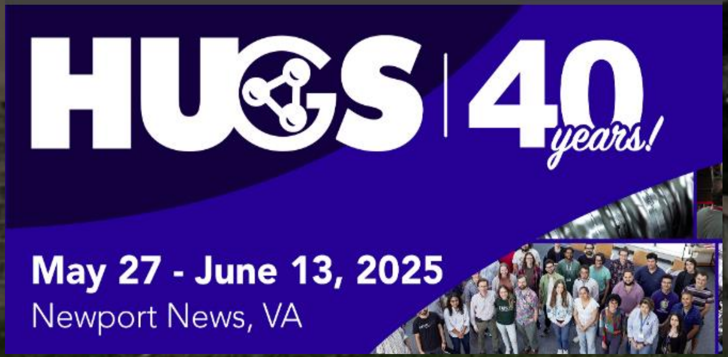
Proton Form Factor Ratio Measurements at High Momentum Transfer via Recoil-Polarization

Mahmoud Gomina

40th Annual Hampton University Graduate Summer (HUGS) Program,

Jefferson Lab, Newport News, Virginia



Jefferson Lab

PARTONIC STRUCTURE OF THE HADRONS

Outline

- Introduction
- Kinematics
- Technique
- SBS Layout for GEP V
- GEp/GMp World Data
- Summary

"If I have have seen further, it is by standing on the shoulders of giants" Isaac Newton

Introduction

- Elastic Form Factors (FF) probe the nucleons' four-current distributions, critical for understanding nucleon structure.

- They are functions of the squared momentum transfer (Q^2) in the *e*-*N* scattering process:

$$Q^2 = 4EE' sin^2\left(\frac{\theta_e}{2}\right)$$

where,
E is the beam energy,
E' is the scattered electron energy, and
θ_e is the electron's scattering angle

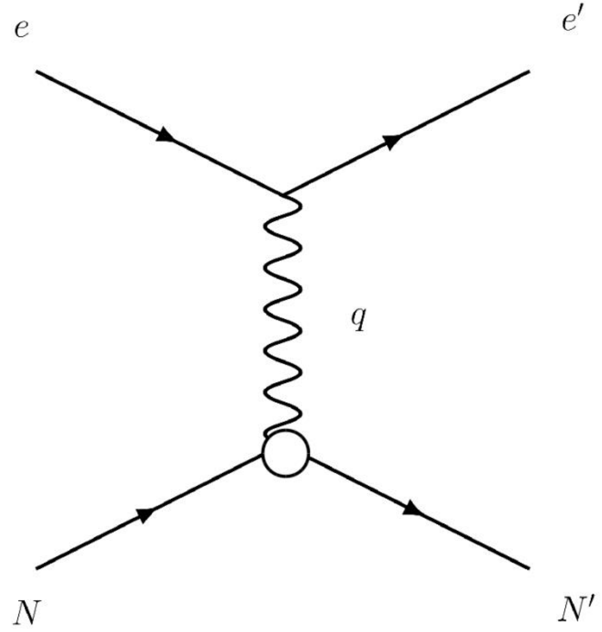


Figure: Tree-level diagram of *e*-*N* elastic scattering

- Electric (GEp) and magnetic (GMp) FFs describe how the proton's charge and magnetization are spatially distributed.

Q^2 determines the resolution of the probe

Introduction: *OPE*

- The differential cross section for scattering of electrons from a spin- 1/2 target in the *OPE* (One-Photon Exchange) approximation (Rosenbluth formula[1]):

$$\frac{d\sigma}{d\Omega} = \eta \frac{\sigma_{mott}}{1+\tau}\left((G_E)^2 + \frac{\tau}{\epsilon}(G_M)^2\right)$$

where,

G_E (Q^2) and G_M (Q^2) are the Sachs Electric and Magnetic form factors,

$\eta = (1 + 2\frac{E}{M_N}\sin^2(\frac{\theta}{2}))^{-1}$ recoil factor

$\epsilon = (1 + \frac{q^2}{Q^2\tan^2(\frac{\theta}{2})})^{-1}$ longitudinal polarization of the virtual photon

$\tau = \frac{Q^2}{4M_N^2}$

Mott cross section for elastic electron scattering

$$\sigma_{\text{Mott}} = \left.\frac{d\sigma}{d\Omega}\right|_{Q^2\to 0} = \frac{\alpha^2\cos^2\frac{\theta_e}{2}}{4E_e^2\sin^4\frac{\theta_e}{2}}\frac{E'_e}{E_e}$$

[1] *Phys. Rev. 79, 615–619 (1950)*

Kinematics

4 momenta of the electron and the target particle are:

$$p_e^{\mu} = (E_e, \overrightarrow{p_e}) \qquad p_e^{\mu\prime} = (E_e', \overrightarrow{p_e}')$$

$$p_p^{\mu} = (E_p = M_p, 0) \qquad p_p^{\mu\prime} = (E_p', \overrightarrow{P_p}')$$

4 momenta conservation requires that:

$$P_e^{\mu} + p_p^{\mu} = p_e^{\mu'} + p_p^{\mu'}$$

electron 4 momentum transfer:

$$\overrightarrow{q} = P_e^{\mu} - p_e^{\mu'} = p_p^{\mu'} - p_p^{\mu}$$

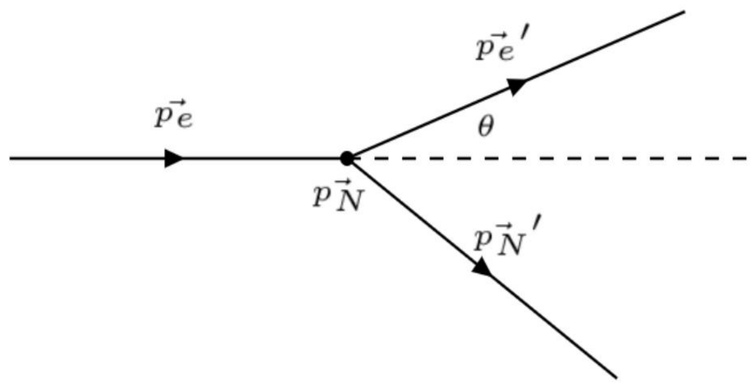


Figure: *e*-*N* scattering

The invariance of the 4 momentum transfer yields: (applying energy conservation and neglecting the electron's mass)

$$\overrightarrow{q}^2 = -2E_eE_e'(1 - \cos\theta)$$

$$\overrightarrow{Q}^2 = -\overrightarrow{q}^2 = 2E_eE_e'(1 - cos\theta)$$

$$\overrightarrow{Q}^2 = 4E_eE_e' \sin^2(\frac{\theta}{2}) \quad \& \quad E_e' = \frac{E_e}{1 + \frac{2E_e}{m} sin^2\frac{\theta}{2}}$$

