COLLEGE OF SCIENCE
PHYSICS
VIRGINIA TECH

From Electromagnetic Form Factors to Deep Exclusive Measurements

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PaSHa
PARTONIC STRUCTURE OF THE HADRONS

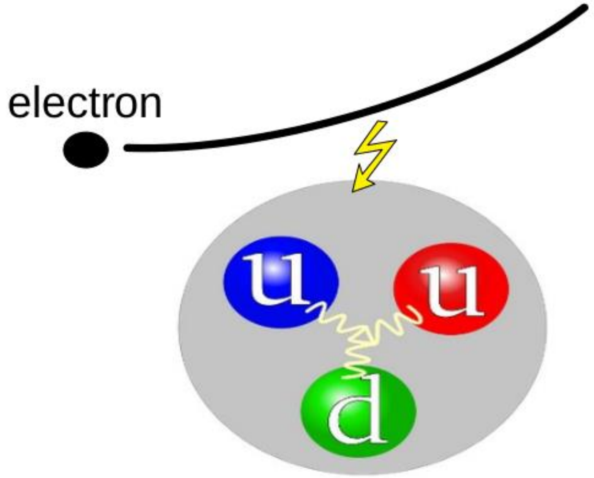
Outline

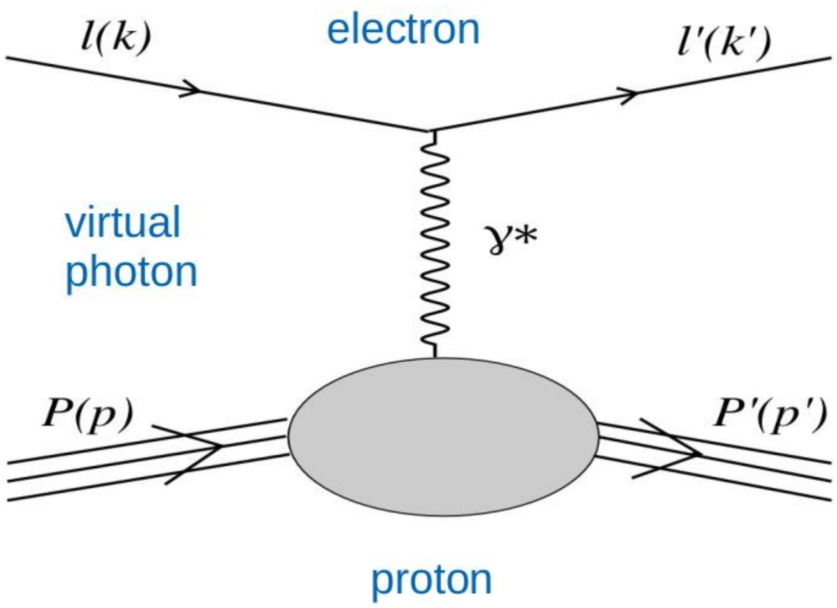
- Introduction
- Form Factor Measurements
- Proton Form Factor Ratio with the SBS
- GPDs and Form Factors

Introduction

Elastic scattering at high energy.

- *ep* ⟶ *e'p'*, with energy transfer via virtual photon





- The EM FF probe the nucleons' four-current distributions, critical for understanding nucleon structure.
- Electric (GEp) and magnetic (GMp) FFs describe how the proton's charge and magnetization are spatially distributed.

Nucleon vertex:

$$\Gamma_\mu(p',p) = \underbrace{F_1(Q^2)}_{Dirac}\gamma_\mu + \frac{i\kappa_p}{2M_p}\underbrace{F_2(Q^2)}_{Pauli}\sigma_{\mu\nu}q^\nu$$

$$G_E(Q^2) = F_1(Q^2) - \kappa_N \tau F_2(Q^2)$$

$$G_M(Q^2) = F_1(Q^2) + \kappa_N F_2(Q^2), \tau = \frac{Q^2}{4M_N}$$

At $Q^2 = 0$ $G_{Mp} = 2.79$ $G_{Mn} = -1.91$

$G_{Ep} = 1$ $G_{En} = 0$

Introduction: *FF Measurement*

Rosenbluth

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

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

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

-leverages linearity of cross section in ε
-measures cross section at fixed Q^2 but varying scattering angle:

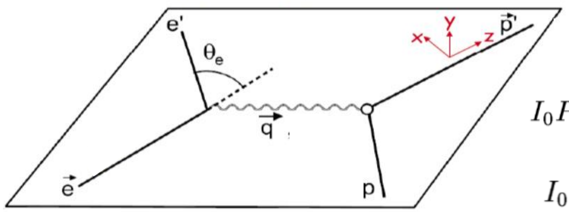
$$\sigma_R = \left(\frac{d\sigma}{d\Omega}\right)_{exp} / \left(\frac{d\sigma}{d\Omega}\right)_M \frac{\epsilon(1+\tau)}{\tau} = \frac{\epsilon}{\tau} G_E^2 + G_M^2$$

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

Polarization method

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

$\vec{e}N \to e\vec{N}$



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

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

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

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

Benefits of the Polarization Method

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

- changing beam energy and detector angle
- Thus, eliminating important sources of systematic uncertainties.

