E12-07-108 (GMp)
Precision Measurement of the Proton Elastic Cross Section at High $Q^2$

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Hampton University

On behalf of the GMp Collaboration

Hall A Collaboration Meeting
January 18, 2017
GMp collaboration

- Hall A collaboration, physics staff, technical staff, accelerator team and shift taker

- Spokesperson: J. Arrington, E. Christy, S. Gilad, V. Sulkosky, B. Wojtsekhowski (contact)

- Postdoc: Kalyan Allada (MIT)

- Graduate students: Thir Gautam (Hampton U.), Longwu Ou (MIT), Barak Schmookler (MIT), Yang Wang (W&M)
Highlights:
- Better than 2% statistics
- High $Q^2$ (up to 16 GeV/c²)
- Relatively low $\epsilon$: the contributions from $G_E^p$ is smaller than those for the large $\epsilon$ SLAC data
- Multiple kinematic settings over the range of $Q^2$

- Calibration of detectors is nearly complete
- First pass analysis is in progress
- We project data analysis to be completed in a year
Outline

- Physics and experimental goals of GMp
- Hall A beamline, spectrometer and detectors
- Statistics collected
- Calibration and data analysis status
- Preliminary cross-section results
- Status and timeline to complete
Proton magnetic form factor

- Form factors encode electric and magnetic structure of the target

At low $Q^2$, form factors characterize the spatial distribution of electric charge and magnetization current in the nucleon

$$|\text{Form Factor}|^2 = \frac{\sigma(\text{Structured object})}{\sigma(\text{Point like object})}$$

In one photon exchange approximation the cross-section in $ep$ scattering when written in terms of $G_E^p$ and $G_M^p$ takes the following form:

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \frac{\epsilon (G_E^P)^2 + \tau (G_M^P)^2}{\epsilon (1 + \tau)}$$

Where,

$$\tau = \frac{Q^2}{4 M^2}, \quad \epsilon = [1 + 2(1 + \tau) \tan^2(\frac{\theta}{2})]^{-1}$$

$$\sigma_{Mott} = \frac{\alpha^2 \cos^2(\theta/2)}{4 E^2 \sin^4(\theta/2)} \frac{E'}{E}$$

$$J_{\text{proton}} = e\tilde{N}(p') \left[ \gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu} q^\nu}{2M} F_2(Q^2) \right] N(p)$$

$$G_E = F_1 - \tau F_2 \quad G_M = F_1 + F_2$$
Goals of GMp experiment as approved

- Precision measurement of the elastic $ep$ cross-section in the $Q^2$ range of 7-14 GeV$^2$ and extraction of proton magnetic form factors
  - To improve the precision of prior measurement at high $Q^2$
  - To provide insight into scaling behavior of the form factors at high $Q^2$

**Statistical:** Better than 2%

**Systematic:**
- Point to point: 0.8-1.1%
- Normalization: 1.0-1.3%
- **Total Error Budget:** 1.2 -2.6%

Need a good control on:
- Beam charge
- Beam position
- Scattering angle, target density, ...
Hall A beamline, spectrometer and detectors

- RHRS SOS Quad is replaced by new quad
- The SOS Quad is installed in LHRS
- VDC is used for tracking information
- Straw Chamber(SC) is used to reduce systematic on VDC tracking efficiency
- Cherenkov and calorimeter are used for particle identification
- S0, S2m are used for trigger and timing

Detector package

- Calorimeter
- S2m
- S0
- SC
- Cherenkov
- VDC

Diagram:
- Beam
- Beam charge measurement devices
- Beam position measurement devices
- Target
- Q1
- Q2
- D
- RHRS SOS Quad
- New Quad
- Unser (DC transformer)
- Harp A (Wire scanners)
- Harp B
- Raster
- BPMA
- BPMB
- Q3
GMp calibration and systematic studies

➢ Calibration of beamline components
  → Beam position: BPMs and raster
  → Beam charge and current: Unser and BCMs

➢ Calibration of spectrometer optics
  → Multifoil carbon target with and without sieve slits
  → Spectrometer momentum (Delta scans)

➢ Beam energy measurements

➢ Target boiling studies

➢ Detector acceptance, efficiency and reconstruction analysis
GMp collected statistics

- Data collected in spring 2016
- Data collected in dedicated GMp period in Fall 2016
- Data collected parasitically with DVCS in Fall 2016

Error bar reflects twice statistical uncertainty

$G^P_M/\mu_p G_D$

$Q^2 [\text{GeV}^2]$
## Summary of GMp collected data (I)

### Spring 2015:

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ (GeV)</th>
<th>HRS</th>
<th>$P_0$ (GeV/c)</th>
<th>$\Theta_{\text{HRS}}$ (deg)</th>
<th>$Q^2$ (GeV/c)$^2$</th>
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### Spring 2016:

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Summary of GMp collected data (II)

**Fall 2016:**

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Beam position calibration

- BPMs are calibrated in Bull's eye scan runs against beam position from wire scanners
- The stability of average beam position was monitored at each kinematics
Beam charge calibration

- Multiple instruments of charge measurement: Unser and two BCMs
  - Two BCMs: Upstream and Downstream with multiple receiver per BCM
    - Old style (analog): x1: u1 and d1
    - Old style (analog): x3: d3
    - Old style (analog): x10: d10
    - New style (digital): unew and dnew.