Kinematics

Table: SBS GEP V Kinematics

Name	E_{beam} GeV	Q^2 GeV^2	θ_{ECal} Degrees	<E'> GeV	θ_{SBS} Degrees	$<P_p>$ GeV
GEP-1	6.476	5.732	29.46	3.660	25.7	3.881
GEP-2	8.588	8.127	27.27	4.257	22.1	5.185
GEP-3	10.668	11.109	27.00	4.768	18.6	6.794
GEP-2a (GEP-0)	4.359	3.860	35.00	2.302	28.5	2.845

Run period (March - August, 2025)

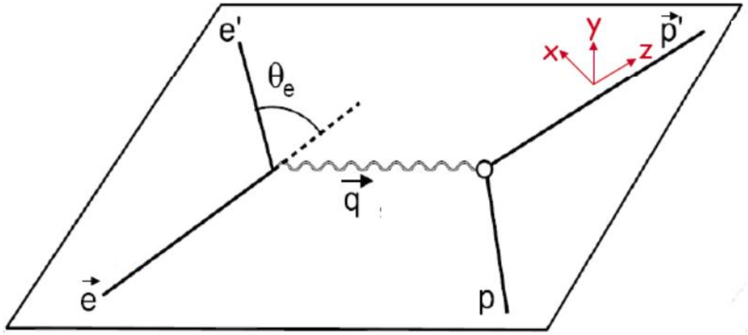
4th kinematic point (GEP-2a or GEP-0) approved at lower Q^2 to complement future positron program

Technique: Polarization Method

- In the *OPE* approx., the scattering of the longitudinally polarized electrons from unpolarized hydrogen results in a transfer of polarization to the recoil proton,

- with two components, P_t perpendicular to, and P_l parallel to the proton momentum in the scattering plane[1]:

$$\vec{e}N \rightarrow e\vec{N}$$



$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2}$$

and $$I_0 P_\ell = \frac{1}{m_p}(E_e + E'_e)\sqrt{\tau(1+\tau)} G_M^2 \tan^2\frac{\theta_e}{2}$$

where,

$$I_0 \sim G_E^2 + \tfrac{\tau}{\epsilon} G_M^2$$

simplifying the ratio of the two components yields the proton form factor ratio:

$$\boxed{\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{(E_e + E'_e)}{2m_p}\tan\frac{\theta_e}{2}}$$

[1] A. I. Akhiezer and M. P. Rekalo, Sov. J. Part. Nucl. 3, 277 (1974); R. Arnold, C. Carlson, and F. Gross, Phys. Rev. C 23, 363 (1981)
Polarization method was first employed by Milbrath et al., Phys. Rev. Lett. 80, 452 (1998) at **MIT-Bates**.

Technique: Benefits

Benefits of the Polarization Method

proton's form factor ratio at a given Q^2 can be obtained without;

- measuring the absolute cross sections
- changing beam energy
- changing detector angle

Therefore, minimizing systematic uncertainties.

Rosenbluth method:

-leverages linearity of cross section in $\epsilon = \left(1 + \frac{q^2}{Q^2 \tan^2(\frac{\theta}{2})}\right)^{-1}$

-measures cross section at fixed Q^2 but varying scattering angle:

$$\sigma_R = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_M \frac{\epsilon(1+\tau)}{\tau} = \frac{\epsilon}{\tau} G_E^2 + G_M^2$$

-G_E and G_M are then obtained from the slope and intercept of the Rosenbluth curve

Setup and Detectors

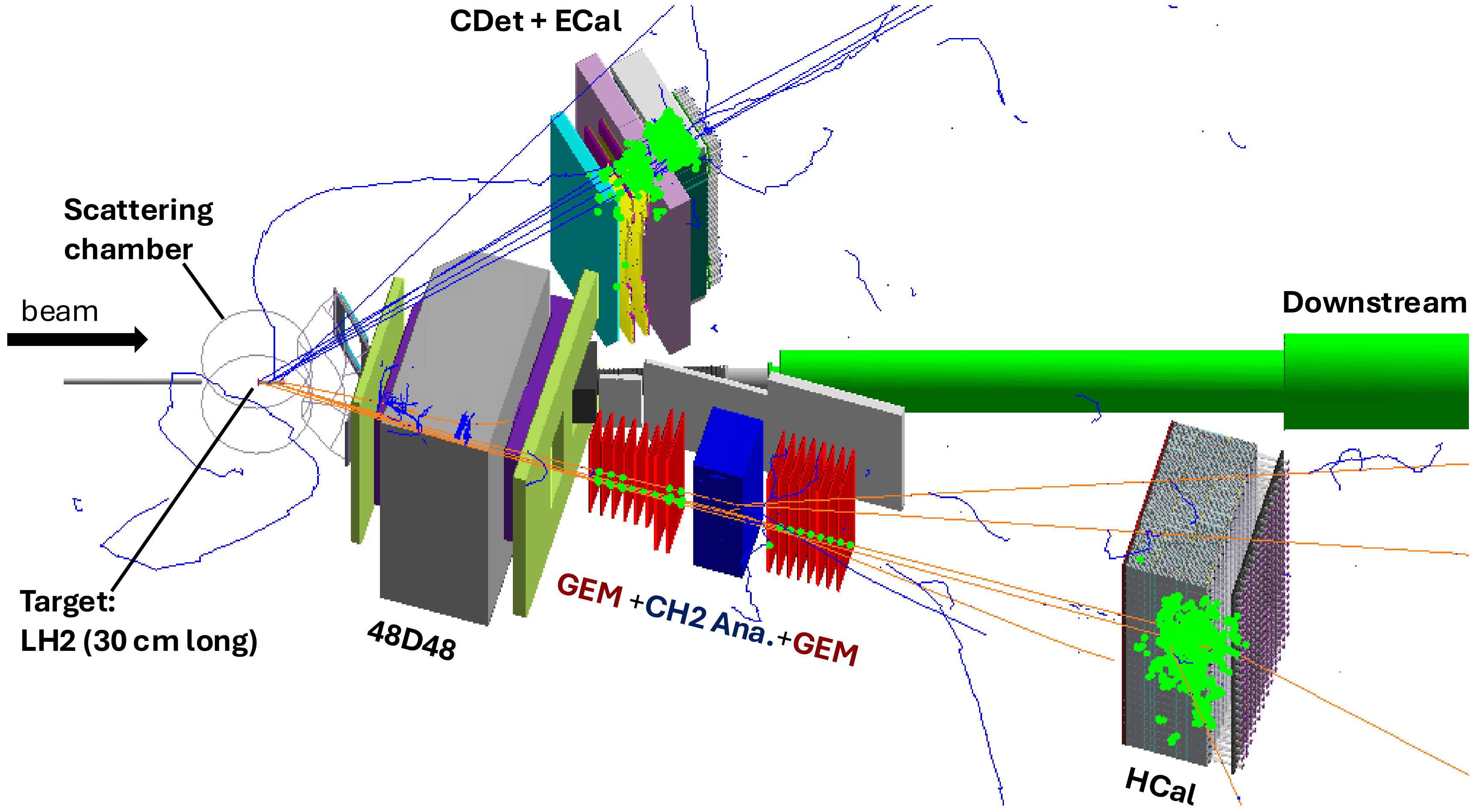
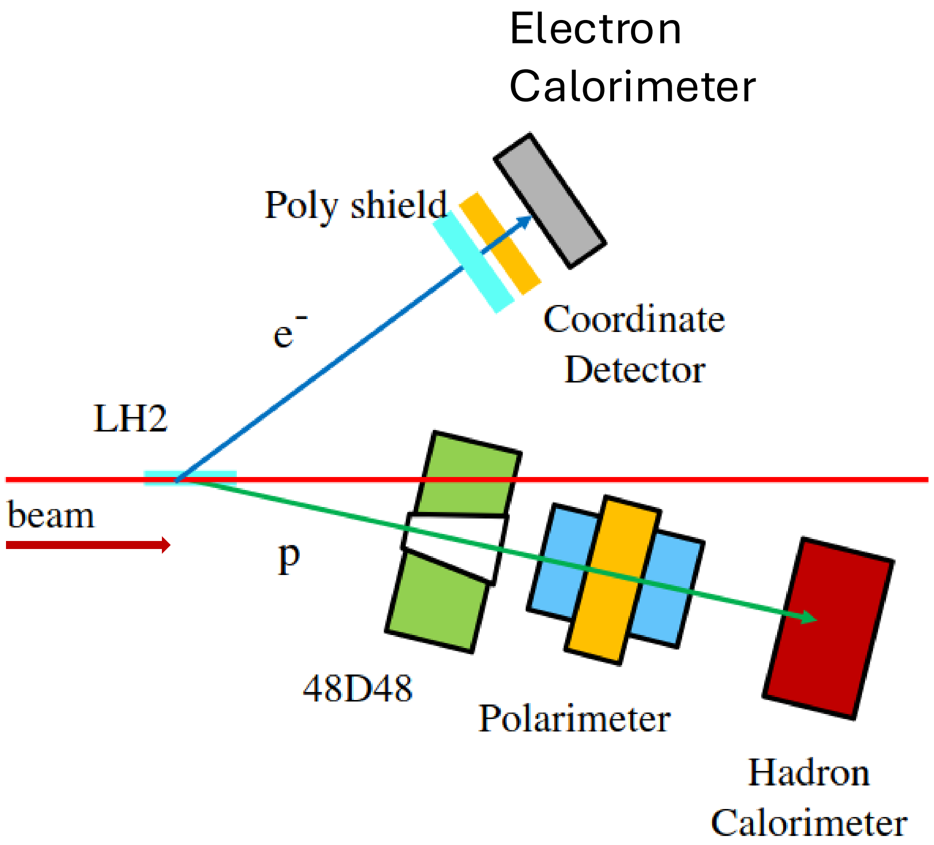