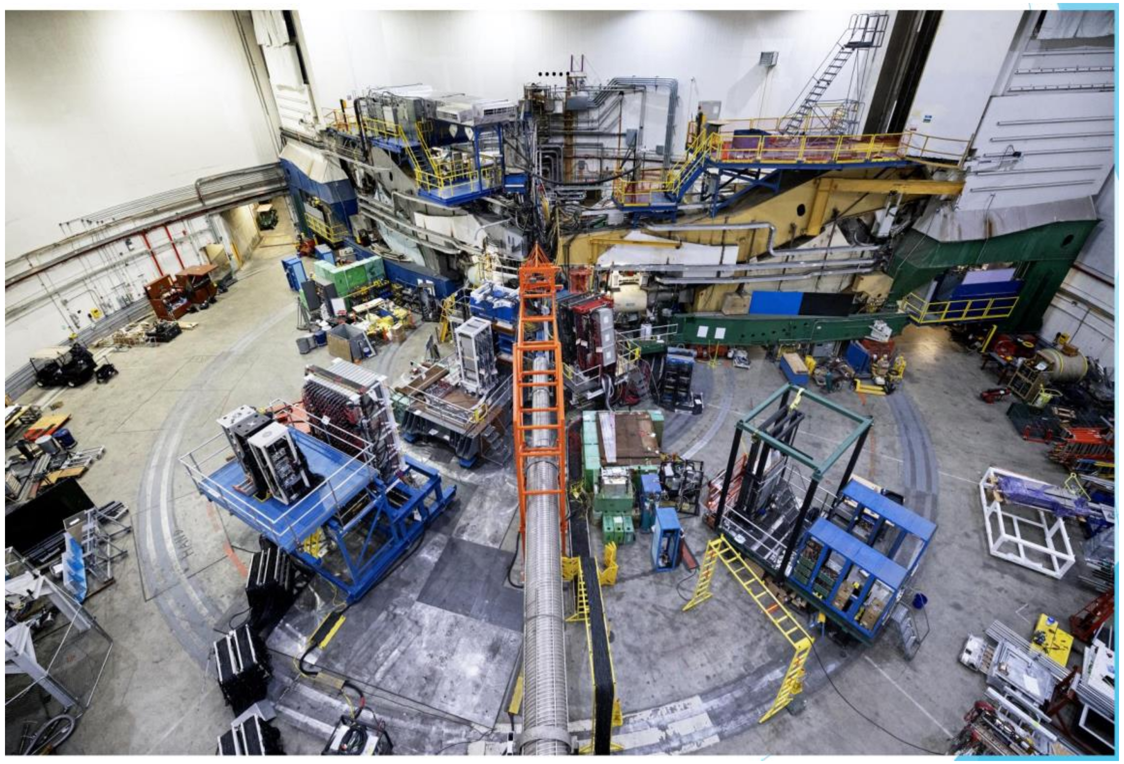
[1] *Phys. Rev. 79, 615–619 (1950)*
Similar polarization process demonstrated by Maxime on Tuesday;
[2] https://indico.jlab.org/event/1059/contributions/19133/attachments/14433/23325/TalkFemto2026.pdf

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

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

SBS Collaboration

The Super BigBite Spectrometer (SBS) collaboration focuses on studying the electromagnetic form factors of the proton and neutron at very high Q^2. *More details in G. D. Cates Friday morning talk [1]*



Some SBS Apparatus in Hall A Layout

SBS FF Experiments

- **E12-07-109 GEp-V:** Measurement of the Proton Form Factor Ratio, GEp/GMp up to 12 GeV^2 Using Recoil Polarization Method.
- **E12-09-016 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).
- **E12-17-004 GEn-RP:** Measurement of the Neutron Electromagnetic Form Factor Ratio GEn/GMn at Q^2 = 4.5 GeV^2 using recoil polarization technique.
- **E12-09-016 GMn:** Precision Measurement of the Neutron Magnetic Form Factor up to Q^2 =13.5 GeV^2.

