Probing Electromagnetic Charge Distribution of Proton at Large Momentum Transfer

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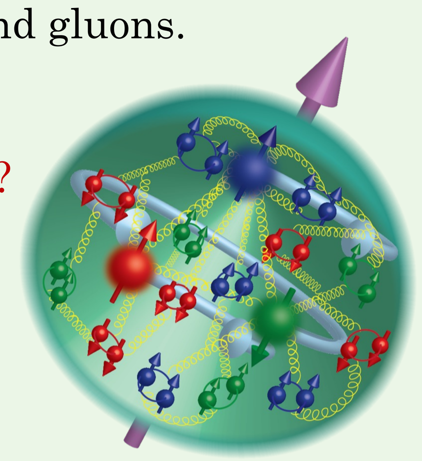
Building Nuclei from Quarks

Building blocks of visible matter are composed of quarks and gluons.

Structure mostly governed by strong interaction.

What do we know about the internal structure of Nucleons?



Mass: ~ 940 MeV, quarks contribute only a few MeV each.

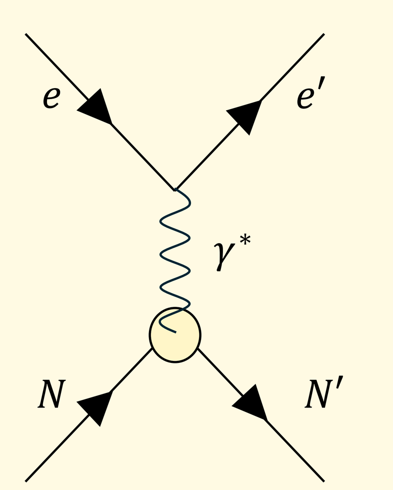
Magnetic Moment: A large fraction is anomalous.

$$\mu_p = +2.79\mu_N \qquad \mu_n = -1.91\mu_N$$

Spin ½: But quark spin contributes only about 30%

Protons and neutrons are composite particles with complex quark-gluon structure, not point-like objects!

Elastic eN Scattering and Sachs Form Factors



Leading-order Feynman diagram for $e + N \rightarrow e + N$ (single-photon exchange or Born term)

Nucleon vertex: $\Gamma^\nu = F_1(q^2)\gamma^\nu + F_2(q^2)i\sigma^{\alpha\nu}\frac{q_\alpha}{2M}$

Dirac FF   Pauli FF

Define Sachs FFs for charge and magnetization

$$G_E(q^2) \equiv F_1(q^2) - \tau F_2(q^2)$$
$$G_M(q^2) \equiv F_1(q^2) + F_2(q^2)$$

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

$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1} \qquad \tau \equiv \frac{-q}{4M^2} = \frac{Q}{4M^2}$$

FFs provide testing ground for QCD models, gives constraints on models of nucleon structure.

Measuring Form Factors

Rosenbluth FF Separation Method

$$\left(\frac{d\sigma}{d\Omega}\right)_{reduced} = \frac{\epsilon(1+\tau)}{\tau}\left(\frac{d\sigma}{d\Omega}\right)_{exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = G_{Mp}^2 + \frac{\epsilon}{\tau}G_{Ep}^2$$

Plot reduced cross section at fixed Q^2 against ϵ,

$\rightarrow \frac{1}{\tau}G_{Ep}^2$ as slope.

$\rightarrow G_{Mp}^2$ as intercept.