Figure: g4sbs GEP3 Kinematic Setup

Apparatus: Hadron Calorimeter Arm

B. Wojtsekhowski



SBS GEp V Sechematics (B. Wojtsekhowski, 2023)[1]

Hadron Arm:
SBS magnet, **GEM** based trackers, **CH2 analyzer**, and **HCal**.

HCal:

- 288 modules (12x24 blocks of 15 x 15 x 100 cm^3)
- each module is made of 40 layers of iron absorbers alternating with scintillators.
- Momentum resolution ~1%
- Angular resolution ~1 mrad

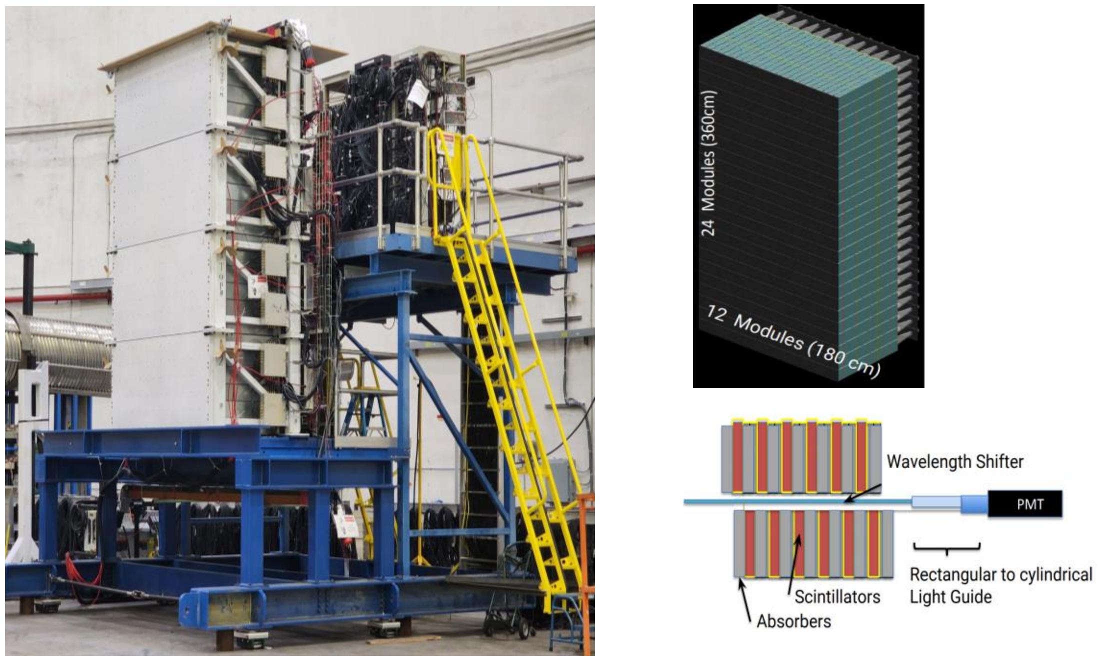
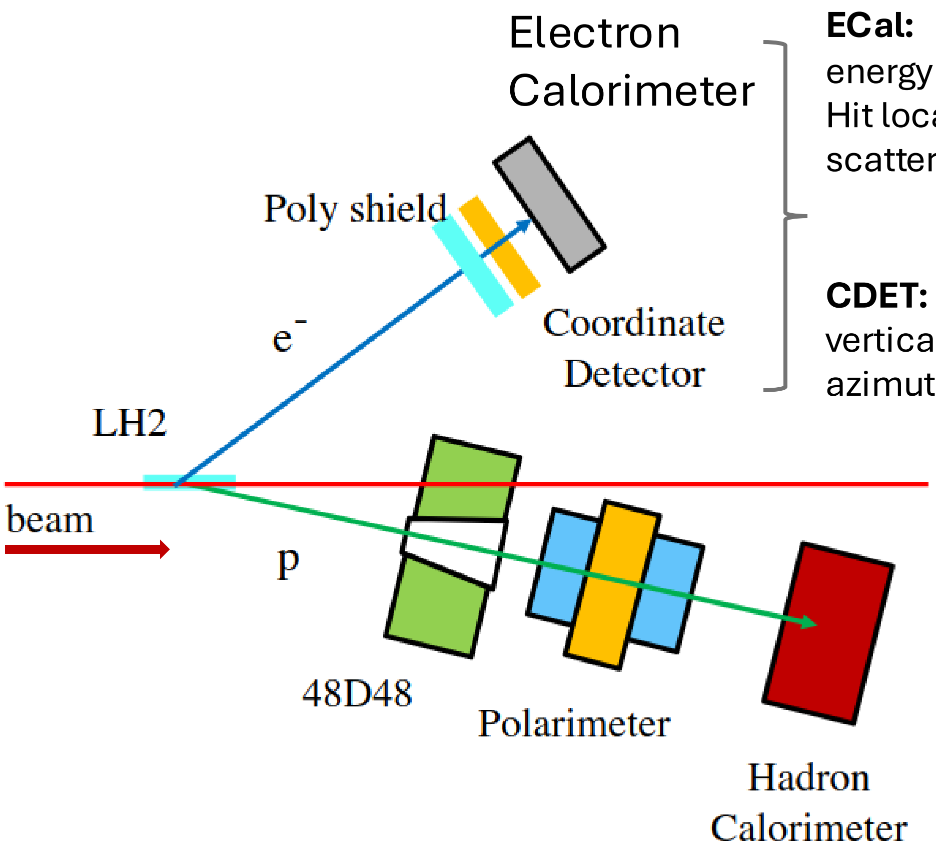