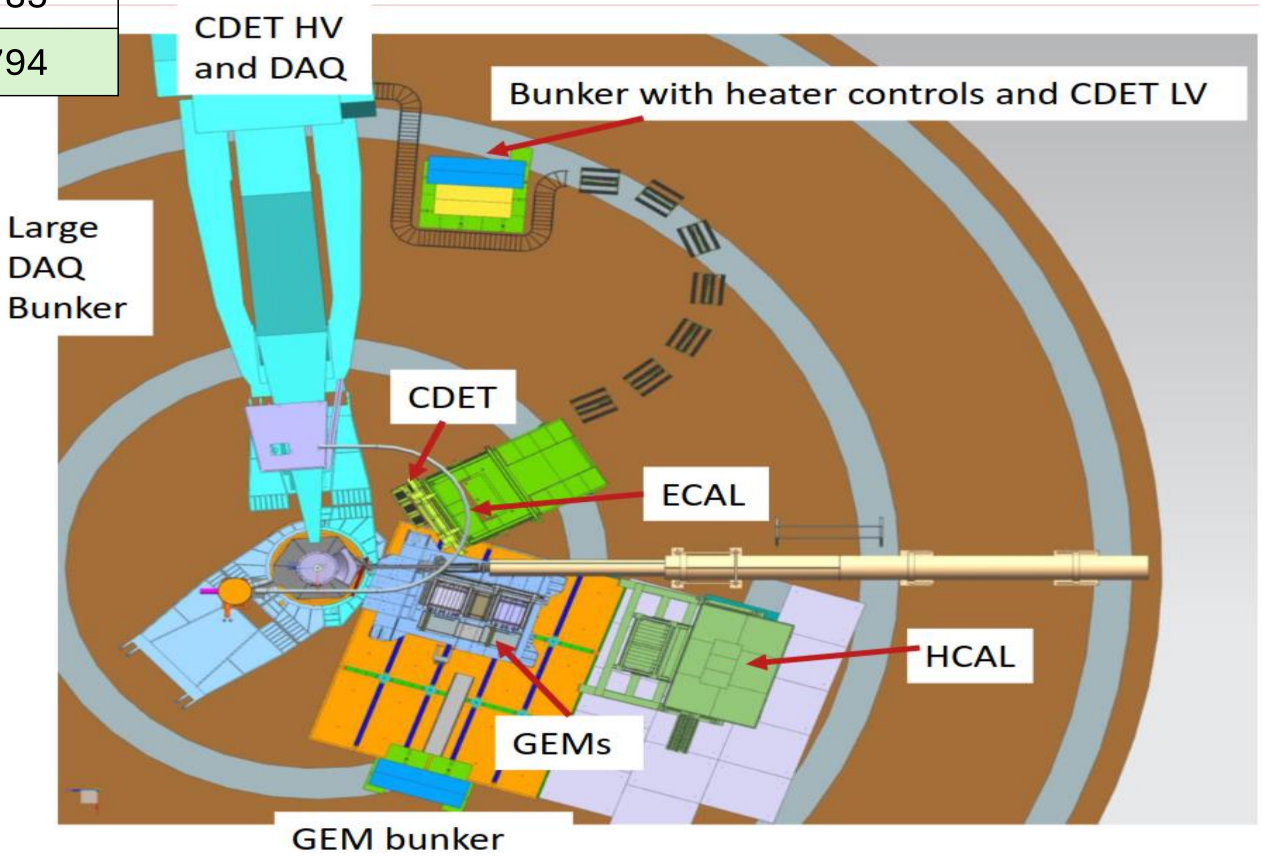
More details in G. D. Cates Friday morning talk [1]

[1] https://indico.jlab.org/event/1059/contributions/19122/attachments/14453/23367/cates_uva_femtography_2026_v4.pdf

