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

Proposal PR-08-007 (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 (<1%) 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-08-007 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**

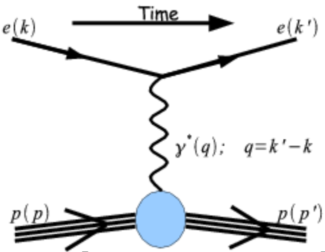
$$\frac{d\sigma_{Mott}}{d\Omega} = \frac{\alpha^2}{Q^2}\left(\frac{E'}{E}\right)^2 cot^2\frac{\theta_e}{2}$$

- **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).

Review of Proton Form Factors

- FFs describe the proton internal structure. Related (NR) 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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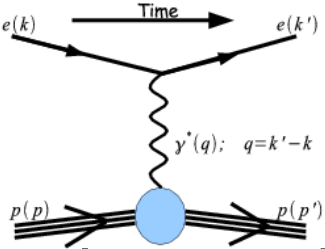

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$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{Mott}}{d\Omega}\frac{1}{1+\tau}\left[G_E^2 + \frac{\tau}{\varepsilon}G_M^2\right]$$

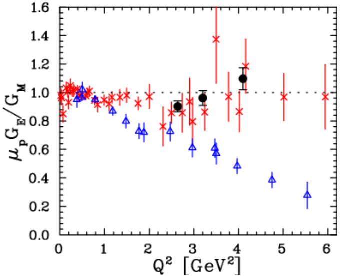
Sachs FF:

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

Surprise

Rosenbluth and Polarization methods do not agree at high Q^2.

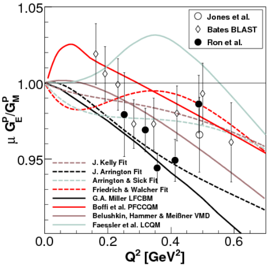
Mostly explained by 2γ exchange.



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

Deviation from $R = 1$ indicated at low Q^2.

Virtual meson cloud? (Friedrich & Walcher).



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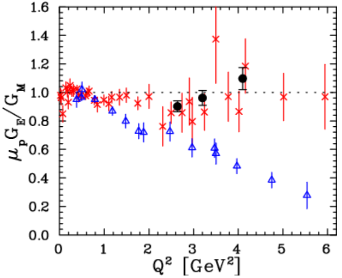

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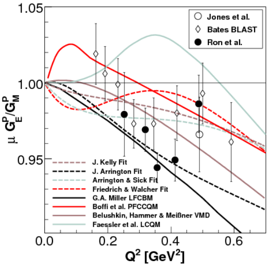

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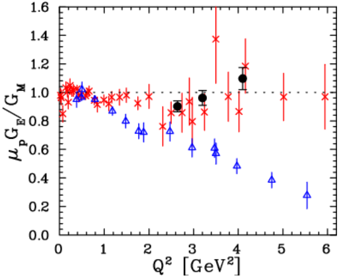

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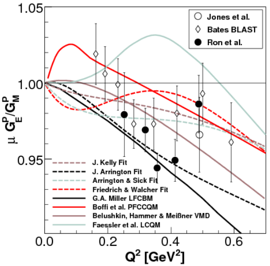

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Surprise

OUR FOCUS IS ON THE LOW Q^2 REGION.

Deviation from $R = 1$ indicated at low Q^2.
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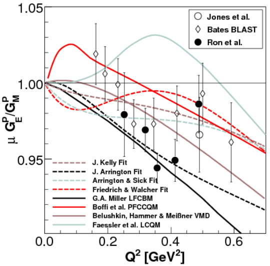

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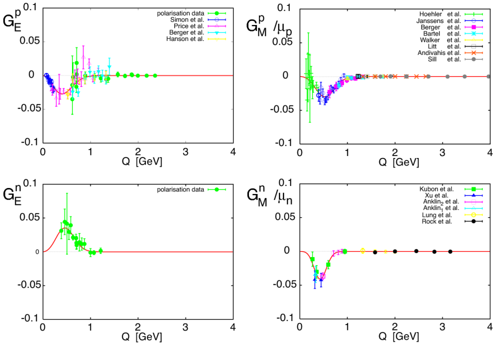
Friedrich & Walcher Analysis