Figure: SBS HCal in Hall A (J. Poudel, SBS Collaboration Meeting 2023)[2]

[1] https://hallaweb.jlab.org/12GeV/SuperBigBite/documents/ERR2023/final/GEP_ERR_BW.pdf

[2] https://indico.jlab.org/event/721/contributions/13216/attachments/10055/14941/SBS_collaboration_HCAL_072023.pdf

Apparatus: Electron Calorimeter Arm



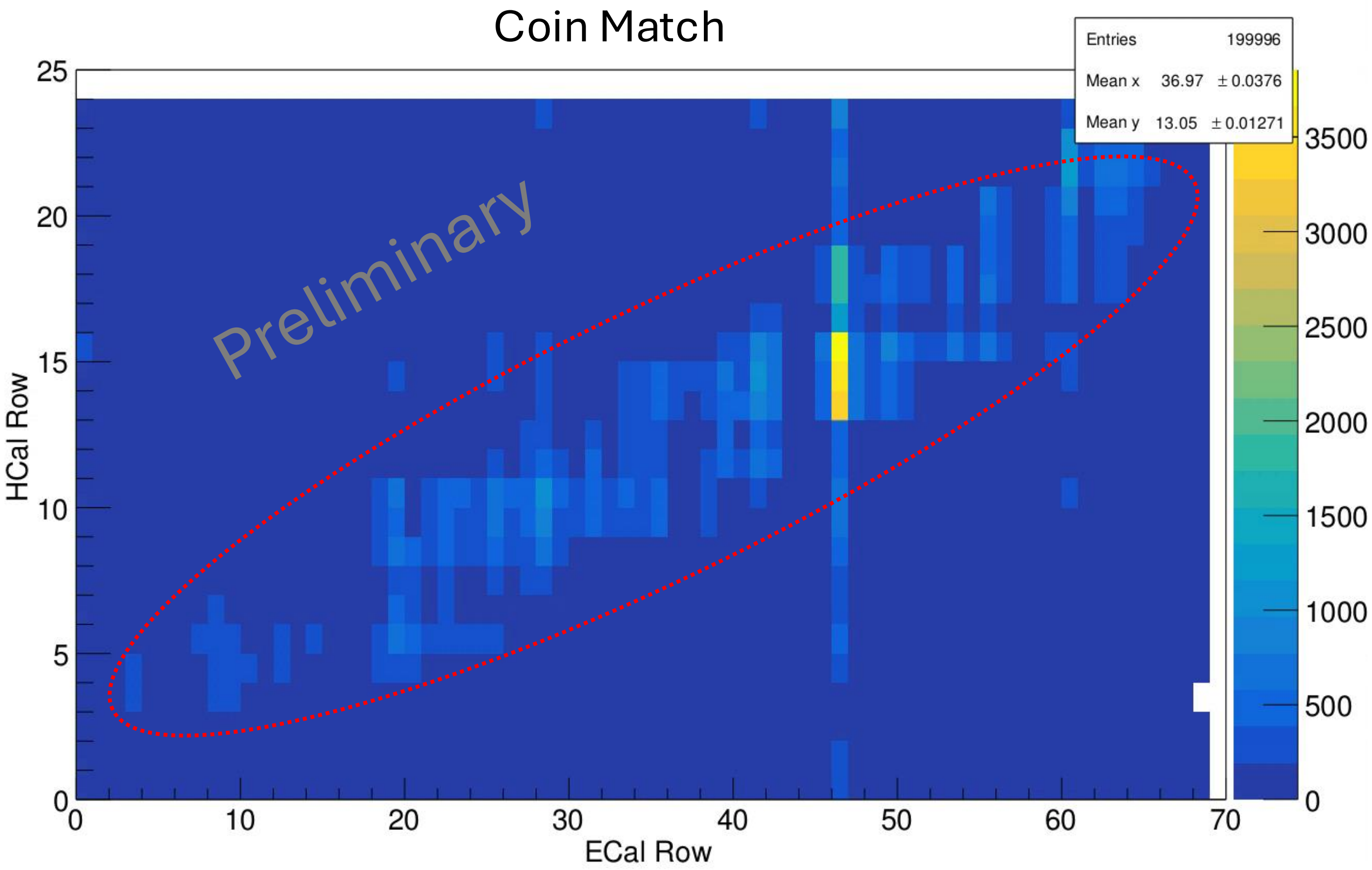
ECal:
energy resolution ~5%
Hit location resolution ~5 mm
scattering angle ~1 mrad

CDET:
vertical hit location ~2 mm
azimuthal angle ~1 mrad

Figure: ECal (1656 channels) for SBS GEp V Experiment

The detector will be located inside a custom oven (T ~ 225°C) to allow constant annealing of the radiation damage during data taking