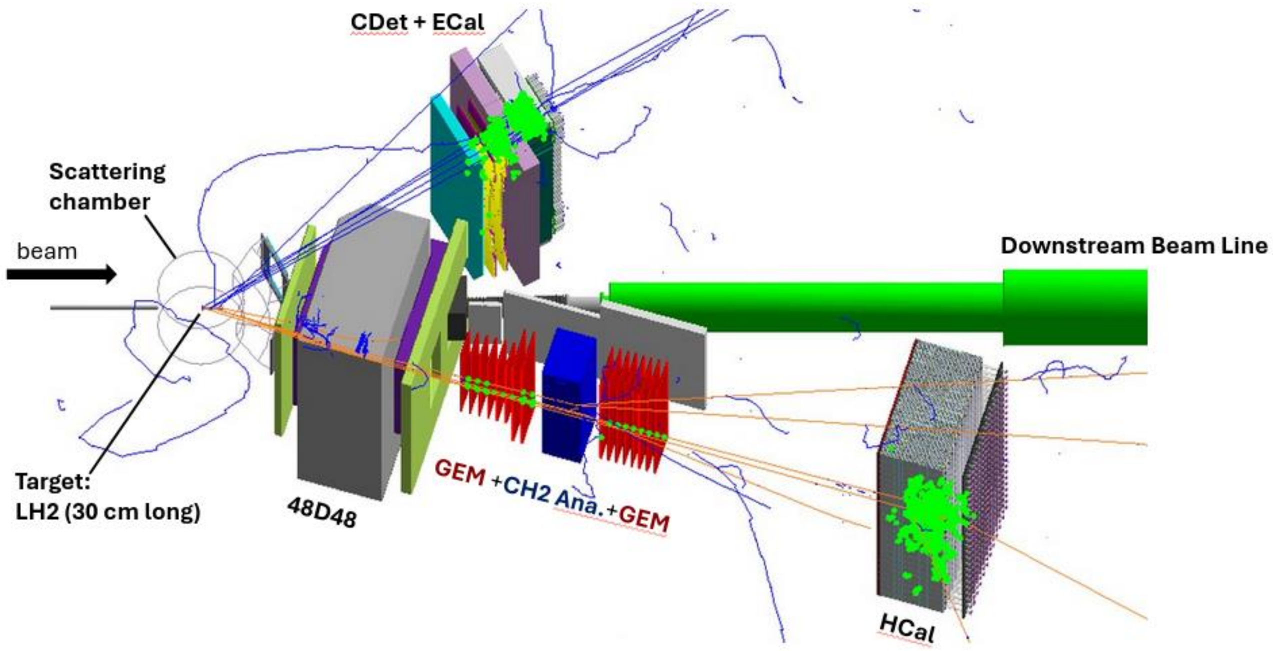
SBS GEp V Experiment E12-07-109

Run period: April-August, 2025

Kinematic point	E_{beam} GeV	Q^2 GeV^2	θ_{ECal} Deg.	<E'> GeV	θ_{SBS} Deg.	$<P_p>$ 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



Apparatus: Electron Calorimeter Arm



g4sbs GEP3 Kinematic Setup: Electron Arm

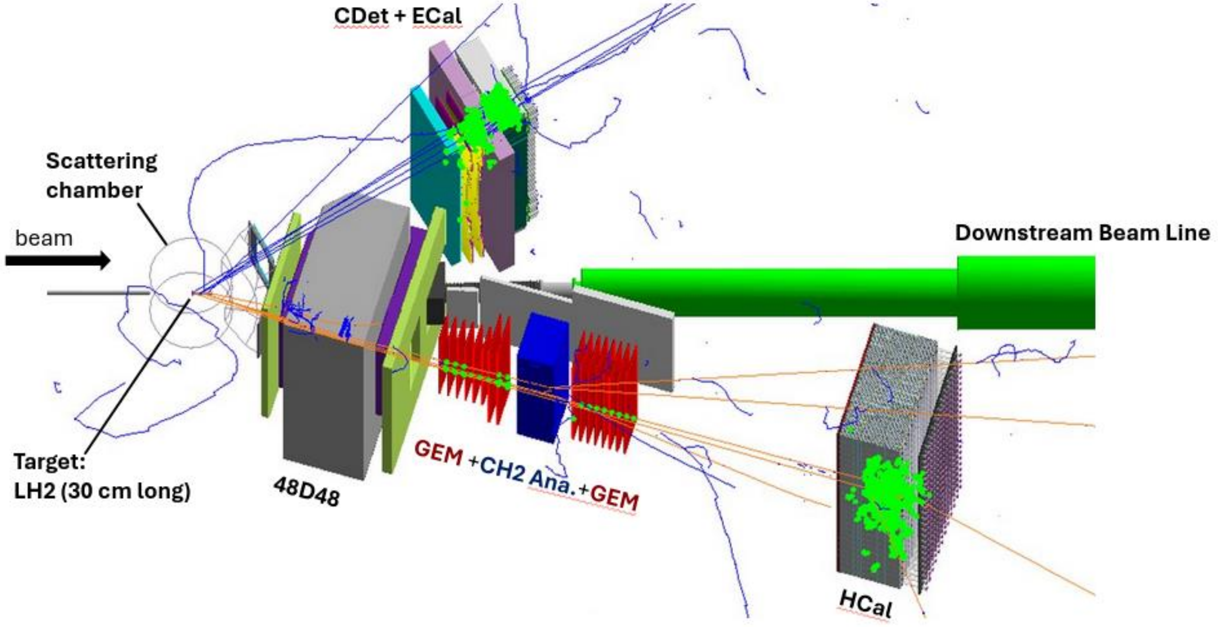
ECal: 1656 channels lead-glass blocks (42.5 x 42.5 x 340 mm^3) viewed via 150-mm long light guides by FEU-84 PMTs

