Proton Form Factor Ratio Measurements at High Q^2 with Super Bigbite

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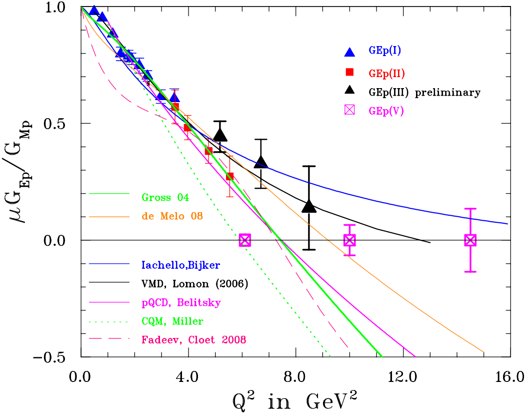
Outline

- Introduction
- The GEp-V experiment
- Physics goals of GEp-V
- Experimental method
- Super Bigbite apparatus
- Current Status

Introduction

- Ground-state EM nucleon FFs are among the most fundamental quantities that describe the nucleon's non-perturbative structure.
- First Hall A G_E^p/G_M^p measurement made the discovery that the ratio drops almost linearly with Q^2 above ~ 1 GeV^2.
  [Jones *et al.*, PRL **8**4 (2000)]
- Subsequent measurements extended Q^2 range up to 8.5 GeV^2.
- New results have stimulated huge amounts of theoretical activity.
- Refined pQCD calculations to explain existing data include an $L = 1$ component in the quark light-cone wavefunction.
  [Belitsky, Ji, Yuan, PRL **9**1 (2003)]
- Most promising and realistic approach based on DSE/Faddeev eqn.
  [Cloët *et al.*, Few-Body Systems, **46** (2009)]

Proton Form Factor Ratio



- Current theoretical models describe proton data well up to $Q^2 \sim 5$ GeV^2.
- Models diverge strongly at higher Q^2 where there are no data to constrain the calculations.
- Evident that only way to achieve clarity in discriminating between theoretical explanations of G_E^p/G_M^p data is to measure it with considerable precision to high values of Q^2.

The GEp-V Experiment

“Large Acceptance Proton Form Factor Ratio Measurements up to 14.5 GeV^2 Using Recoil-Polarization Method”

E. Brash, E. Cisbani, M. Jones, M. Khandaker, L. Pentchev, C.F. Perdrisat, V. Punjabi, B. Wojtsekhowski (spokespersons), and the Hall A Collaboration.

- GEp-V (E12-07-109) approved for 60 days by JLab PAC32 in Aug., 2007.

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GEp-V Theory Report (F. Gross, N. Mathur)

“Measurement of the ratio G_E^p/G_M^p through polarization transfer continues to be of great theoretical interest. The proton charge form factor is a fundamental quantity that can only be measured (in this Q^2 range) at JLab, and an accurate measurement of it is of lasting fundamental importance.”

Physics Goals of GEp-V: Ratio F_2/F_1

- Hadronic current:

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

- Sachs form factors:

$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2, \quad \text{where} \quad \tau = Q^2/4M^2_{\text{nucleon}}$$

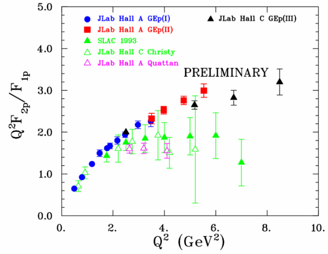
- Differential cross section:

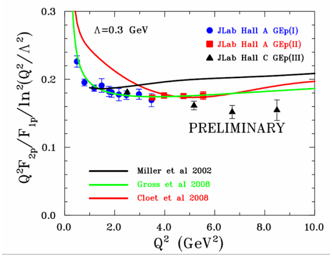
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}\left(G_E^{\,2} + \frac{\tau}{\epsilon}G_M^{\,2}\right)\Big/(1+\tau),$$

where $\epsilon^{-1} = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]$

- Ratio F_2/F_1:

$$\boxed{G_E/G_M = \frac{1 - \tau F_2/F_1}{1 + F_2/F_1}}$$

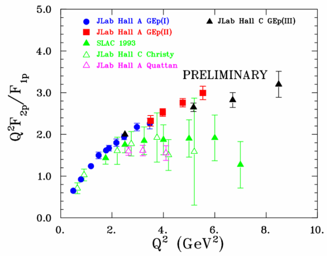


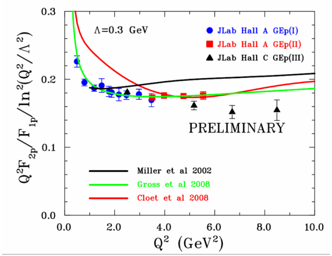


- Refined pQCD calculation (Belitsky, Ji, Yuan) including quark OAM predicts

$$\boxed{Q^2 \frac{F_2}{F_1} \propto ln^2\left(\frac{Q^2}{\Lambda^2}\right)}$$

where Λ is a non-perturbative mass scale.