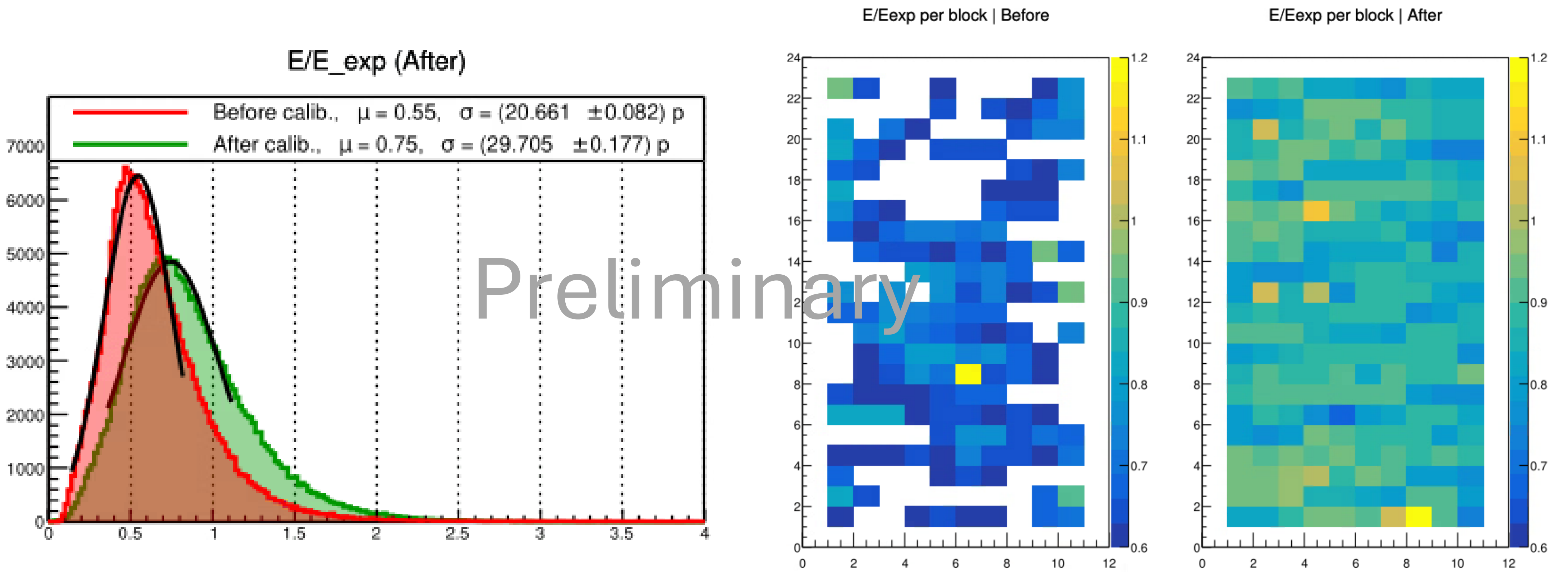
Elastic Events with Geometrical Match



GEp data from ongoing run in Hall A

- Region for elastic candidate
- Diagonal show strong one-to-one correspondence

Preliminary HCal Calibration



HCal: Before and After Calibration

Projected Result of GEp/GMp

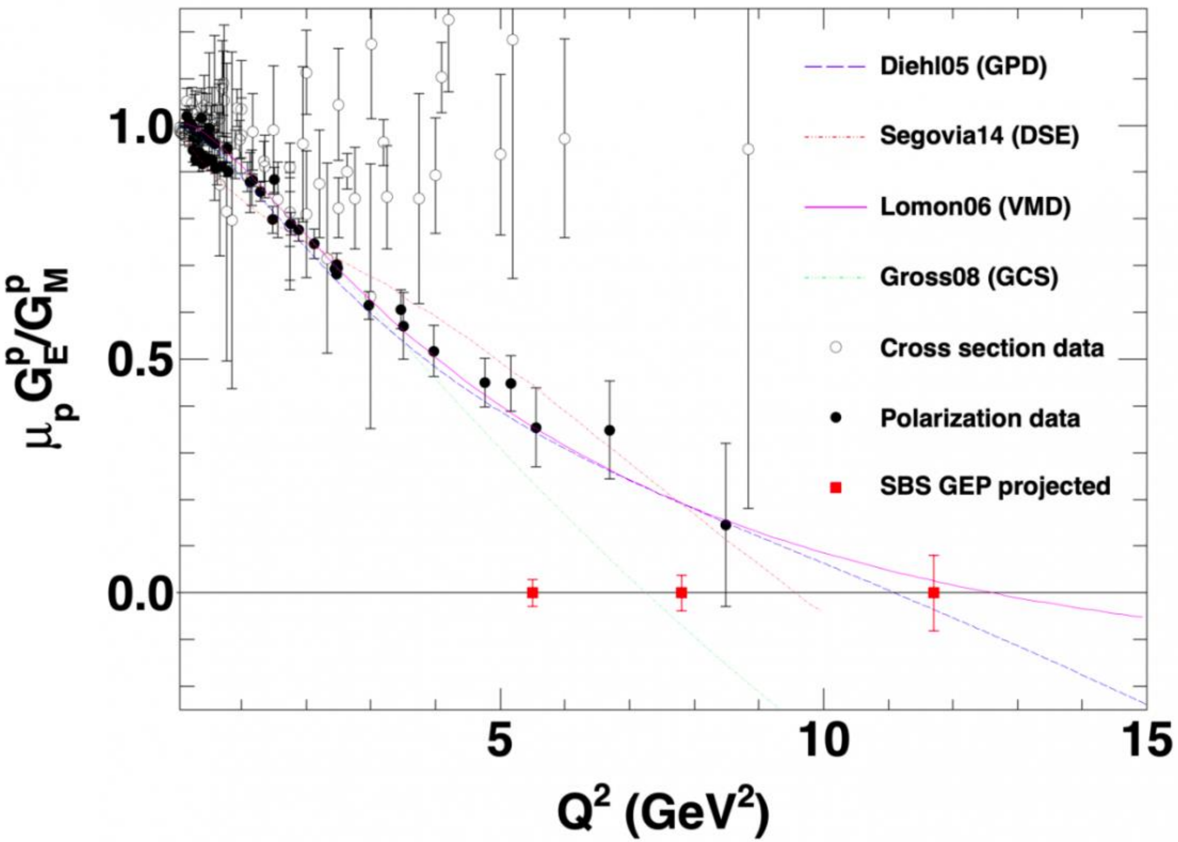


Figure: GEp/GMp ratio for **charge and magnetization** distribution in the proton, scaled by the proton's magnetic moment (μ_p), as a function of $\mathbf{Q^2}$

- **spatial distribution** of **charge** shrinks faster than **magnetization** for deeper probe into the proton.
- Rosenbluth (Cross section) suggested a flat ratio with increasing Q^2.
- Polarization method portray decreasing ratio with increasing Q^2.
- discrepancy may be due to the Two-photon Exchange (TPE) effects.