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

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

ECal was located inside a custom oven (T ~ 225°C) to allow constant annealing of the radiation damage during data taking

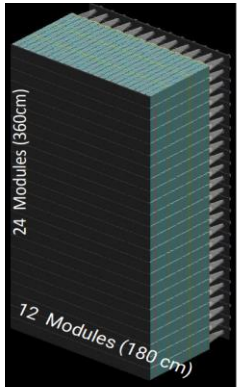
Apparatus: Hadron Calorimeter Arm

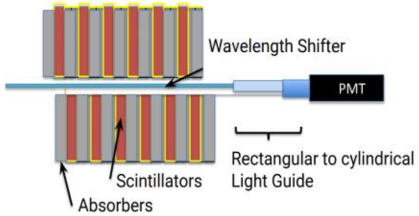


g4sbs GEP3 Kinematic Setup: Hadron Arm

HCal:

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

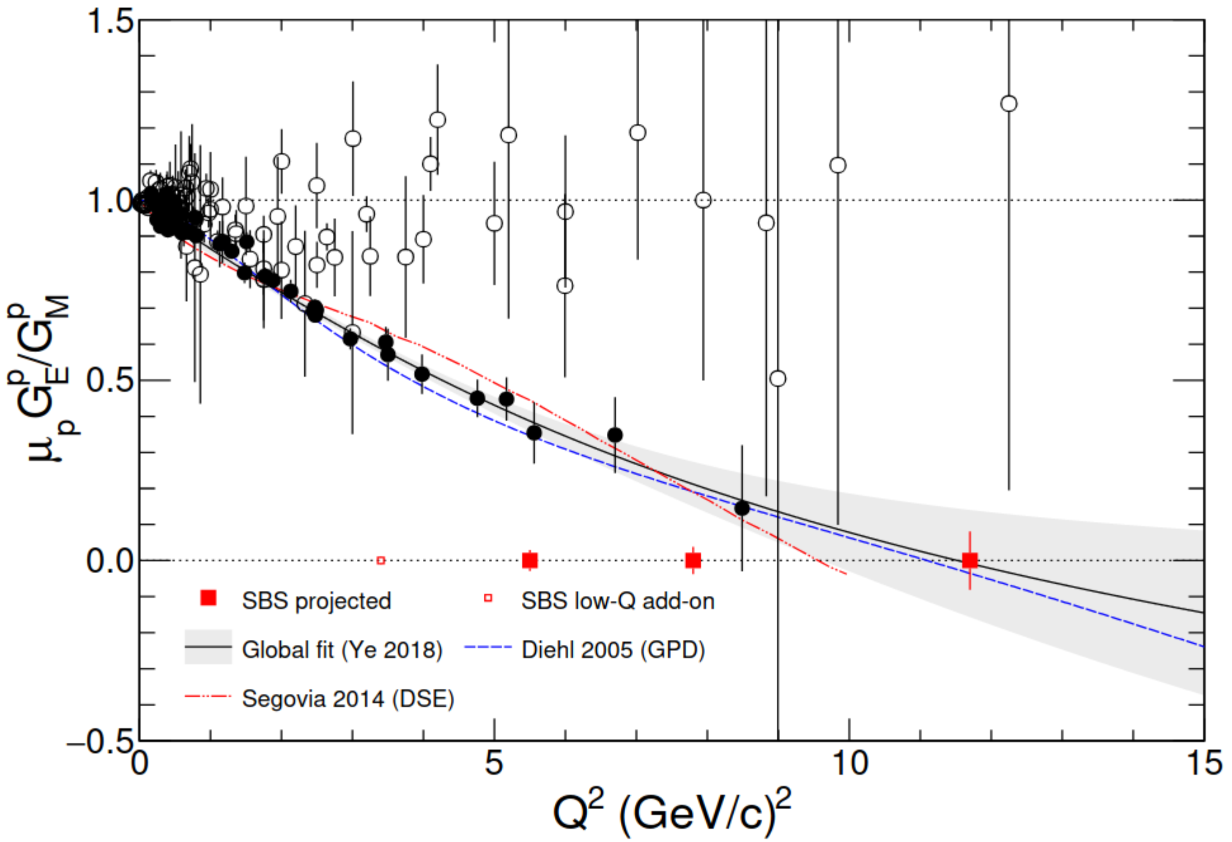




SBS HCal in Hall A (J. Poudel, SBS Collaboration Meeting 2023)[1]