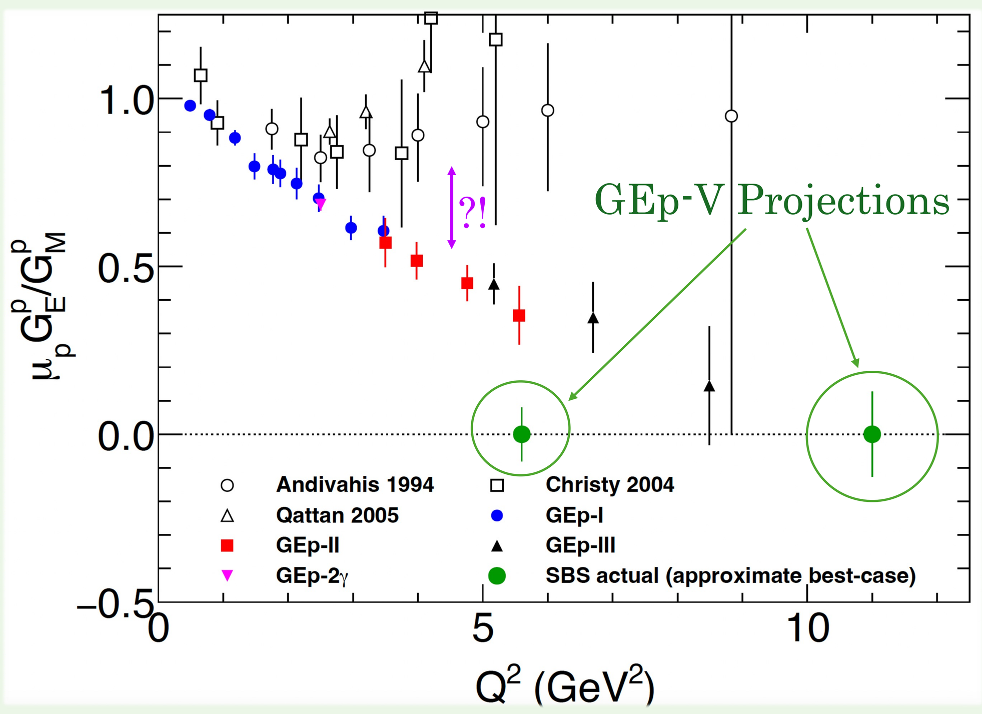
- At high Q^2, contribution from G_{Mp} dominates cross section.
- Also, at high Q^2 effects beyond Born approximation cannot be neglected.
- Therefore, for large momentum transfer isolation of charge FF is difficult.

Recoil Polarimetry

Direct measurement of form factor ratio.

Measures the ratio of transferred polarization P_t and P_l.

Only one measurement needed for each Q^2.

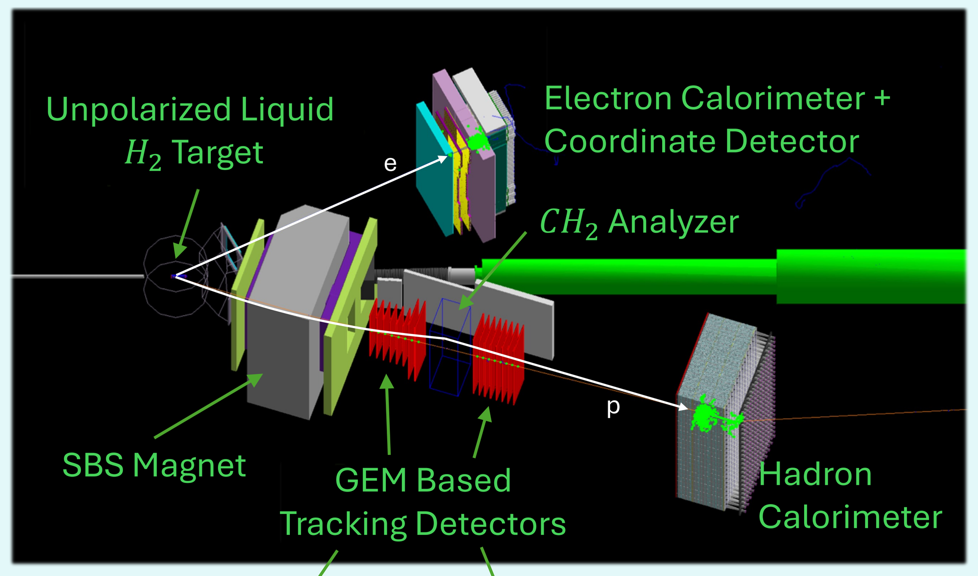


There is a clear discrepancy between JLab Rosenbluth separation results (open data points) and Polarization transfer results (filled data points)!