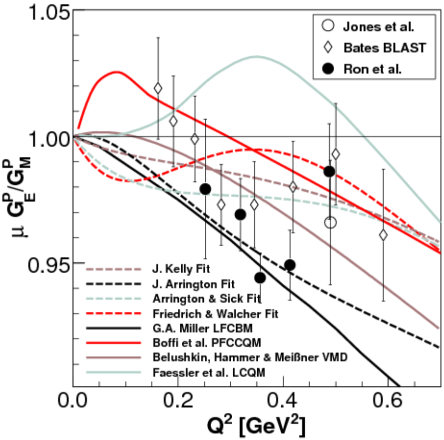
- **2003** - Bump/Dip structure in all 4 FFs. Plot shows FF data vs. fit: 2-dipoles + bump (deviations are model-dependent and hard to interpret).
- 2007 - LEDEX & Bates BLAST data show deviations from unity. Inconsistent with the F & W analysis.



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

Latest Measurements & Analyses

- 2003 - Bump/Dip structure in all 4 FFs. Plot shows FF data vs. fit: 2-dipoles + bump (deviations are model-dependent and hard to interpret).
- 2007 - LEDEX & Bates BLAST data show deviations from unity. Inconsistent with the F & W analysis.



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

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

Extracting the Individual FFs

Can combine high precision R and cross section data:

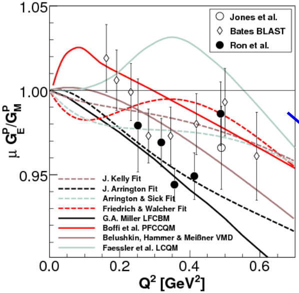
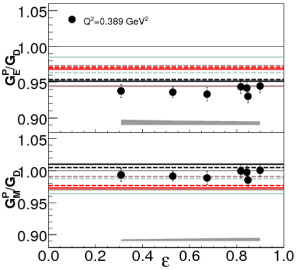


Table 1.
Differential cross sections: The quoted errors are only random errors. A normalization error of ± 4% has to be added.

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

:. Lett. B35, 87 (1971).

Extract individual FFs ($Q^2 = 0.389$ GeV^2):

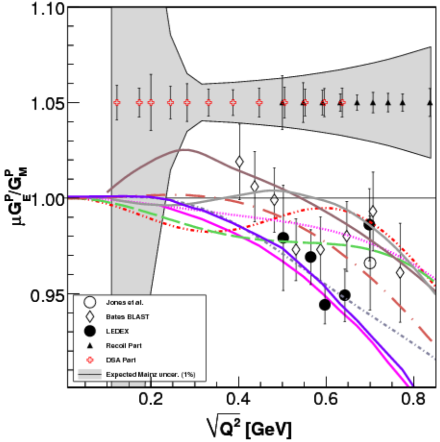


Deviation at 0.389 GeV^2 due to G_E!

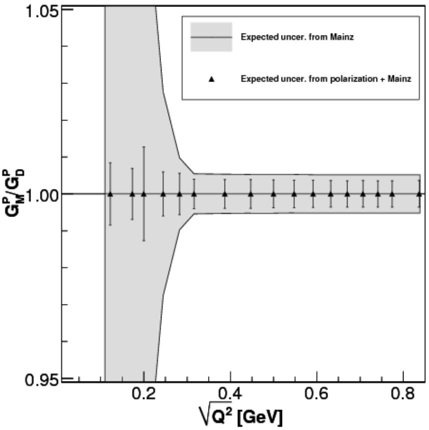
(G. Ron *et al.*, Phys. Rev. Lett. 99, 202002 (2007).)

Complementary to the Mainz XS Measurement

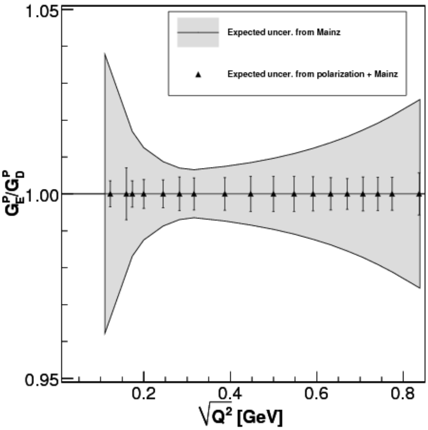
- Mainz experiment has taken data.
- Measured cross sections down to $Q^2 \approx 0.01\,\mathrm{GeV}^2$.
- Having cross sections + polarizations:
  - Reduces correlations between G_E and G_M.
  - Reduces correlations between Q^2 points.
  - Checks experimental consistency (eg. 2-γ).
- Ratio + Mainz data→ Dataset of individual FFs with unprecedented precision!



