Measurement of the Proton Elastic Form Factor Ratio At Low Q^2

Proposal PR-08-010 (PR-07-004 Update)

J. Arrington, D. Day, D. Higinbotham, R. Gilman, G. Ron, A. Sarty spokespersons
a Hall A Collaboration experiment

PAC33, Jan 14-17 2008

- 2 part, high-precision measurement of the proton EM form factor ratio $\mu_P G_E / G_M$.
- 2 different methods used.
- Access very low Q^2.
- Direct measurement of proton structure, many implications for analysis of other experiments.

The PR-08-??? Collaboration

- Argonne National Lab
- Jefferson Lab
- Rutgers University
- St. Mary's University
- Tel Aviv University
- UVa
- CEN Saclay
- Christopher Newport University
- College of Willian & Mary
- Duke University
- Florida International University
- Institut de Physique Nuclaire d'Orsay
- Kent State University
- MIT
- Norfolk State University
- Nuclear Research Center Negev
- Old Dominion University
- Pacific Northwest National Lab
- Randolph-Macon College
- Seoul National University
- Temple University
- Université Blaise Pascal
- University of Glasgow
- Jožef Stefan Institute and University of Ljubljana
- University of Maryland
- University of New Hampshire
- University of Regina
- University of South Carolina

And the Hall A Collaboration

Review of Proton Form Factors

- **Cross section for scattering from a** *spinless, point-like* **particle**

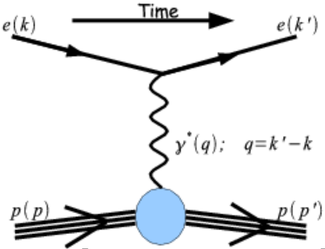
$$\frac{d\sigma_{Mott}}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 cot^2\frac{\theta_e}{2}$$

- **For a spin-$\frac{1}{2}$ particle with internal structure**

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega}\frac{1}{1+\tau}\left[G_E^2 + \frac{\tau}{\varepsilon}G_M^2\right]$$

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

$$j_\mu = \bar{u}'(k')\gamma_\mu u(k)$$



$$J^\mu = \bar{u}'(p')\left[F_1(Q^2)\gamma^\mu + \frac{\kappa F_2(Q^2)}{2M} i\sigma_{\mu\nu}q^\nu\right]u(p)$$

Lowest order perturbation theory in QED, elastic ep scattering is given by single photon exchange (Born Approximation).

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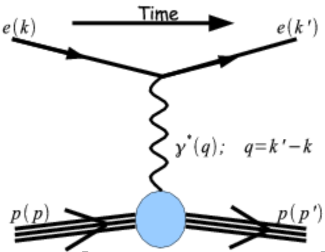

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Review of Proton Form Factors

- **FFs describe the proton internal structure. Related to the charge and magnetization densities (Fourier).**
- FFs Approximately follow Dipole Form

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

- Define $R \equiv \mu_P \frac{G_E}{G_M}$. From normalization $R(Q^2 = 0) = 1$. If both FFs follow dipole $R = 1$.

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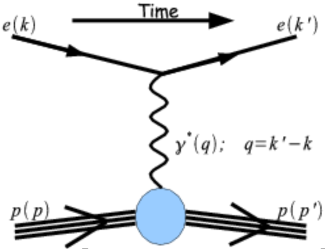

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Sachs FF:

$$G_E \equiv F_1 - \tau F_2 \;;\; G_M \equiv F_1 + F_2$$

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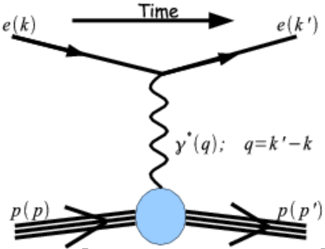

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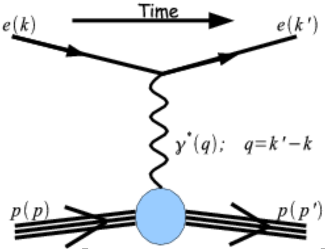

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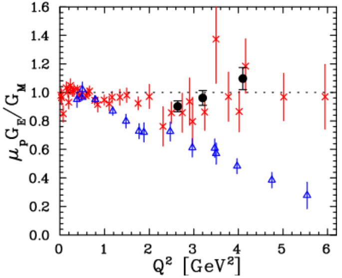
Mostly explained by 2γ exchange.