Models of Two Photon Exchange largely solve the difference and push Rosenbluth results towards polarization transfer results.

SBS GEp-V Experiment

Conducted in Jefferson Lab Hall A in 2025

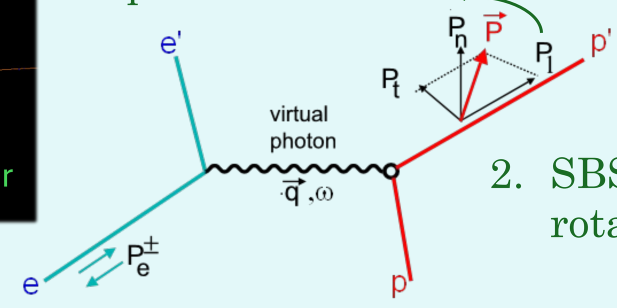


Two kinematic points

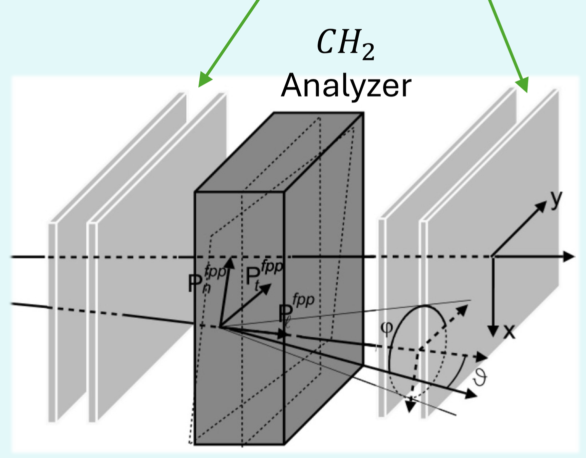
$Q^2 = 5.6GeV^2(3.7C)$ & $Q^2 = 11GeV^2(94.2C)$

How Polarization Transfer Method Works

1. At target polarization transfer from a longitudinally polarized electron to a proton.



2. SBS magnet rotates P_l into P_n



3. Analyzer preferentially deflect the proton by nuclear spin orbit force in direction $\vec{p}\times\vec{S}$.
4. If one spin state is dominant, this creates an asymmetry in the azimuthal angular distribution.

$$f^{\pm}(\theta,\phi) = \frac{\epsilon(\vartheta,\varphi)}{2\pi}\left[1 \pm A_y\left(P_t^{fpp}\sin\varphi - P_n^{fpp}\cos\varphi\right)\right]$$

Analyzing power

$$A = \frac{f^+ - f^-}{f^+ + f^-} = A_y\left(P_t^{fpp}\sin\varphi - P_n^{fpp}\cos\varphi\right)$$

5. **Form factor ratio is given by polarization component ratio**

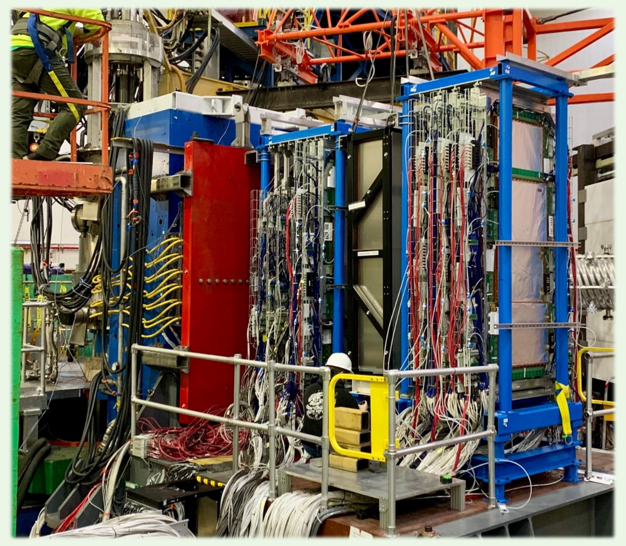
$$\mu_p\frac{G_{Ep}}{G_{Mp}} = -\mu_p\frac{E_e + E_e'}{2M_p}\tan\frac{\theta_e}{2}\left(\frac{P_t^{fpp}}{P_n^{fpp}}\sin\chi_\theta + \gamma_p(\mu_p - 1)\Delta\phi\right)$$

Precession angle

Systematic uncertainties, Analyzing power of the polarimeter, and electron beam polarization cancel in the ratio.