Individual FFs (our R + Mainz XS) vs. Mainz alone



Projected uncer. on G^P_M/G_D vs. Mainz (assuming 1% XS)



Projected uncer. on G^P_E/G_D vs. Mainz (assuming 1% XS)

Jump 2 Slides

Direct Impacts

- Improved proton+neutron gives improved isoscalar and isovector form factors.
  - Absolute uncertainties on proton/neutron FFs are what really matters. Proton has better relative measurements than neutron, but comparable absolute uncertainties.
- Improved proton+neutron gives improved 2 quark flavor decomposition (assumed strange FFs equal 0).

Possible Impacts on other experiments - PV

- Determination of strange quark form factors by HAPPEX and G0 parity violation experiments depends on knowledge of the EMFF.
- G. Ron *et al.* PRL 99, 202002 (2007), adjusts the expected HAPPEX-I non-strange asymmetry by about -0.5ppm, corresponding to a smaller effect from the strange quarks, by about 1/2 σ.
- New results could shift the expected HAPPEX-III result by one standard deviation.
- Knowledge of the effect on G0 requires precise form factors over a wide Q^2 range.

Zemach Radius

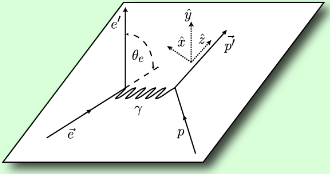
- $E_{hfs}(e^- p) = \left(1 + \Delta_{QED} + \Delta_R^P + \Delta_{h\nu p}^P + \Delta_{\mu\nu p}^P + \Delta_{weak}^P + \Delta_S\right) E_F^P$
- **Structure dependent term**
  $\Delta_S = \Delta_Z + \Delta_{pol}, \ \Delta_Z = -2\alpha m_e r_Z \left(1 + \delta_Z^{rad}\right)$
- **Zemach radius:** $r_Z = -\frac{4}{\pi} \int_0^\infty \frac{dQ}{Q^2} \left[G_E(Q^2) \frac{G_M(Q^2)}{1 + \kappa_P} - 1 \right]$
- **A leading theoretical uncertainty from Δ_Z:**
  r_Z = 1.05 $\pm$ 0.02 fm leads to Δ_Z = 40 $\pm$ 1ppm.
- **Low Q^2 evaluation relies on assumptions of extrapolation to $Q^2 = 0$, parametrizations all basically enforce similar G_E and G_M low Q^2 dependence by having $\approx$ linear extrapolation.**
- **New measurements would reduce the Zemach radius uncertainty by $\sim$ 2.**

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

Opportunity for Part I With a 1.2 GeV Beam

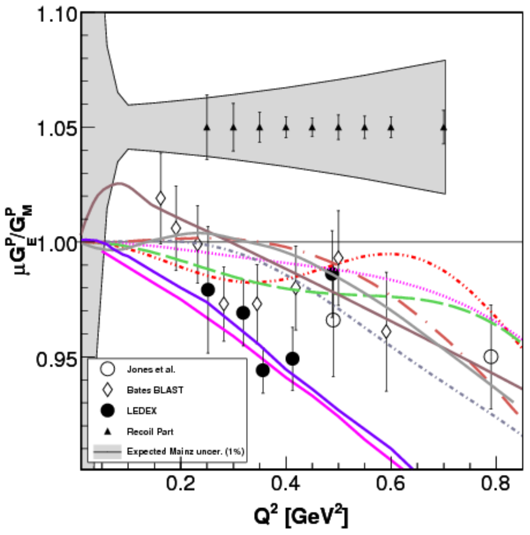
(May 2008 - No existing approved experiment can run)

- Experiment entirely consistent with HRS_L (protons) + BigBite (electrons) setup.
- Statistics slightly worse.
- Systematics similar.
- Total about the same.
- Senior PhD. Student (involved in BigBite detector package construction) interested.
- Available beam time $\approx$ our Part I request.