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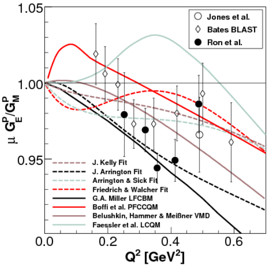

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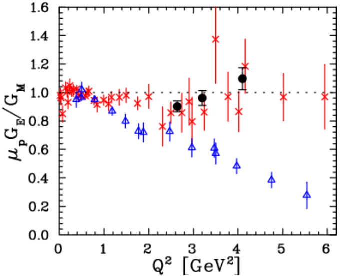

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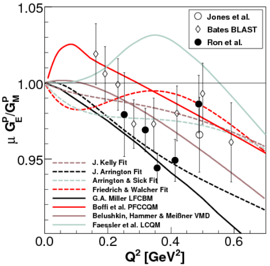

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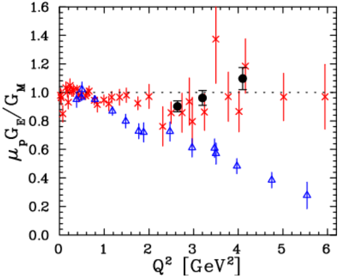

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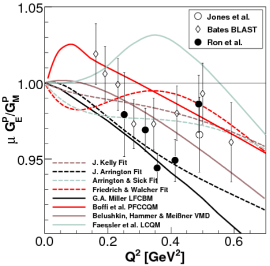

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OUR FOCUS IS ON THE LOW Q^2 REGION.

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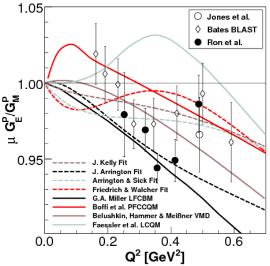

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Latest Measurements & Analyses

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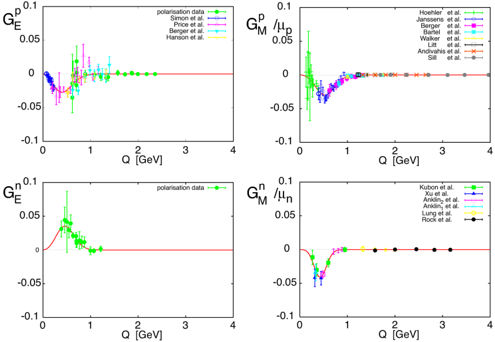
- 2007 - LEDEX & Bates BLAST data show deviations from unity and hints of narrow structure.



J. Friedrich & T. Walcher, Eur. Phys. J. A17, 607 (2003).

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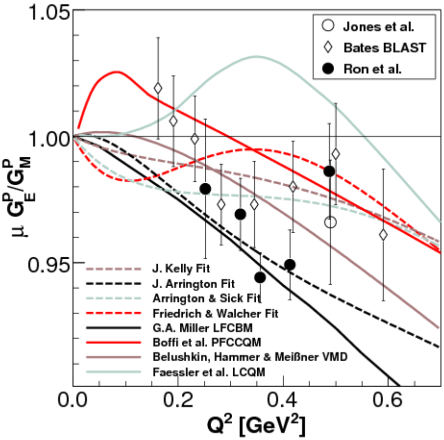