Experimental Setup

Super BigBite Spectrometer – Hadron Arm



A large aperture dipole magnet with iron-dominated horizontally oriented magnetic field.

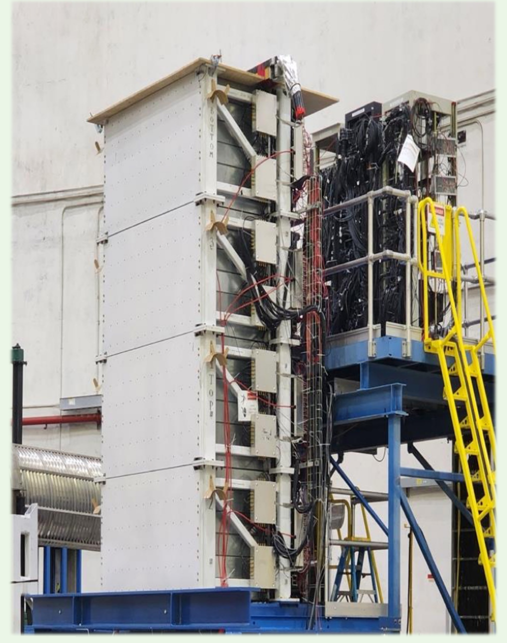
Eight-layer **GEM** based front tracker
- Spatial resolution ~ $70\mu m$
- Timing resolution ~ $10ns$

CH2 analyzer where protons undergo spin dependent secondary scattering

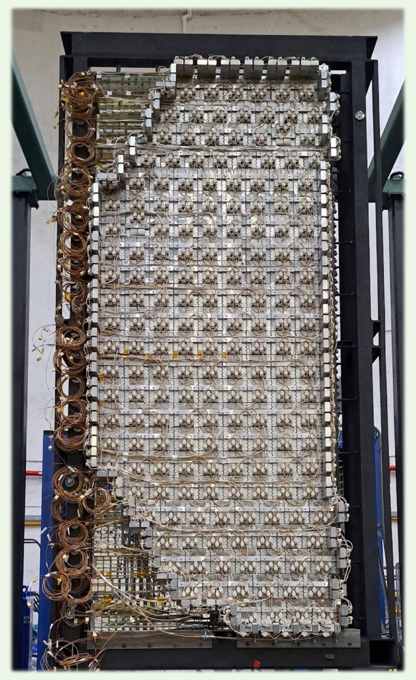
Eight-layer **GEM** based back tracker

HCAL - A sampling calorimeter
- Energy resolution ~ 30%
- Timing resolution ~ $0.5ns$ for $8GeV$ protons

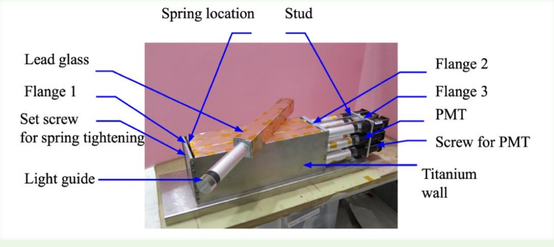
Target: 30cm LH_2



Electron Arm Detectors



ECAL - 1656 lead glass crystals



- Expected 5-6% energy resolution.
- Crystals heated > 200°C for continuous annealing.