Q^2 (GeV^2)	$(\Delta\ \mathrm{Ratio}/\mathrm{Ratio})_{stat.}$ (%)
0.25	1.45
0.3	1.06
0.35	0.66
0.4	0.46
0.45	0.39
0.5	0.52
0.55	0.46
0.6	0.43
0.7	0.38

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."

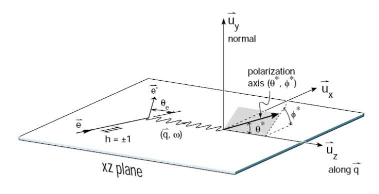
- Mainz experiment has taken data.
- Planned ~1% stat. uncertainties lead to gray error band.
- Plot compares our TOTAL expected uncertainties to Rosenbluth extraction of the form factor ratio from the Mainz data (up to 5 times better in the "bump" region).



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 $\rightarrow$ Systematics cancel out.**



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

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

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

Q^2 (GeV^2)	$(\Delta R/R)_{tot.}$ (%)
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

- **With septa $\rightarrow$ reach VERY low Q^2 while keeping scattered electron at high momentum (less effect from target field).**

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.
- 3 Angles at 1 pass beam, 4 at 2 pass, 5 at 3 pass.
- 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-08-027 (g_2^P).

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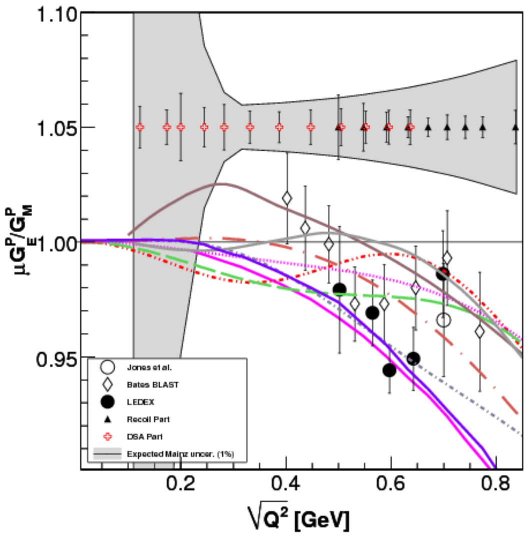
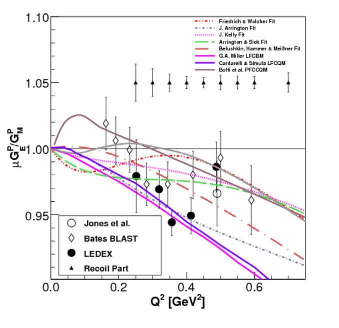


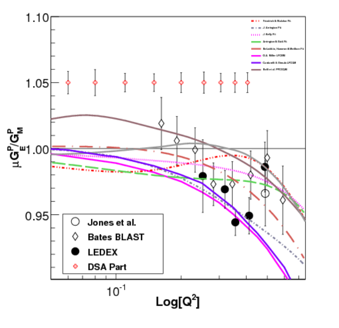
Summary

Part I - Recoil Polarization



14 Days of 80% polarized beam

Part II - Double Spin Asymmetry

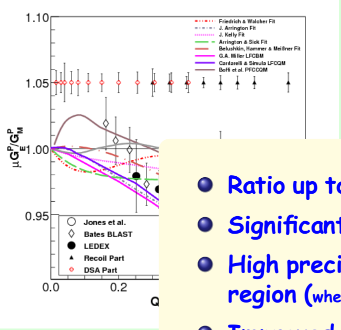


11 Days of 80% polarized beam

Hall A is uniquely suited for this experiment!

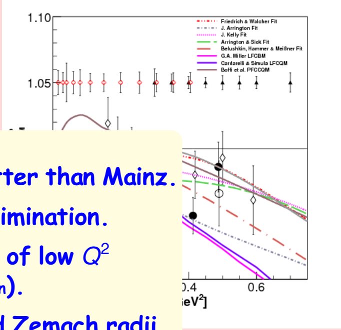
Summary

Part I - Recoil Polarization



14 Days
polariz

Part II - Double Spin Asymmetry



% polarized
m

- Ratio up to 5 times better than Mainz.
- Significant model discrimination.
- High precision mapping of low Q^2 region (where G_M^P poorly known).
- Improved magnetic and Zemach radii, IS/IV/u/d form factors.
- Q Range: $0.23 < \langle R^P \rangle_{ch} < 1.6$ fm.