- Calibrated BCMs against Unser up to 73 µA in Fall 2016
- Calibration coefficients from multiple measurement have negligible drift within uncertainties
- Beam current determination is much better than 1%
- Estimated Current uncertainty in GMp experiment is ~0.06 µA
Beam charge calibration

RHRS 22790

χ²/ndf 13.07/17
Prob 0.7314
p0 1.04 ± 0.09871
p1 0.0003832 ± 9.016e-07

Estimated current noise(Δl)=2/sqrt(t)

First ramp
Second ramp

Estimated current noise(Δl)=2/sqrt(t)
BCM global calibration

\[ \chi^2 / \text{ndf} = 32.09 / 33 \]

\[ \text{Prob} = 0.512 \]

\[ p_0 = 1.128 \pm 0.07009 \]

\[ p_1 = 0.0003827 \pm 7.645e-07 \]
Target boiling studies

- Target used: 15 cm LH2 target in Loop2 and single foil carbon target
- Carbon target is used to separate possible rate systematic from boiling
  - Range of beam current: 3-67 µA
  - Raster size: 2×2 mm²

LH2: (-2.7±0.39)% /100 µA
Precision calibration of optics for extended target

Angles (in-plane $\phi$ and out-of-plane $\theta$) and vertex calibrations
→ new sieve (hole density approximately double to traditional HRS sieve)
→ 9 carbon foil targets

Delta calibration
→ LH$_2$ target

New sieve used for GMp optics

Sieve pattern of central carbon foil target

Crosses indicate the hole centers
Positions at the sieve plane are reconstructed by $\theta$ and $\phi$
Reconstructed sieve pattern from multi-foil carbon targets

LHRS, $\theta_{HRS} = 42^\circ$

$\Delta \theta < 0.6$ mrad, $\Delta \phi < 0.3$ mrad
HRS vertex calibration

→ Blue lines indicate the real foil target positions
→ $\Delta$ shows the difference between the data gaussian fitting center and real position

LHRS vertex optics calibration @42 degrees
HRS Momentum Calibration

- We took delta scans at ±4%, ±2% and 0% dipole setting
- Clearly, the optimization readout is in the order of $10^{-4}$
Reconstructed invariant mass

- This plot is from a one pass run on the Left HRS during Fall 2016 after optics calibration
- Clearly, the raster and ionization energy loss correction shifted the invariant mass peak by ~1.5 MeV from proton mass
Particle identification analysis

- We did particle identification studies using Cherenkov and calorimeter.
- Got preliminary PID efficiency at one pass and the cuts were set to select good electrons.

\[ E_{\text{beam}} = 2.222, \quad \theta = 42 \]
Status of acceptance study

→ Took data on single foil carbon target to study the acceptance of the spectrometer
→ Used single arm simulation which gives an uniformly distributed phase space for carbon target without physics weighting
→ Used external code to get physics weighting which is the ratio of born cross section to radiative correction factor

Data/MC = 0.9525
Status of acceptance study

- Shapes are consistent at very different kinematics
- The discrepancy observed in high delta probably comes from spectrometer model

Quasi elastic Kinematics

Data/MC = 0.9395
Data to SIMC comparison at 1pass LH2

→ SIMC uses same model of spectrometer as single arm but includes all radiative contribution within the code
→ Data and SIMC distribution integrals are reasonably consistent
→ Improvement of spectrometer model is ongoing

Data/MC = 1.00289
## Punch list

### System calibration

<table>
<thead>
<tr>
<th>System</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>BCM</td>
<td>Completed for first pass analysis</td>
</tr>
<tr>
<td>BPM</td>
<td>80% completed</td>
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<tr>
<td>Raster</td>
<td>Completed for first pass analysis</td>
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<tr>
<td>Optics</td>
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<tr>
<td>Cerenkov</td>
<td>Completed for first pass analysis</td>
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<tr>
<td>Calorimeter</td>
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<tr>
<td>VDC/Straw</td>
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<tr>
<td>Detector Position Study</td>
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### Data analysis

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<th>Status</th>
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<td>Acceptance</td>
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<tr>
<td>Tracking efficiency</td>
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<tr>
<td>Trigger efficiency</td>
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<tr>
<td>Particle identification</td>
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<td>Time of flight</td>
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<tr>
<td>DAQ dead time</td>
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<tr>
<td>Data analysis at First pass</td>
<td>70% completed</td>
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Summary

• 12 GeV GMp experiment data taking completed successfully
• Equipment operated stably and satisfactorily
• First pass data replay is close to completion
• Projected milestones:
  → Preliminary cross-section results in four months
  → First publication to be submitted by the end of 2017
Thank you everybody!
Reduction of track reconstruction systematics

- The standard tracking system of two VDCs in HRS cannot resolve u-v matching ambiguities when multiple clusters are presented, resulting in increased probability of mis-reconstructed events.

- Straw chamber was installed as a third readout plane to reduce systematics of track reconstruction efficiency.

- Potential tracks formed by matching VDC clusters are projected and compared with hit position in the straw chamber plane.

- This procedure was tested with 2 pass beam and improved the track reconstruction efficiency to 98%.

![Diagram showing track matching process]

- Good track
- Spurious track
- Straw chamber
- Clusters in VDC
- Straw fired by electrons