A. Puckett (2019) SBS GEp Experiment (E12-07-109) Re-Approved by JLab PAC
https://puckett.physics.uconn.edu/2019/08/22/sbs-gep-experiment-e12-07-109-re-approved-by-jlab-pac47/

Summary

- Elastic Form Factors (FF) probe the nucleons' four-current distributions.
- Proton FF ratio measurement (using polarization method) up to ~12 GeV^2, which is beyond current experimental data.
- Experiment at JLab using the Super Bigbite Spectrometer with the new electron arm upgrade.
- GEp V schedule: March – August, 2025.

SBS Collaboration Meeting September, 2024

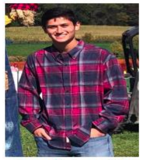
Prof. Marie Boer

Dr. Deb. Biswas
Post Doc

Dr. Kemal Tezgin
Post Doc

Keagan Bell
Student

Yihang Ma
Research Associate



Ryan McLaughlin
Student

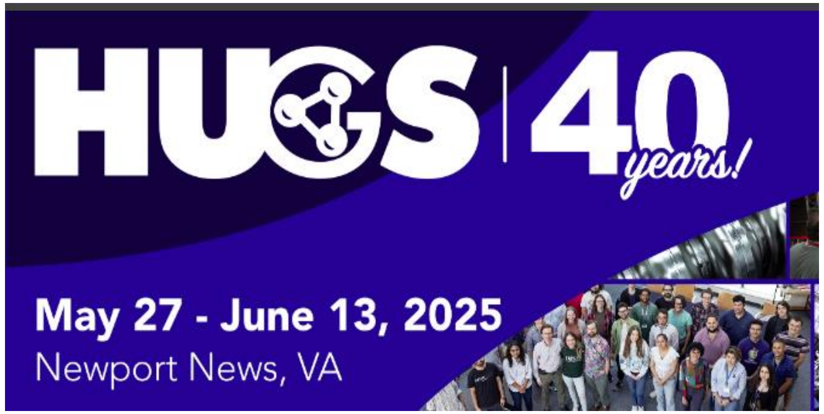
VT PaSHa Team

COLLEGE OF SCIENCE PHYSICS VIRGINIA TECH.

Jefferson Lab

4-VA Advancing The Commonwealth

OFFICE OF THE EXECUTIVE VICE PRESIDENT AND PROVOST



HUGS Team

Acknowledgements

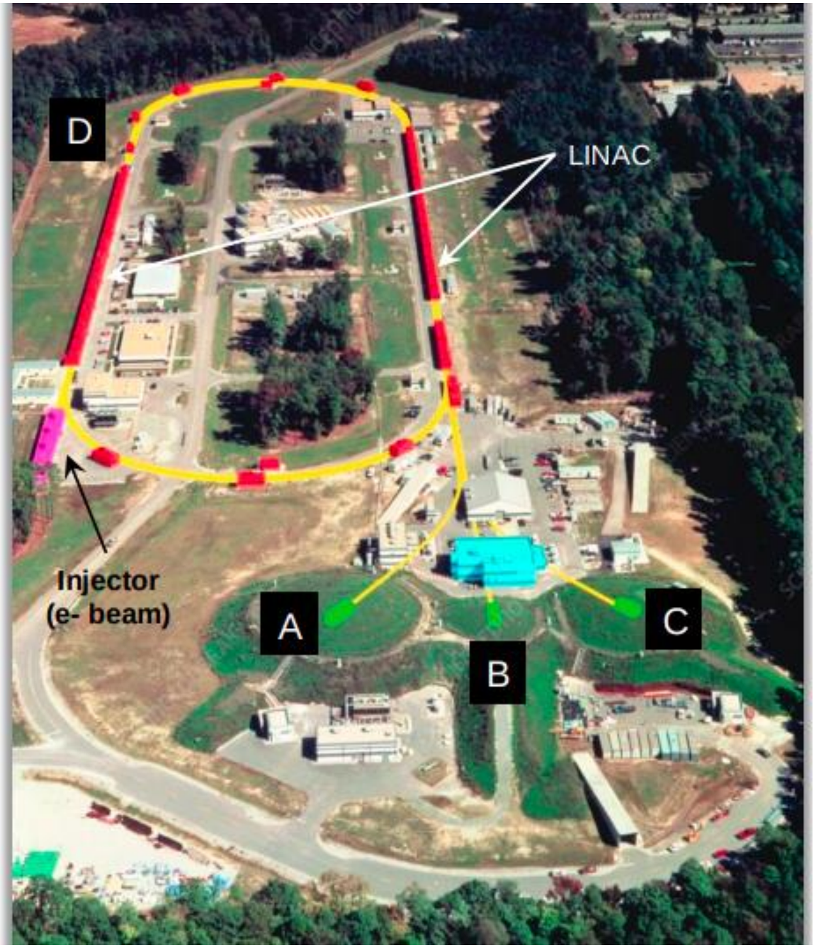
Supported by:

- DOE grant (DE-SC0025657),
- Virginia Tech College of Science,
- SBS Collaboration,
- 4-VA via the VT Office of the Executive Vice, President and Provost

Thank you

Bonus Slides

Jefferson Lab (JLab)