11+14=23 Days, from reducing overlap

Backup Slides

Compatibility with Q_{weak}

- Beam polarization fine - with longitudinal 1-pass beam in Hall C, Hall A polarization 95, 90, 85% of Hall C for 1, 2, 3 pass beam.
- Measurements use currents $\sim$ 85 nA.
- Uses 1, 2, 3 pass beam.
- Would need 1-pass split to get to lowest Q^2.

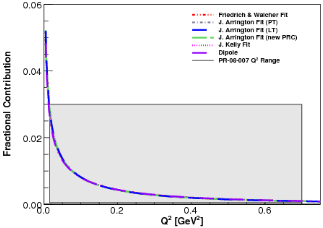
Quantifying the Zemach Radius

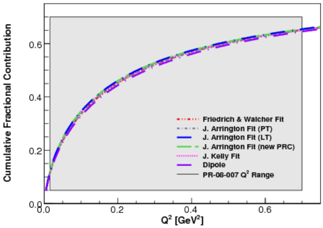
Different calculations/fits disagree:

- Friedrich & Walcher - 1.0431fm
- Arrington (LT) - 1.0708fm
- Arrington (Pol) - 1.0403fm
- Arrington (new PRC) - 1.0707fm
- Kelly - 1.059fm
- Dipole - 1.0149fm

A 5% variation between fits $\rightarrow \approx$2ppm in HFS.
Uncertainty from Δ^{pol} $\approx$0.6ppm.

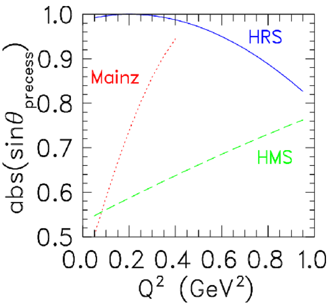
G_M largely unmeasured as Q^2 *to* 0. Results are consistent due to (the assumed) nearly identical extrapolations for G_E and G_M for $Q^2 \rightarrow 0$.





Could this be done elsewhere? - Recoil Polarization

- Our proposed uncertainties on *R* are 0.5-1.1% (stat.)
- Mainz FPP systematics ≈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.
- Due to larger minimum spectrometer angles, low Q^2 requires low electron energies $\rightarrow$ large e' deflection in the target field.

Mainz is clearly not the best facility for this measurement.

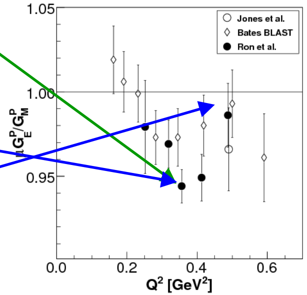
Part I - Systematics

- 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.

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?**
  - **Standard fits overpredict** $G_E^P(Q^2 = 0.4)$ **by** $\approx$**1-2%.**



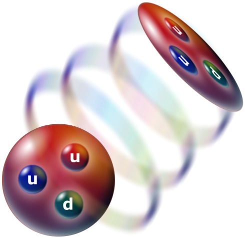
Charge Densities

From Miller *et al.***:**

- **For low** Q^2, $R \approx 1 - \frac{Q^2}{6}\left(R_M^{*2} - R_E^{*2}\right)$.
- G_E, G_M **do not represent true densities due to relativistic effects (Lorentz contraction).**
- **Move to light-cone variables to get transverse densities:**

$$F_1(Q^2) \approx 1 - \frac{Q^2}{4}\langle b^2\rangle_{Ch}$$
$$F_2(Q^2) \approx \kappa\left(1 - \frac{Q^2}{4}\langle b^2\rangle_{M}\right)$$

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

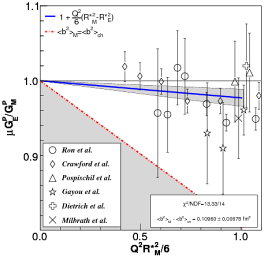


Charge Densities

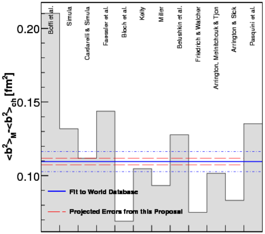
Fit to world data for low Q^2:

$$\left\langle R_M^{*2}\right\rangle - \left\langle R_E^{*2}\right\rangle = -0.0139 \pm 0.00678 \ \mathbf{fm}^2$$

$$\left\langle b^2\right\rangle_M - \left\langle b^2\right\rangle_{ch} = 0.10960 \pm 0.00678 \ \mathbf{fm}^2$$



Proton magnetization extends further than proton charge (pion cloud? quark OAM?).
All calculations and fits agree that $\left\langle b^2\right\rangle_M > \left\langle b^2\right\rangle_{ch}$, but different value.
New measurements will challenge some of the fits/calculations.