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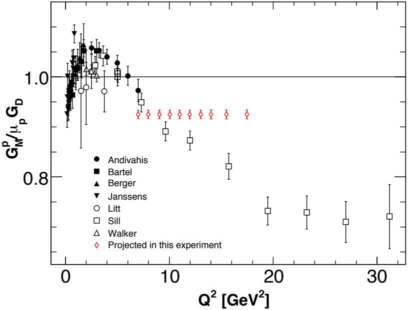
GEp-V will

- significantly increase the Q^2 range up to 14.5 GeV^2
- study the spin-flip part of the hadronic current
- constrain GPDs at high t
- provide critical test of FF models and reaction dynamics

Precision Measurement of G_M^p at High Q^2

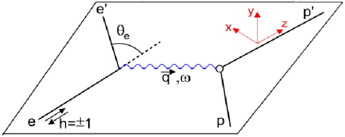


- Measure *ep* elastic x-section in $Q^2 \sim$ 7-17 GeV^2 with unprecedented precision ($<$ 2%) (using HRSs in Hall A) [E12-07-108, J. Arrington, S. Gilad, B. Moffit, B. Wojtsekhowski (spokespersons)].
- Obtain G_M^p by removing contribution of G_E^p from measured x-section using results on G_E^p/G_M^p [E12-07-109, GEp-V].
- Provide important new constrains on GPDs, especially at high Q^2.
- G_M^p essential for accurate normalization of other FF measurements.

Experimental Method of GEp-V: Recoil Polarization

- Best sensitivity to proton FF achieved via recoil polarization ratio in $p(\vec{e}, e'\vec{p})$

$$
\begin{aligned}
I_0 P_t &= -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan\frac{\theta_e}{2} \\
I_0 P_\ell &= \frac{1}{m_p}(E_e + E'_e)\sqrt{\tau(1+\tau)}\, G_M^2 \tan^2\frac{\theta_e}{2} \\
I_0 &\propto \epsilon G_E^2 + \tau G_M^2
\end{aligned}
$$



$$
\begin{aligned}
\frac{G_E}{G_M} &= -\frac{P_t}{P_\ell}\frac{(E_e + E'_e)}{2m_p}\tan\frac{\theta_e}{2} \\
\frac{F_2}{F_1} &= \left(1 - \frac{G_E}{G_M}\right) \Big/ \left(\tau + \frac{G_E}{G_M}\right)
\end{aligned}
$$

- Ratio method developed by C.F. Perdrisat and V. Punjabi and used in several JLab experiments.
- G_E/G_M at a given Q^2 obtained without measuring absolute x-section and without change of beam energy or detector angle.
- Analyzing power of polarimeter and beam polarization cancel out.

Challenges of High Q^2 Measurements

$$\begin{aligned}
\text{Form factor} &\propto \frac{1}{Q^4} \\
\text{Cross section} &\propto \frac{E^2}{Q^4} \times \frac{1}{Q^8} \\
\text{Figure}-\text{of}-\text{Merit} &\propto \epsilon A_y^2 \times \sigma \times \Omega \\
&\propto \frac{E^2}{Q^{16}}
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Maximum luminosity ⇒ large background

Large solid angle ⇒ small bend ⇒ huge background

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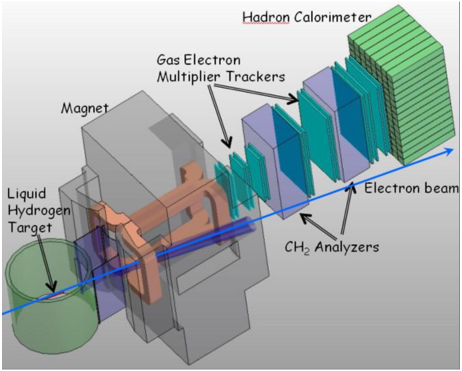
$$\begin{aligned} \text{Need large statistics} &\Rightarrow \text{maximum luminosity and solid angle} \\ \text{Maximum luminosity} &\Rightarrow \text{large background} \\ \text{Large solid angle} &\Rightarrow \text{small bend} \Rightarrow \text{huge background} \end{aligned}$$

Solution?

