	$\mu_p G_E/G_M$ (OPE)
5.994	167 ± 4	7.1 ± 4.6	1.000 ± 0.011	0.75 ± 0.25
7.020	104 ± 3	9.3 ± 5.3	0.967 ± 0.015	1.18 ± 0.35
7.943	71.0 ± 2.7	4.1 ± 3.9	0.943 ± 0.018	1.0 ± 0.5
8.994	49.8 ± 1.7	0.7 ± 3.0	0.934 ± 0.016	0.5 ± 1.2
9.840	36.9 ± 2.4	1.9 ± 3.5	0.909 ± 0.029	1.1 ± 1.0
12.249	18.0 ± 0.8	1.2 ± 1.8	0.858 ± 0.019	1.3 ± 1.1
15.721	8.6 ± 0.5	-0.2 ± 1.2	0.840 ± 0.025	(-0.9 ± 2.8)

High accuracy L/T, 1998

A Precision Measurement of G_{E_p}/G_{M_p} at $Q^2 = 2.0$ and 4.0 GeV^2

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J.P. Chen, E. Chudakov, J. Gomez, J. Hansen, M. Kuss, K. de Jager, J.Lerose, M. Liang,
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When Q^2 is held constant between the different measurements, the momentum of the proton also stays the same, as does the spectrometer excitation. This means that the proton's momentum can be matched at the level of the spectrometer's resolution, which is about 1.5×10^{-4}. The absolute value of the momentum transfer is known to the level of 10^{-3}, limited by knowledge of the spectrometer angles. This provides a substantial improvement to the measurement and matching of Q^2 over the capabilities of the prior experiments.

An important benefit from the use of the proton spectrometer at constant excitation is a uniform determination of the solid angular acceptance of the experiment. This is achieved

PAC15 report

Letter –of-Intent: LOI-99-003

Title: A Precision Measurement of G^E_p/G^M_p at Q^2 = 2.0 and 4.0 GeV^2

Spokespersons: B. Wojtsekhowski, W. Bertozzi, K. Fissum, D. Rowntree

Precision measurements of G^E_p are of great interest for providing information on the proton's substructure. New precision measurements using recoil polarization from Hall A experiment 93-027 indicate a decreasing ratio of G^E_p/G^M_p with Q^2, contradicting some of the previous measurements using a Rosenbluth separation. This LOI discusses a new precision measurement in Hall A using the Rosenbluth technique. It would require control and understanding of systematic effects at the level of 1% in measurements of relative cross sections. The PAC acknowledges the interesting suggestions for limiting potential systematic errors presented in this letter but is not convinced that this 1% level can be achieved. In addition, as a cross-check on the recoil polarization technique a polarized beam-polarized target measurement would be more straightforward than the extremely challenging high-precision Rosenbluth separation discussed here. Also, while the PAC appreciates the importance of demonstrating the potential for doing high-precision Rosenbluth measurements with regard to future possible measurements (e.g. Coulomb Sum Rule), the PAC is not convinced that the physics motivation discussed in the present letter warrants the significant effort required to carry out such a difficult experiment.

PAC18 report

Proposal: E-01-001

Scientific Rating: A^-

Title: New measurement of G_E/G_M for the proton.

Spokesperson: R. E. Segel and J. Arrington

Motivation: The disagreement between the Rosenbluth method and the polarization transfer method of existing determinations of G_E/G_M motivates this experiment to make a new Rosenbluth measurement with several improvements to the experimental method. It is of great importance to determine if there is a fundamental problem with either the Rosenbluth or polarization transfer methods, as they are also used for many other experiments.

Measurement and Feasibility: The new measurement will detect protons, which have fixed momentum at fixed Q^2, independent of epsilon. By simultaneously making measurements at very low Q^2, where there is no controversy, systematic errors are reduced compared to the previous Rosenbluth measurements, which detected electrons over a wide range of momentum at fixed Q^2, and did not have a simultaneous low Q^2 measurement. Radiative corrections are also smaller using protons. The experiment uses standard equipment and methods, and appears to be straightforward to carry out.

Issues: The PAC believes it would be of higher scientific value to emphasize more precise measurements at the lower values of Q^2 , where the Rosenbluth method and polarization transfer already have a significant difference. It will be very important to check the assumed linearity of the Rosenbluth separation with respect to epsilon at the optimal Q^2 values by taking data at more epsilon points than proposed.

Recommendation: Approve for 10 days in Hall A.