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

Proton Form Factor Data and SBS Projections



Proton FF ratio scaled by its μ_p, as a function of Q^2 [1]

- Rosenbluth (Cross section): flat with increasing Q^2.
- Polarization: decreasing with increasing Q^2.
- discrepancy attributed to TPE effects, *discussed in slide 10 of Afanasev Tuesday talk* [2]
- SBS projected statistical uncertainty 0.029-0.081 assumes 70% overall event reconstruction efficiency resulting from SBS detectors and DAQ dead-time [1].

Figure from A. Puckett's 2024 PAC proposal [1] *https://www.jlab.org/exp_prog/proposals/24/PR12-24-010.pdf*
[2] https://indico.jlab.org/event/1059/contributions/19128/attachments/14430/23321/Afanasev_Femtography2026.pdf

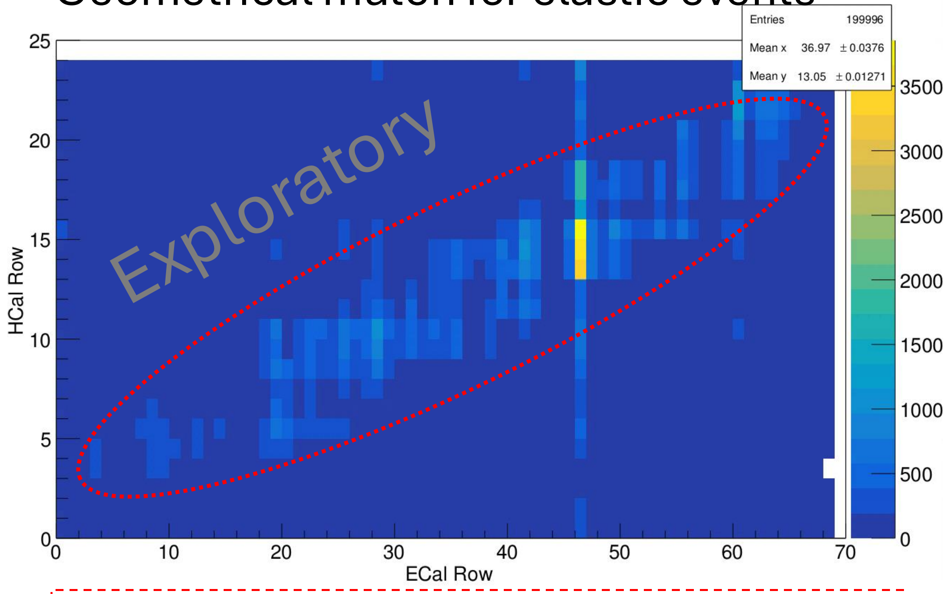
Analysis Effort: HCal Timing Alignment

Goal: minimizing the time difference between pairs of hit times within HCal clusters