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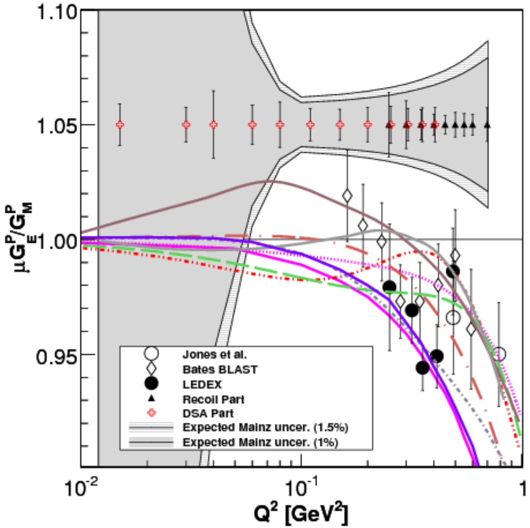
C. B. Crawford *et al.*, Phys. Rev. Lett. 98, 052301 (2007).

From the PAC31 report on PR-07-004: "Since Mainz is presently running an experiment which using Rosenbluth separation can determine the same ratio in the same region of Q2 , consideration should be given to these results and especially their level of uncertainties before approval to proceed with this proposal is given."

- Mainz experiment concluded.
- Took all planned data points.
- Optimistic assumtion is that they will get ∼1% uncertainties (realistically, possibly ∼1.5%).
- Plot compares our expected uncertainties to Rosenbluth extraction of the form factor ratio from the Mainz data.



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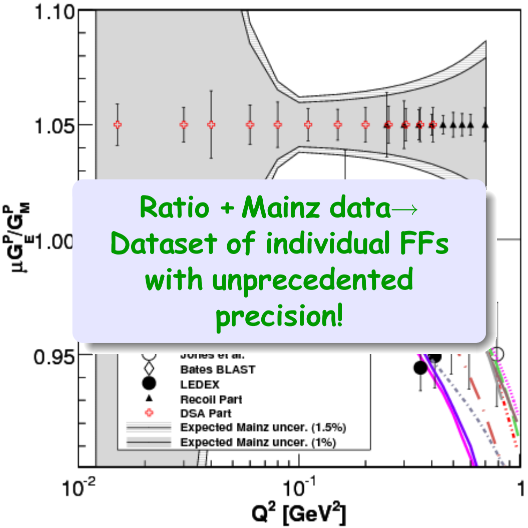


Ratio + Mainz data→ Dataset of individual FFs with unprecedented precision!

Some Impacts on Proton FFs

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

- $R(Q^2 = 0.356) = 0.9441 \pm 0.011$ - 5σ **from unity!**
- **In combination with world data:**
  - $Q^2 = 0.3 - 0.45 GeV^2$ - $R = 0.96 \pm 0.007$.
  - $Q^2 = 0.45 - 0.55 GeV^2$ - $R = 0.987 \pm 0.008$.
  - 3σ **difference between** Q^2 **ranges** $\rightarrow$ **Hints of narrow structure? Need more data.**
  - **Standard fits overpredict** $G_E^P(Q^2 = 0.4)$ **by** $\approx$**1-2%.**

Possible Impacts on other experiments

- **DVCS**:
  - DVCS measurements focus on the high Q^2, small t (equivalent to small Q^2 in ep elastic) region.
  - Need elastic scattering results to disentangle $\rightarrow$ requires knowledge of elastic form factors (at $Q^2_{ep} = -t$).
  - Knowledge of the FFs is a limiting uncertainty, especially in regions where BH $\gg$ DVS.
- **HAPPEx** measurement of the weak form factors $\rightarrow$ the new data adjust the measured asymmetry by about -0.5 ppm, corresponding to a smaller effect from strange quarks, on data with a statistical uncertainty of $\approx$1 ppm.
- Similar effect possible in **G0** results.
- New result would shift the expected **HAPPEx-III** result by one standard deviation.