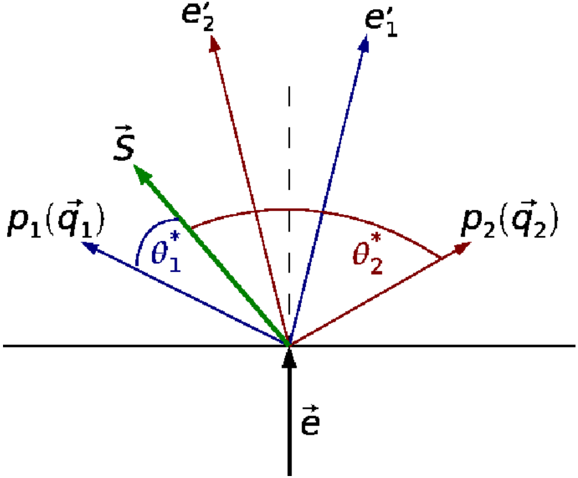


G. Miller, E. Piasetzky, and G. Ron, Submitted to PRL. [arXiv:0711.0972]

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.

Part II Coordinate System



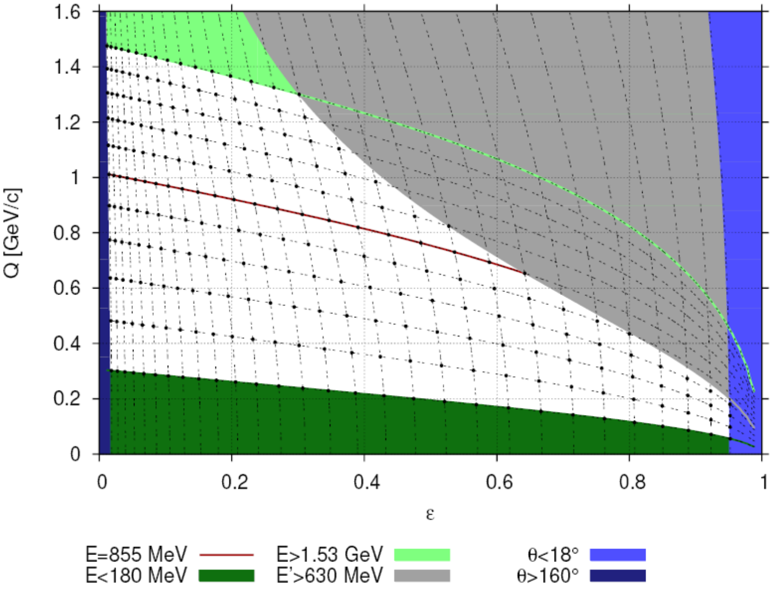
Part II with no Septum

(Yes, we can do it)

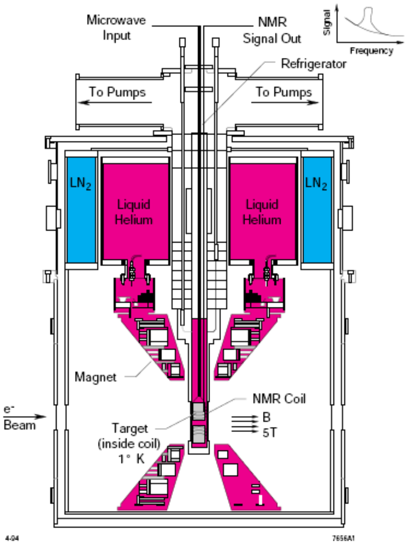
- Q^2 range $0.015 - 0.4 \rightarrow 0.06 - 0.4$ GeV^2.
- Uncertainties roughly similar.
- Use 1, 2 pass beam.
- Still need chicane, local beam dump.