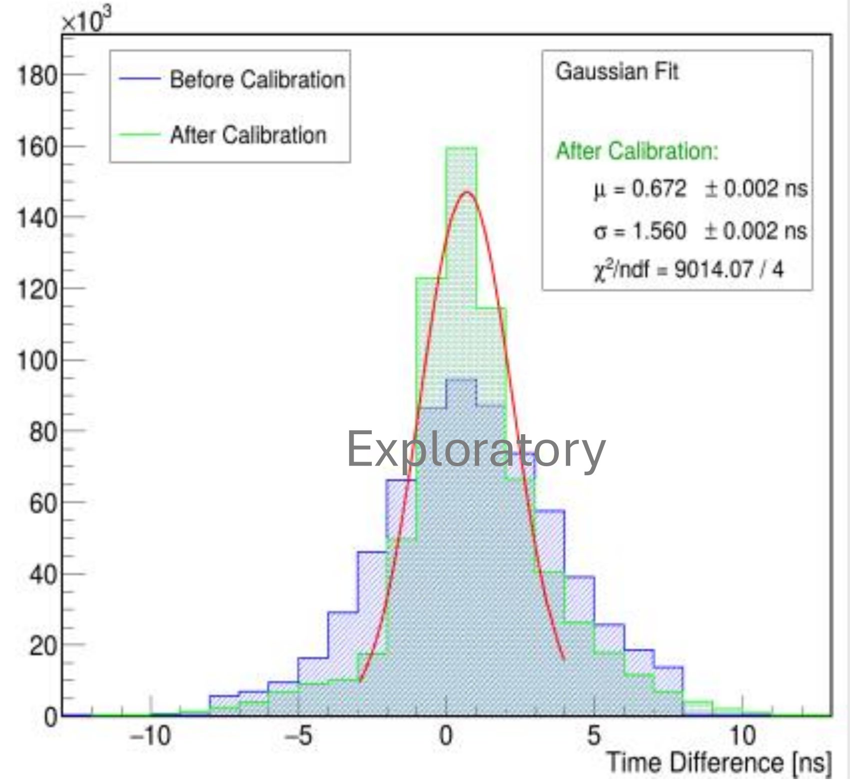
$$\chi^2 = \sum_{i=1}^{N_{event}} \sum_{j=1}^{N_{hit}^{(i)}-1} \sum_{k=j+1}^{N_{hit}^{(i)}} \left(t_{corr,j}^{(i)} - t_{corr,k}^{(i)}\right)^2$$

where $t_{corr} = t_{raw} - t_0$

Geometrical match for elastic events



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



- Resolution (after) improved to ~1.56 ns.
- Further improvements anticipated as analysis progresses.