- Super Bigbite with modern tracking detector based on Gas Electron Multiplier (F. Sauli, 1997).

The Super Bigbite Apparatus



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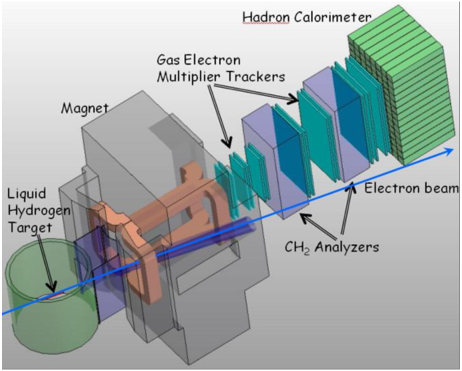

- Relevant FOM for proposed measurements within the SBS project exceeds those of all competing experiments by a factor of 10 to 50!

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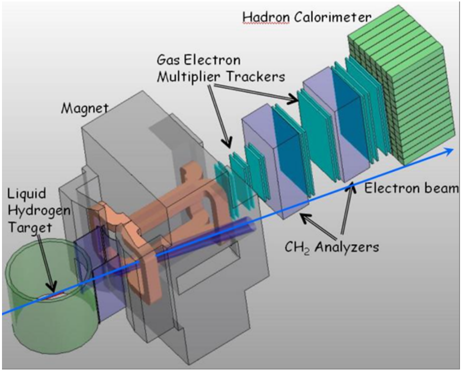

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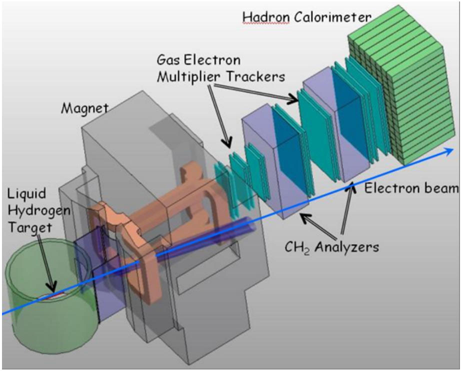

- Relevant FOM for proposed measurements within the SBS project exceeds those of all competing experiments by a factor of 10 to 50!
- SBS capabilities derived from using a large open-geometry dipole magnet together with a detector package with direct view of target.
- GEM-based tracking system able to tolerate the very high rates.

Parameters of Super Bigbite

$$\begin{aligned}
\text{Large solid angle, } \Omega &\sim 5 - 76 \text{ msr} \\
\text{Large momentum acceptance, } P &\sim 2 - 10 \text{ GeV}/c \\
\text{High luminosity capability, } \mathcal{L} &\sim 8 \times 10^{38} \; e^{-}/\text{s} \times \text{nucl.}/\text{cm}^2 \\
\text{Small scatt. angle capability, } \theta_{\text{min}} &\sim 3.5^{\circ} \\
\text{Very good angular resolution, } \sigma_{\theta} &= 0.14 + \frac{1.3}{P[\text{GeV}/c]} \; [\text{mrad}] \\
\text{Good vertex resolution, } \sigma_{y} &\sim 1 - 2 \text{ mm} \\
\text{Good momentum resolution, } \frac{\sigma_{P}}{P} &= (0.29 + 0.03 \times P[\text{GeV}/c]) \; [\%]
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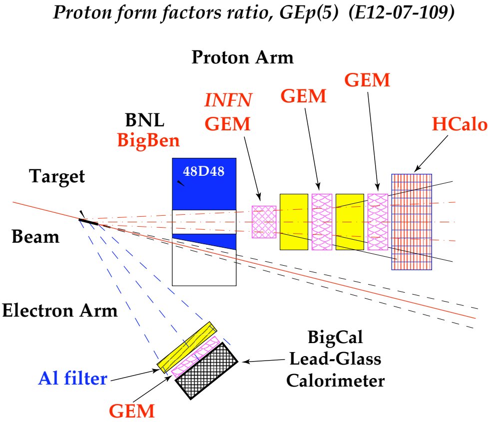
These features combined will give SBS at least ×10 advantage compared to any existing or proposed nucleon FF experiments at JLab!