Zemach Radius

- **Hyperfine splitting of the H spectra can be written:**

$$E_{hfs}(e^- p) = \left(1 + \Delta_{QED} + \Delta^P_R + \Delta^P_{h\nu p} + \Delta^P_{\mu\nu p} + \Delta^P_{weak} + \Delta_S\right) E^P_F$$

- **Structure dependent term**

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

- **Zemach radius:**

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

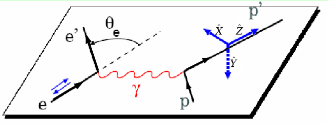
- **Differences in parameterization to the Zemach radius lead to $\sim$1 ppm correction to theory.**
- **Theory itself is at 1 ppm level !**

The Proposed Measurement

Part I - Recoil Polarimetry

Polarization Transfer - Review

Polarization Transfer - *Scatter* polarized electrons off unpolarized protons → measure recoil proton polarization.



$$I_0 P_x = -2\sqrt{\tau(1+\tau)}\,tan\frac{\theta_E}{2} G_E G_M$$

$$I_0 P_z = \frac{E+E'}{M}\sqrt{\tau(1+\tau)}\,tan^2\frac{\theta_e}{2} G_M^2$$

$$R \equiv \mu_P \frac{G_E}{G_M} = -\mu_P \frac{E+E'}{2M} tan\frac{\theta_e}{2}\frac{P_x}{P_z}$$

Part I - Overview

Part I conditionally approved in PAC31 (PR-07-004).

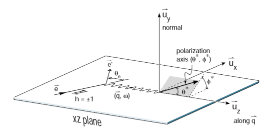
- Hall A FPP, $E_e \sim 0.85 GeV$, 80% polarization
- PRL 99, 202002 (2007) data took 12-18 hours / Data point with $P_e = 40\%$, we request 1 day / Point (2 days at 0.25 GeV^2)
- Systematics $\sim 0.4\%$ at 0.5 GeV^2, better for lower Q^2
- Standard Hall A setup

Q^2 (GeV^2)	(Δ Ratio/Ratio)$_{stat.}$ (%)
0.25	1.00
0.3	0.73
0.35	0.46
0.4	0.32
0.45	0.28
0.5	0.37
0.55	0.34
0.6	0.32
0.7	0.31

The Proposed Measurement

Part II – Double Spin Asymmetry

Part II - Overview



- **Measure asymmetry in $\vec{p}(\vec{e}, e')$ simultaneously in both HRSs (equal acceptance).**
- **Take the ratio of asymmetries → Systematics cancel out.**

$$\mu_P \frac{G_E^P}{G_M^P} = -\mu_P \frac{a(\tau,\theta) cos\theta_1^* - \frac{f_2}{f_1}\Gamma a(\tau,\theta)\cos\theta_2^*}{\cos\phi_1^* \sin\theta_1^* - \frac{f_2}{f_1}\Gamma \cos\phi_2^* \sin\theta_2^*}$$

$$a(\tau,\theta) = \sqrt{\tau(1 + (1+\tau)\tan^2(\theta_e/2))}$$

θ_i^* (ϕ_i^*) **- polar (azimuthal) angle of the target spin with respect to the $\vec{q}$ in the i^{th} spectrometer.** $\Gamma = \frac{A_1}{A_2}$. $f_1 \approx f_2$

- **Install septa in HRSs → reach VERY low Q^2 while keeping scattered electron at high momentum (less effect from target field).**

Q^2 (GeV^2)	(Δ R/R)$_{tot}$. (%)
0.015	0.80
0.030	0.65
0.040	1.42
0.060	0.63
0.080	0.83
0.100	0.51
0.150	0.47
0.200	0.52
0.250	0.51
0.300	0.52
0.350	0.52
0.400	0.53

Part II - Systematics

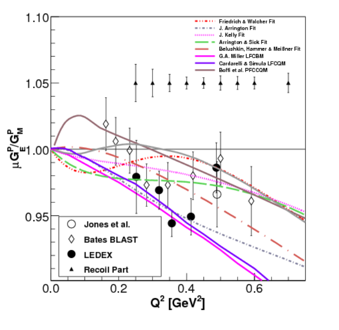
- Mostly cancel out when taking the ratio of asymmetries.
- Beam and Target polarization identical for both HRSs (and constant when considering small time slices).
- Only second order effect from dilution factor.
- Main systematic uncertainty is scattering angle reconstruction $\rightarrow$ use accurate target field map and perform optics study of septum magents with target field (expect little degradation in resolution, $E'_e > 1$ GeV/c).
- High rate (low Q^2) $\rightarrow$ uncertainties dominated by systematics.