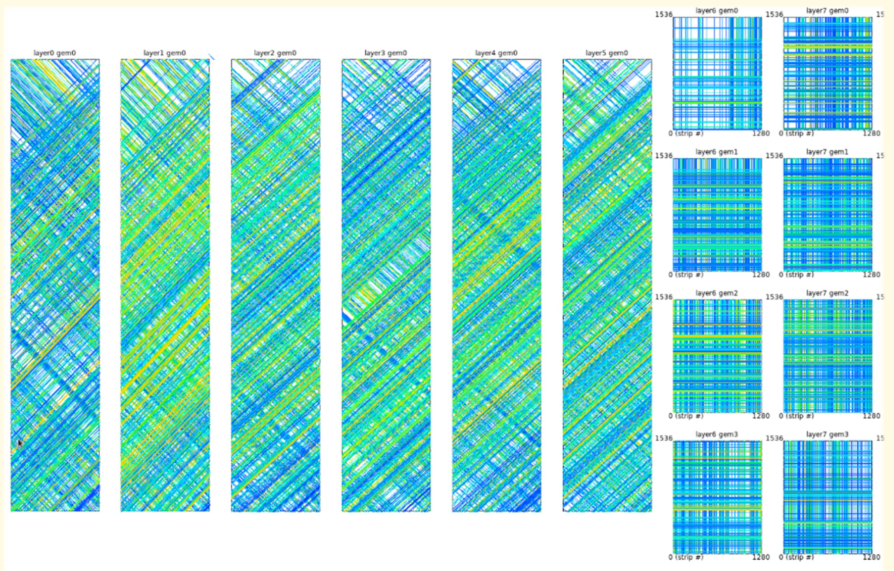
CDET (Coordinate Detector)
- Determines out-of-plane scattering angles of electrons.
- Scintillator detector with wavelength shifting fibers.

Status of Data Analysis

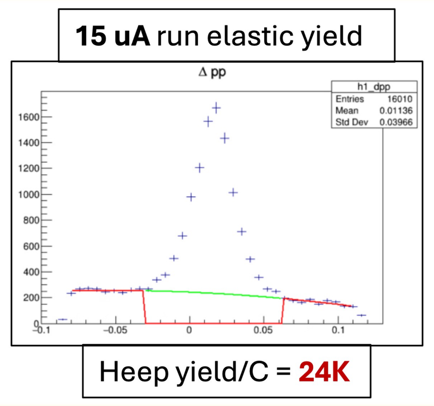
Calibrations and optimization work is ongoing towards a first complete reconstruction pass.

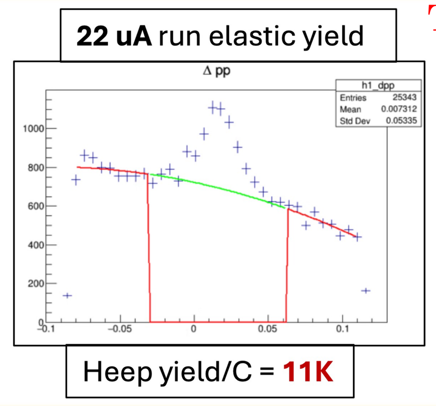
The primary challenge is GEM track reconstruction in a high-occupancy environment with a low signal-to-background ratio.

GEM Front Tracker occupancies above 40% significantly increase the complexity and processing time of both 1D clustering and 2D hit formation, especially for MIP-like protons.