Q^2 (GeV^2)	$(\Delta R/R)_{tot.}$ (%)
0.060	0.54
0.080	1.40
0.100	0.51
0.150	0.53
0.200	0.69
0.250	0.67
0.300	0.70
0.350	0.75
0.400	0.81

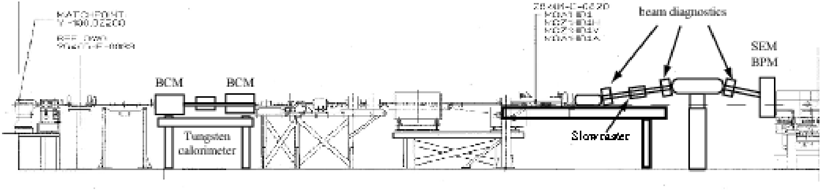
Mainz Phase Space



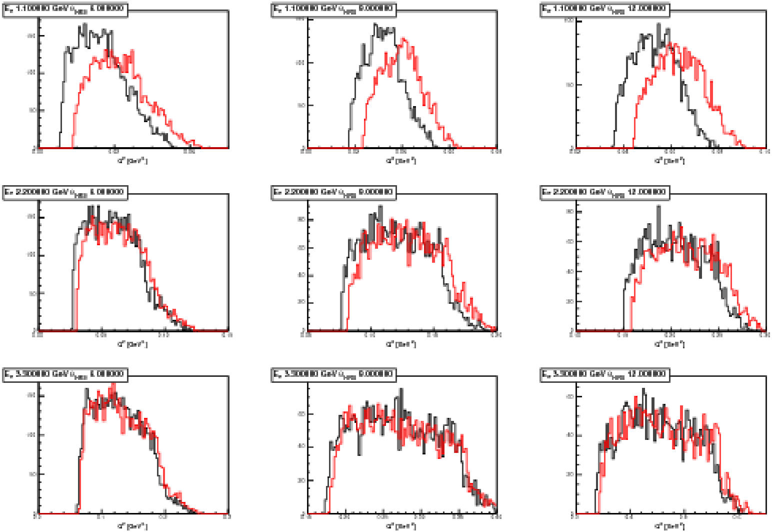
Target Schematic



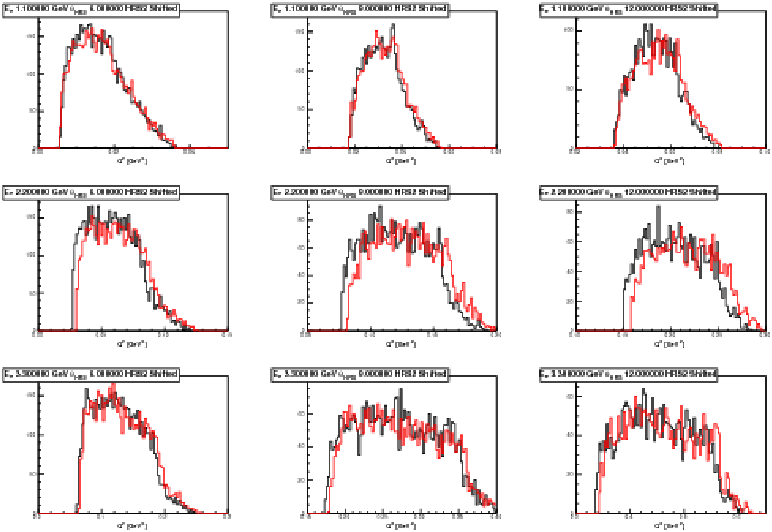
Beamline Schematic



Q^2 Acceptances



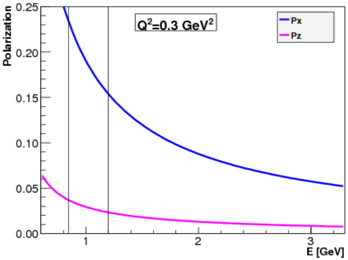
Q^2 Acceptances (Shifted)



Is this a 12 GeV Experiment?

Recoil Polarization

- Requires 1-pass beam.
- Minimum beam energy 2.2 GeV.
- Polarization observables drop sharply with increasing beam energy (forward electron angles).
- To get the same uncertainties with 2.2 GeV beam → 150 hours/point.



Is this a 12 GeV Experiment?

DSA

- Requires 1-pass beam.
- Limits Q^2 range to (0.05 GeV^2 $\rightarrow$), assuming speta are installed.
- Maybe posible to run with 1-Linac configuration.

Density Plots