Schematic of GEp-V Setup



- Recoil proton polarization measured using the large-acceptance SBS.
- Double polarimeter with large GEM trackers (50 $\times$ 200 cm^2) together with a highly segmented hadron calorimeter.
- Electron detected in coincidence by a large EM calorimeter, “BigCal”.
- 40-cm long LH_2 standard Hall A cryotarget.

Kinematics of GEp-V

Q^2 (GeV^2)	E_{beam} (GeV)	P_p (GeV)	θ_{SBS} (deg)	$E_{e'}$ (GeV)	θ_{BigCal} (deg)	$\Delta[\mu_p G_E^p / G_M^p]$
5.0	6.6	3.48	28.0	3.94	26.3	0.023
10.0	8.8	6.20	16.7	3.47	35.3	0.065
14.5	11.0	8.61	12.0	3.27	39.0	0.135

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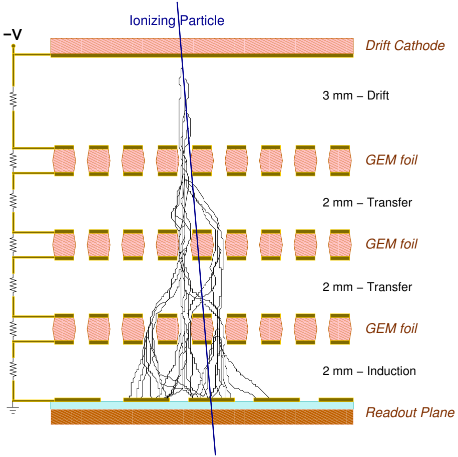
PAC35 on GEp-V

PR12-07-109: *"The PAC recommends the beam time be reduced from 60 to 45 days by only measuring the ratio* $\mu G_E/G_M$ *up to a maximum value of* Q^2*=12 GeV*^{2}*. Different models can already be discriminated at this lower* Q^2 *value and the trend in the behaviour of the ratio* $\mu G_E/G_M$ *can be established before reaching* Q^2*=14.5 GeV*^{2}*."*

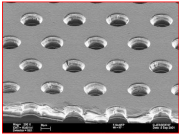
- Reduction in background rates on proton side.
- Rates about the same on electron side.
- Reduced error bar on $\mu_p G_E^p/G_M^p$.

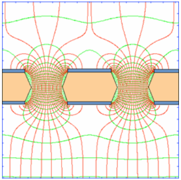
Q^2 (GeV^2)	E_{beam} (GeV)	P_p (GeV)	θ_{SBS} (deg)	$E_{e'}$ (GeV)	θ_{BigCal} (deg)	$\Delta[\mu_p G_E^p/G_M^p]$
12.0	11.0	7.27	17.4	4.60	29.0	0.08

GEM Working Principle



GEM foil: 50 μm Kapton + few μm copper on both sides w/ 70 μm holes, 140 μm pitch



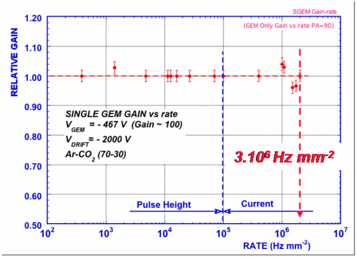


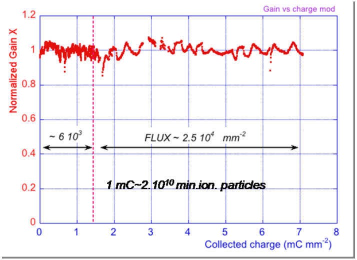
Strong electrostatic field in the GEM holes

- Recent technology: F. Sauli, Nucl. Instrum. Methods A386 (1997) 531.
- Readout independent from ionization and multiplication stages.

- SBS GEM chambers are modular in design (40 $\times$ 50 cm^2 modules).
- Chambers configurable for all FF measurements within the SBS program.

GEM Rate Capability / Rates in GEp-V





- No gain loss up to $\sim$ 300 MHz/cm^2.
- No visible aging detected as a function of integrated charge.