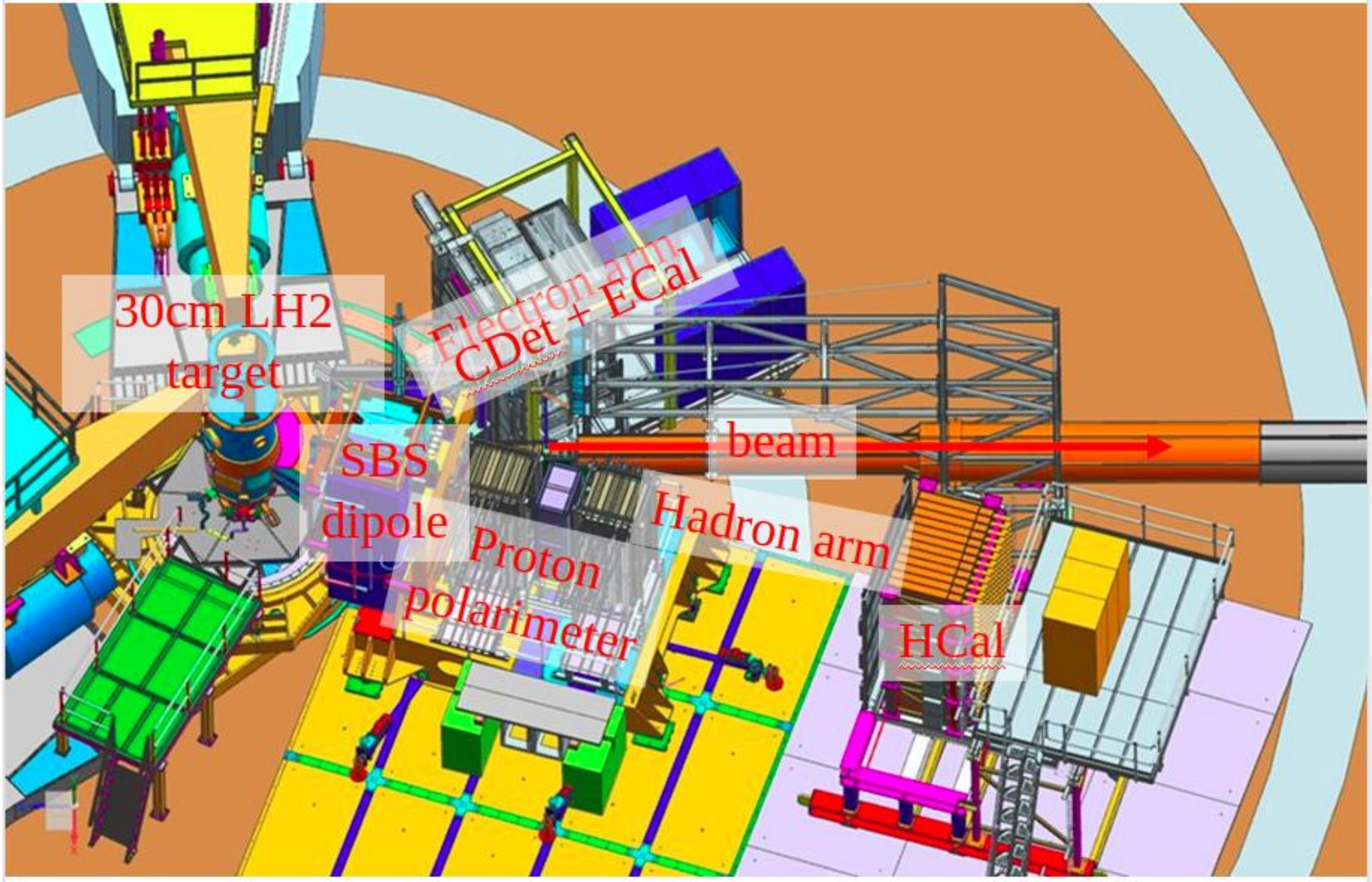


Aerial View of the Continuous Electron Beam Accelerator Facilty (CEBAF) at JLab[1]

- Jefferson Lab (JLab) is a DoE owned national accelerator facility located in Newport News, VA
- The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is a racetrack-shaped electron accelerator located 25 feet underground.
- It can deliver up to 12 GeV continuous wave (CW) electron beam with unparalleled intensity and precision.
- JLab has 4 experimental Halls (A, B, C, and D). This experiment is scheduled to run in Hall A.
- My research is based on the next experiment in Hall A **(Schedule to start at the end of March 2025)** with the SBS collaboration.

[1] *P. Datta's GHP 2025 Talk* https://indico.jlab.org/event/868/contributions/15926/attachments/12325/19618/PDATTA_GHP_2025.pdf

Model Experimental Layout



Experimental layout in Model (Jones, 2023)[1]

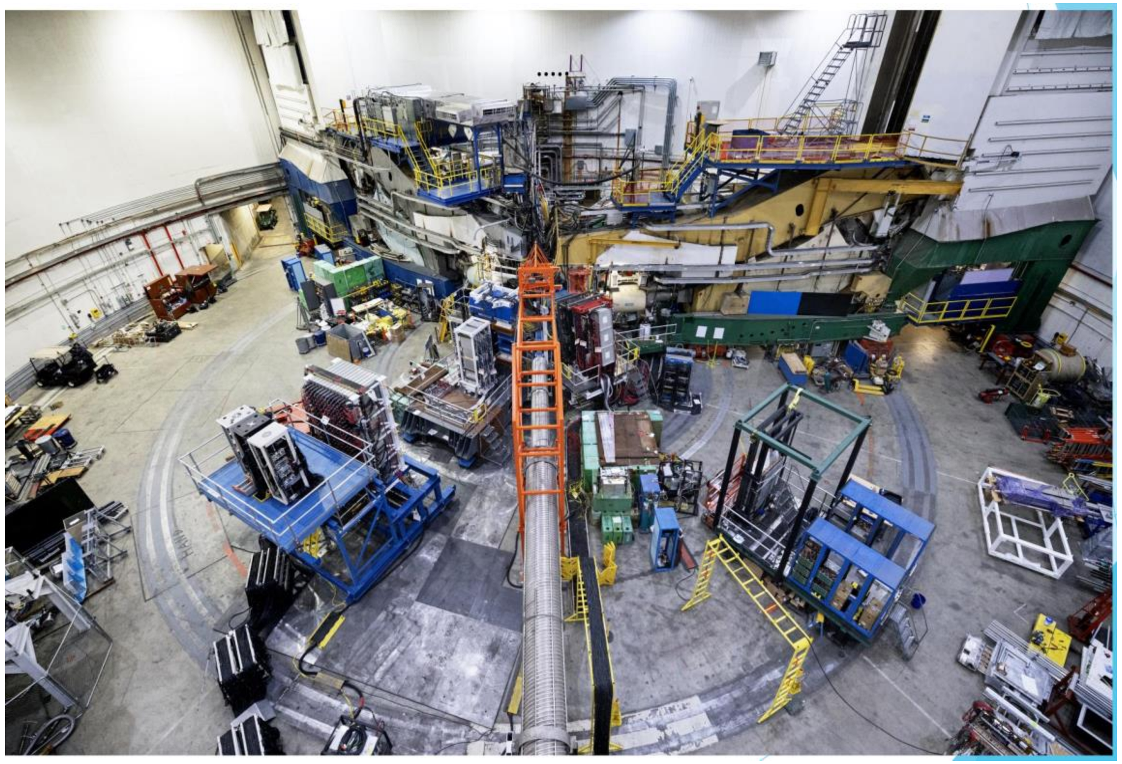
[1] Jones, D. (2023) The GEp-5 Experiment. *SPIN Conference September 2023*

SBS Collaboration

The JLab Super BigBite Spectrometer (SBS) Collaboration is a research group working on high-precision nucleon structure experiments at JLab using the Super BigBite Spectrometer (SBS) in Hall A. The collaboration focuses on studying the electromagnetic form factors of the proton and neutron at very high Q^2.

SBS Experiments: four ground-breaking measurements of the nucleon's elastic form factors. The experiments in this program are:

- **GEp-V:** Measurement of the Proton Form Factor Ratio, GEp/GMp up to 12 GeV^2 Using Recoil Polarization Method **(E12-07-109)**.
- **GEn-II:** Measurement of the Neutron Electromagnetic Form Factor Ratio GEn/GMn at High Q^2 (5.0, 6.8 and 10.2 GeV^2) **(E12-09-016)**.
- **GEn-RP:** Measurement of the Neutron Electromagnetic Form Factor Ratio GEn/GMn at Q^2 = 4.5 GeV^2 using recoil polarization technique **(E12-17-004), ran with K_{LL} (E12-20-008)**.
- **GMn:** Precision Measurement of the Neutron Magnetic Form Factor up to Q^2 =13.5 GeV^2 **(E12-09-016)**.