Part II - Requirements

- 11 days of 80% polarized beam in Hall A.
- Installation of UVa polarized target.
- Installation of septa on HRSs.
- Upstream chicane for beam deflection.
- Installation of local beam dump.
- All installations also required for PR-07-001 (δ_{LT}). if other proposals for this PAC need this we should say so, will review proposals after they are all submitted.

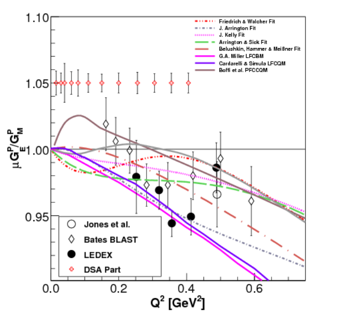
Summary

Recoil Polarization



14 Days of 80% polarized beam

Double Spin Asymmetry



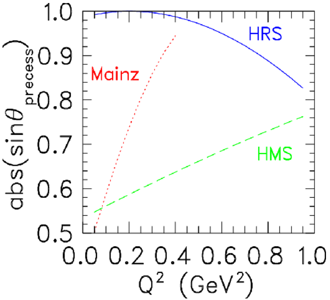
11 Days of 80% polarized beam

Hall A is uniquely suited for this experiment!

Backup Slides

Could this be done elsewhere? - Recoil Polarization

- Our proposed uncertainties on R are 0.5-1.1%
- Mainz cross sections give $\approx$1.4% errors on R
- Mainz FPP systematics $\approx$4%
- Spin transport favors Hall A. Systematics for Hall C unclear



Could this be done elsewhere (Mainz)? - DSA

As Mainz has a low energy electron beam and has spectrometers, we investigated doing this experiment there.

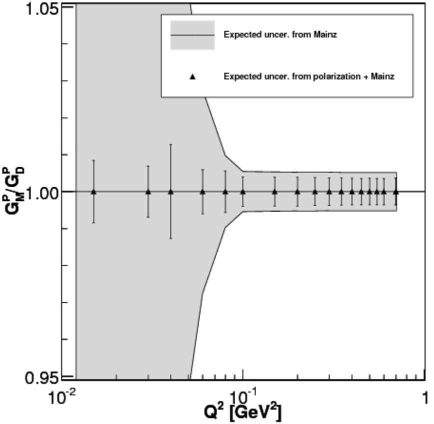
- None of the infrastructure for this experimet currently exists at Mainz (polarized target, septa, chicanes, etc.)
- A1 Hall does not have fully symmetric spectrometers $\rightarrow$ increases systematic uncertainties
- Low energy beam $\rightarrow$ large e' deflection in the target field

Mainz is clearly not the best facility for this measurement.

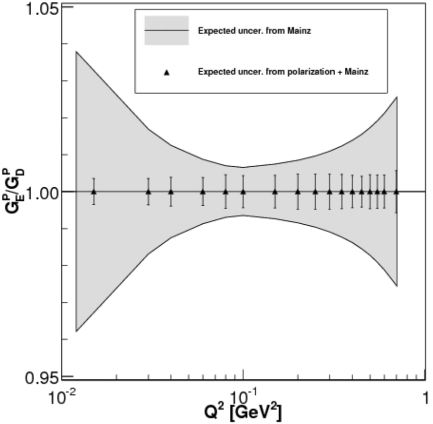
Part I - Systematics

- Measurements with quadrupoles turned off.
- Measurement of R at $Q^2 =\sim 2.2$ GeV^2, in the "spin hole"; variation of spin direction in focal plane very sensitive to spin transport there.
- Done previously with HRS-R for $G_E^P - I$; never done for HRS-L. Since we need high precision, we plan to redo these tests.
- Also considering other methods to decrease the systematic uncertainties.

Individual FFs vs. Mainz



Projected uncer. on G_M^P/G_D vs. Mainz (assuming 1% XS)



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