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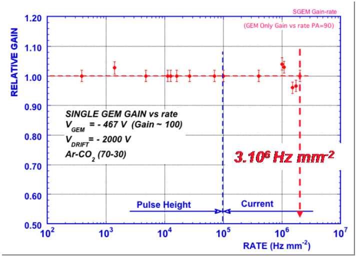

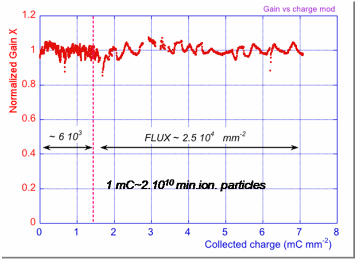

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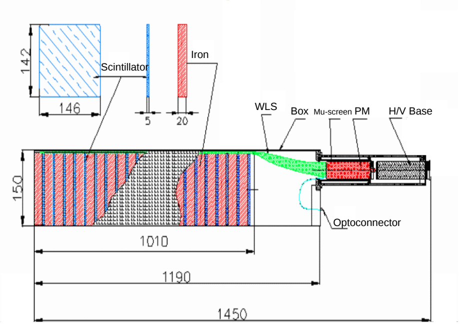
Rates in GEp-V Trackers

	γ induced hits (kHz/cm^2)	Charged hits (kHz/cm^2)	Total hits (kHz/cm^2)
First Tracker	437	119	556
Second Tracker	7	352	359
Third Tracker	1	124	125
BigCal Coord. Det.	34	96	130

Hadron Calorimeter for SBS



- Primarily for detecting recoiling proton in coincidence with electron in EM calorimeter (BigCal) for *ep* elastics in GEp-V.
- Sampling calorimeter - (absorber+scintillator) layers with WLS fibers (based on COMPASS HCAL1).
- 242 blocks of iron/scintillator plates arranged in a 11 × 22 matrix.

- Linear response and good energy and position resolutions (from COMPASS):

$$\frac{\sigma_\pi(E)}{E[GeV]} = \frac{59.3 \pm 2.9}{\sqrt{E}} + (7.6 \pm 0.4)\%$$

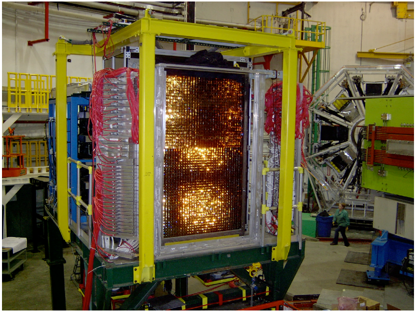
$$\frac{\sigma_e(E)}{E[GeV]} = \frac{24.6 \pm 0.7}{\sqrt{E}} + (0.7 \pm 0.4)\%$$

$$\sigma_{x,y} \sim 1.4 \text{ cm}$$

$$\sigma_{\text{time}} \sim 1.4 \text{ ns}$$

$$\left\langle \frac{e}{h} \right\rangle \sim 1.2 \pm 0.1$$

Electromagnetic Calorimeter for GEp-V



- Two main purposes for "BigCal" in GEp-V:
  - Position correlation between elastic *e* in BigCal and *p* in HCAL used in trigger to reduce rate to levels acceptable for DAQ.
  - Applying kinematic correlations of elastic *e* in BigCal to analyze where elastic *p* is expected in front GEM tracker to identify *p* tracks even at very high random hit multiplicity.
- Required energy resolution better than $10\%/\sqrt{E}$ and position resolution of $\sim$ 1 cm.
- 1744 lead-glass blocks arranged in a 32×54 matrix.

Trigger in GEp-V

- Critical part of experimental design in achieving a reasonable data rate.
- Two main features:
  - high energy threshold in HCAL (3-4 GeV for proton) and in BigCal (2.5 GeV for electron);
  - “smart” coincidence electronics based on FPGA.
- Rate in electron arm $\sim$ 60 kHz.
- Rate in proton arm $\sim$ 1.5 MHz.
- Coincidence time window of 50 ns $\Rightarrow$ 5 kHz trigger rate.
- Using angular correlation between $e-p$ elastics at the trigger level reduces the coincidence trigger to $\sim$ 1 kHz.

Current Status

- SBS will take best quality data in a good set of high priority experiments.
- Over 100 collaborators from 30 institutions.
- Conceptual design report in place.
  (http://hallaweb.jlab.org/12GeV/SuperBigBite/SBS_CDR/)
- Two technical reviews completed.
- Prototype GEMs currently undergoing beam test in Hall A.
- GEM trackers design / front tracker construction - INFN $1.1M approved.
- SBS budget proposal incorporated in JLab's long-term capital funding request to DOE.