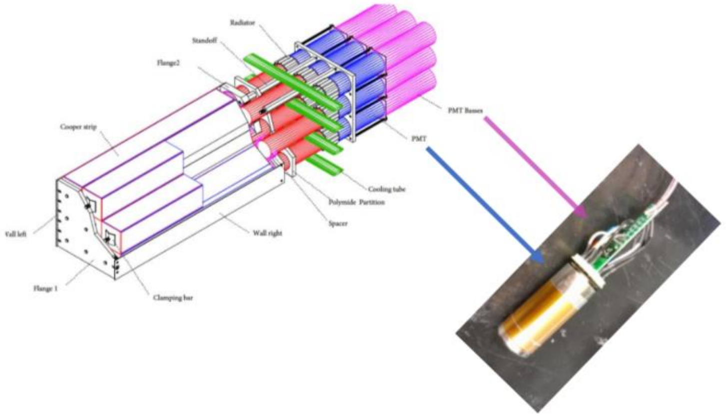


Hall A Layout

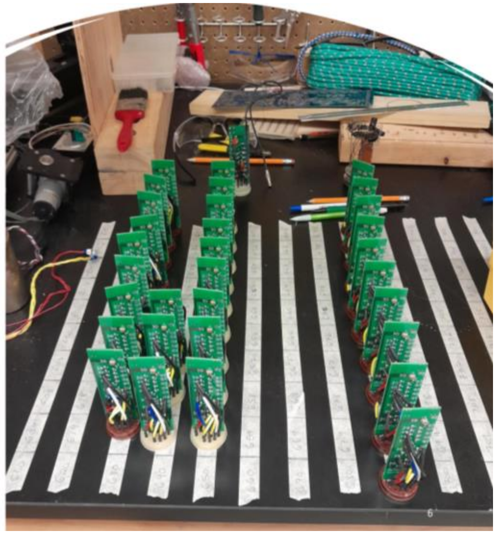
GEp V Experiment: PMT Work

ECal for the SBS electron arm

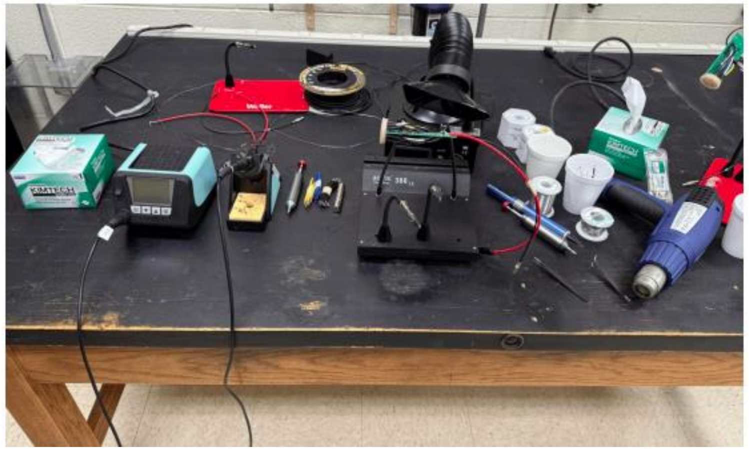
- The detector consist of 1656 lead-glass blocks (42.5 x 42.5 x 340 mm^3) viewed via 150-mm long light guides by FEU-84 PMTs
- The 1656 channels are made up of 184 Super Module (SM), each with 9 PMT installed in 3 by 3 array.
- PMT HV bases were modified by JMU, and assembled at JMU, VT and JLab.



ECal SM Schematics



Some bases (w/o HV and signal cables) at JMU



Work station (for assemblying bases) at VT

Electron Calorimeter Installation (People)

Photos from Simona's slides: *https://indico.jlab.org/event/893/contributions/15728/attachments/12098/19119/ECAL_SM.pdf*

PMT Test and Shielding

Mu-Metal Fabrication:

- shielding was implemented in the 3×3 PMTs matrix to reduce magnetic field to <0.1 mT,
- achieved with 4" long, 18 mm (6 mm tri-layer wrapping) mu-metals and,
- the PMT photocathode positioned at 1.5" depth as shown below.

Assembled base, PMT and mu-metal

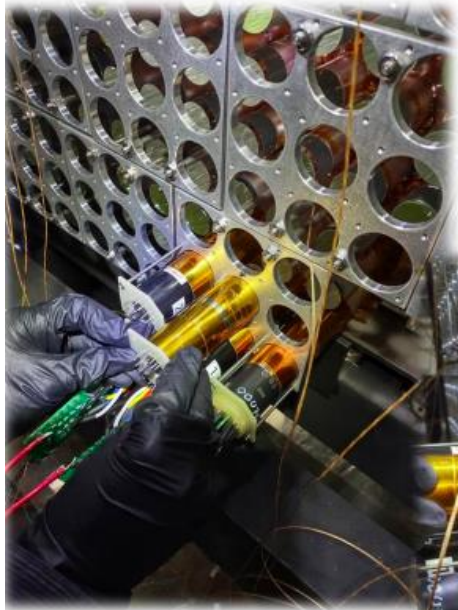
ECal PMT Test Setup at JLab

HV and Dark Current Test:

- The assembly (base+PMT+mu-metal) was covered in a dark box after connecting **HV** and **signal** cables,
- then HV (in steps up to ~1,500 V) was supplied,
- PMT signal and dark current were read to determine if assembly is good and labeled for installation.

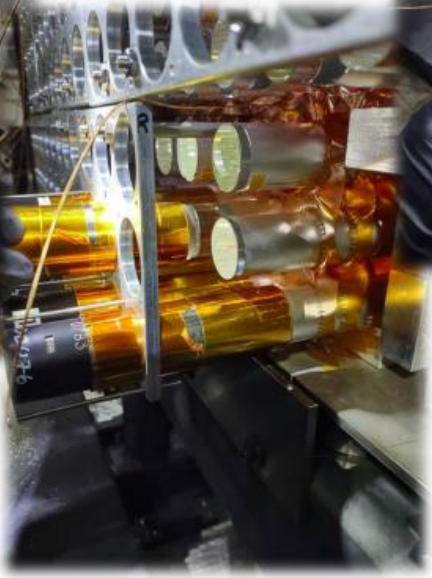
PMT Installation

Needs to ensure good transmission between PMT and guide line through cookie



Inserting PMT through hole in the backplate

Aligning PMT/cookie to the lightguide



Placing the mu-metal for the PMT photocathode at the right depth – see silver line on the PMT; this must be done before putting in the screws

Putting in the screws by hand

Using a torque screw driver: setting = 2

Photos from Simona's slides: *https://indico.jlab.org/event/893/contributions/15728/attachments/12098/19119/ECAL_SM.pdf*