To do accurate L/T at high Q^2

$$d\sigma = d\sigma_e' \frac{\alpha^2}{4\varepsilon_e^2} \frac{\cos^2\frac{\vartheta}{2}}{\sin^4\frac{\vartheta}{2}} \frac{1}{1+\frac{2\varepsilon_e}{M}\sin^2\frac{\vartheta}{2}} \left\{ \frac{F_e^2 - \frac{t}{4M^2}F_m^2}{1-\frac{t}{4M^2}} - \frac{t}{2M^2} F_m^2 \operatorname{tg}^2\frac{\vartheta}{2} \right\}$$

$$d\sigma = \frac{\pi\alpha^2 d\,|t|}{\varepsilon_e^2 t^2} \left\{ F_e^2(t) \left[\frac{(4M\varepsilon_e + t)^2}{4M^2 - t} + t \right] - \frac{t}{4M^2} F_m^2(t) \left[\frac{(4M\varepsilon_e + t)^2}{4M^2 - t} - t \right] \right\}$$

for $-t = Q^2 = 10\,GeV^2$ or $-\tau = \frac{Q^2}{4M^2} = 2.82$
using $E_e = 11GeV$ got $\theta_p = 21.0$ deg. and $\epsilon = 0.76$
using $E_e = 7.5GeV$ got $\theta_p = 14.6$ deg. and $\epsilon = 0.46$

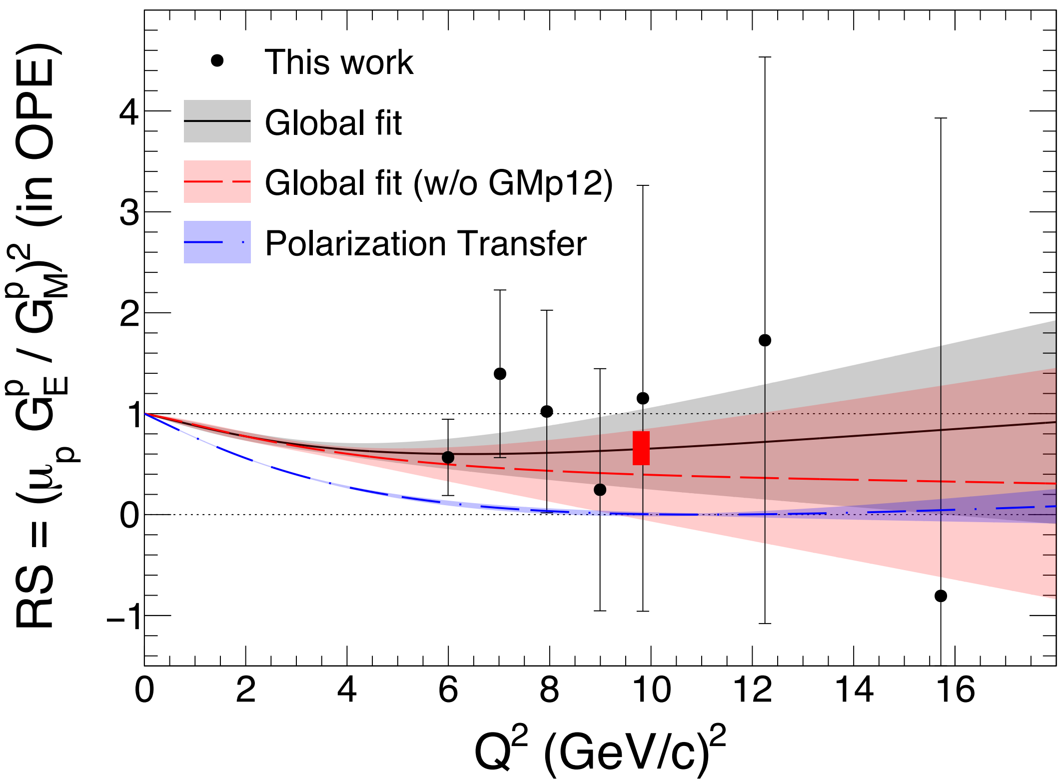
$\Delta\epsilon = 0.3$, so the $\sigma_E/\sigma_M = 0.033$, but $\Delta\sigma_E/\sigma_M$ is just 0.011

Solution for accurate L/T at high Q^2

Accuracy for beam energy 10^{-3} leads to the cross section 3.4×10^{-4}

Accuracy for $Q^2 = -t$ defined by the spectrometer on the level of 5×10^{-4}

and leads to cross section 3×10^{-3}, so $\mu_p G_E / G_M$ to 15% accuracy.



Summary

- Accurate measurement of the L/T ratio at high Q^2 will significantly boost understanding of the basic process.

- Accurate measurement of the L/T ratio at high Q^2 is possible using fixed momentum proton spectrometer.

- HMS and SHMS with 7 GeV/c allow to do this experiment in 20 days for Q^2 = 10 GeV^2 to accuracy $\delta(\mu G_E)/G_M \sim$ 15%

- Also provide constraint on F_3