GPDs and EM FF

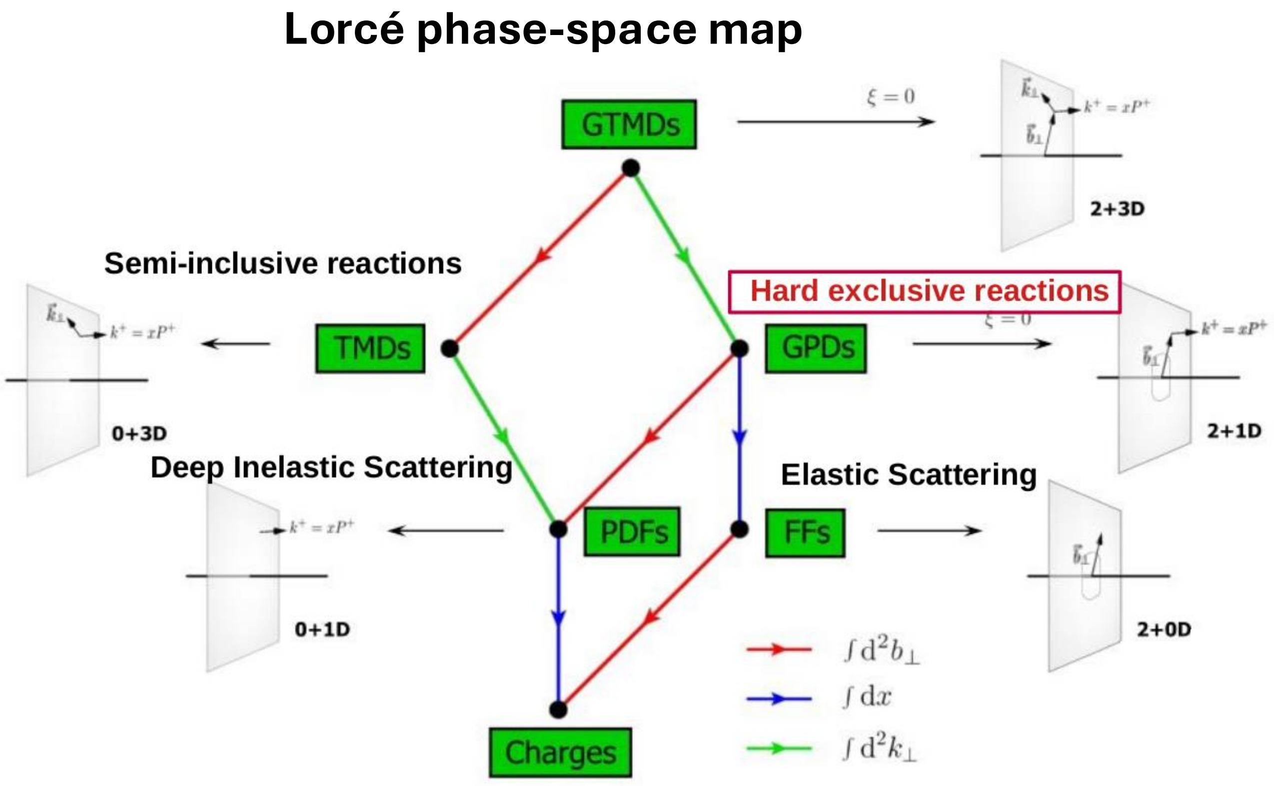


Figure from Marie's colloquium talk at UVa, April 2026

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t)$$ Dirac FF

$$\int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t)$$ Pauli FF

Summary and Outlook

- FF probes nucleon's charge and magnetization.
- SBS has successfully measured all EM FF to very high Q^2 regions.
- SBS analysis ongoing, GEp in early stages after run in 2025 while neutron FFs analysis are in advanced stages.

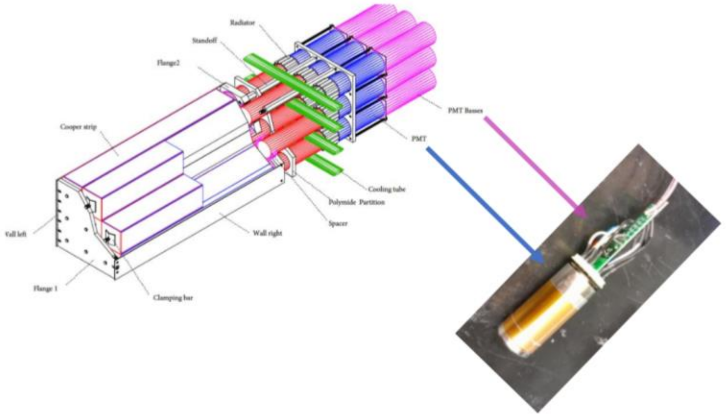
Thank you

Bonus slides

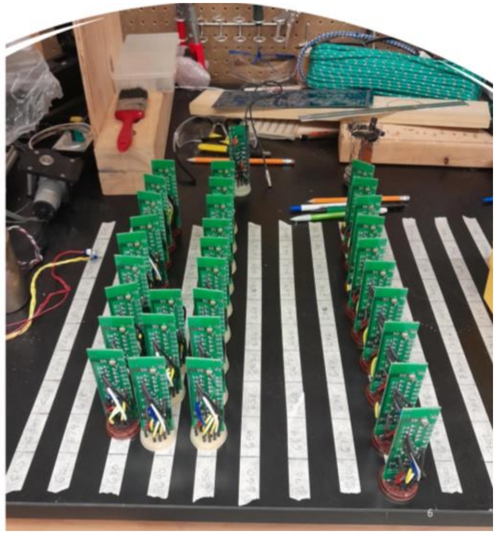
GEp V Experiment: PMT Work

ECal for the SBS electron arm

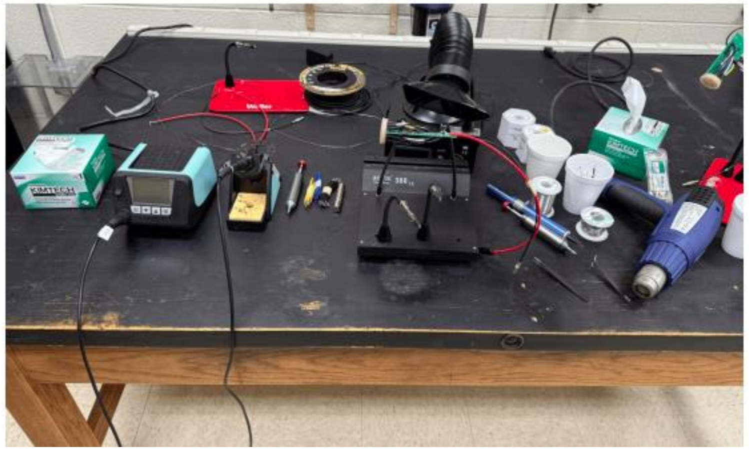
- The detector consist of 1656 lead-glass blocks (42.5 x 42.5 x 340 mm^3) viewed via 150-mm long light guides by FEU-84 PMTs
- The 1656 channels are made up of 184 Super Module (SM), each with 9 PMT installed in 3 by 3 array.
- PMT HV bases were modified by JMU, and assembled at JMU, VT and JLab.



ECal SM Schematics



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



Work station (for assemblying bases) at VT

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.

ECal PMT Test Setup at JLab

Assembled base, PMT and mu-metal

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.

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