More than 40% of the strips of GEM Front Tracker fire during one single event

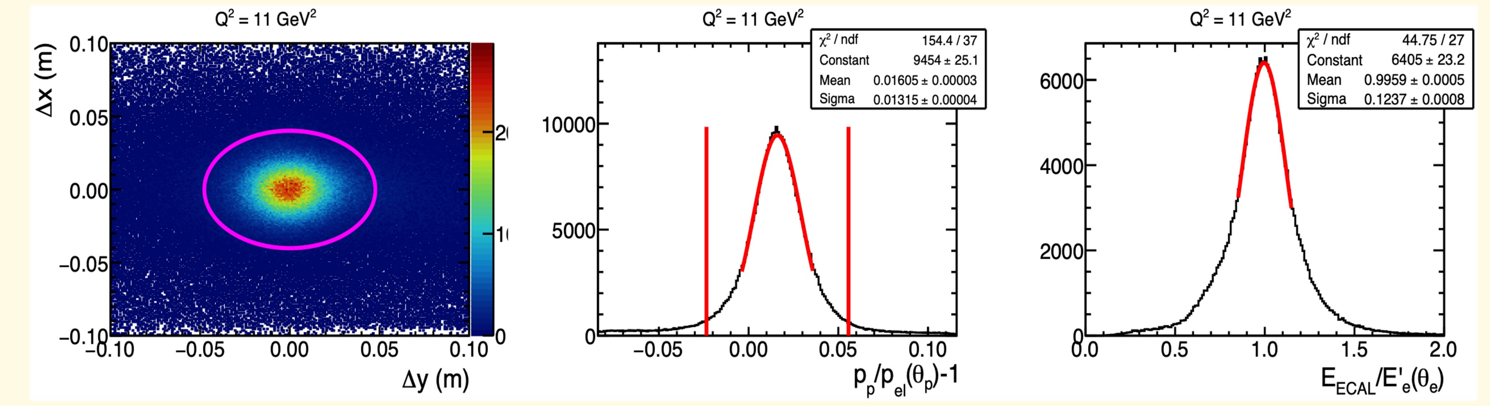




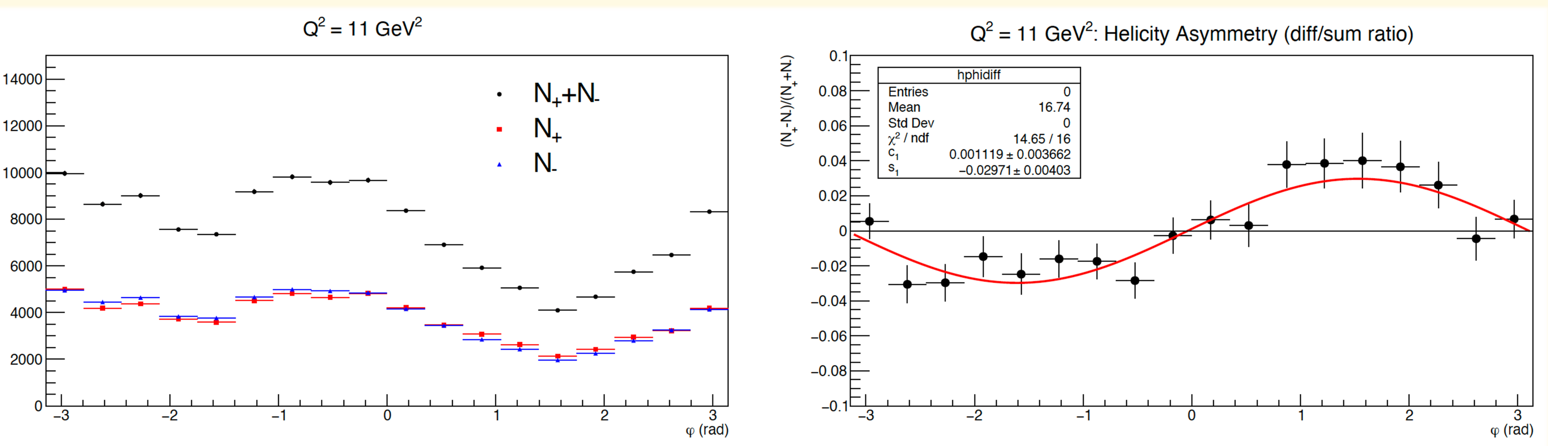
Ideal expected elastic yield from simulation with no background and without radiative corrections is about 94K/C.

Elastic Event Reconstruction

These distributions quantify elastic event reconstruction quality. Δx and Δy are position residuals between measured ECAL clusters and the elastic kinematic prediction using the proton track. p_p/p_{el} is the ratio between measured and expected proton momentum from elastic kinematics. The ratio E_{ECAL}/E_e' compares measured electron energy in ECAL to the kinematically expected value.



Asymmetry Reconstruction



Preliminary asymmetry analysis done by Prof. Andrew Puckett (UConn) for $Q^2 = 11GeV^2$. Asymmetry indicates analyzing power is inline with expectation.

Upcoming Analysis

Finish initial detector calibrations and perform a first pass mass replay of data.
Model background distributions using Simulation and refine elastic event selection cuts.
Extract asymmetries for both kinematics settings.

Acknowledgements/References

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