# Optimization of Gas Electron Multiplier (GEM) Detectors targeting $G_E^p - V$ Experiment at Hall A

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# Content

- Super Bigbite Programme(SBS) at Jefferson Lab
- Measurement of Proton Form Factor Ratio at high $Q^2$ - Thesis Experiment
- Gas Electron Multiplier (GEM) Detectors made at UVA
- High Background problem and solutions
- Summary and Future work

## Experiments and Measurements

- $G_M^n$ : measure $G_M^n/G_M^p$ up to $Q^2 = 13.5 GeV^2$ $LD_2$ target- data taking done
- $G_E^n$-II : measure $G_E^n/G_M^n$ up to $Q^2 = 10 GeV^2$ polarized $^3He$ target- run one done
- $G_E^n - RP$ : measure $G_E^n/G_M^n$ up to $Q^2 = 4.5 GeV^2$ $LD_2$ target - Jan 2024
- $G_E^p$-V : measure $G_E^p/G_M^p$ up to $Q^2 = 12 GeV^2$ using a target of $LH_2$- Fall 2024

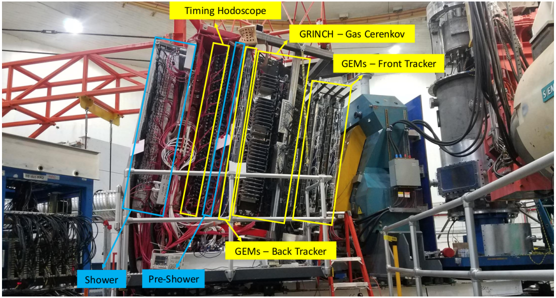
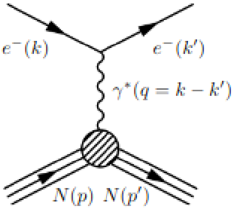



Figure: Bigbite Spectrometer in $G_M^n$

# Electron-Nucleon Scattering : Single Photon Approximation




- Amplitude for electron-nucleon scattering : $-iM = j^{\mu}(-ig_{\mu\nu}/q^2)J^{\nu}$
- Electron transition current : $j^{\mu} = -e\overline{u}_e(k')\gamma^{\mu}u_e(k)$
- Nucleon transition current : $J^{\mu} = \overline{u}(p')[F_1(Q^2)\gamma^{\mu} + (\kappa/2M)F_2(Q^2)i\sigma^{\mu\nu}q_{\nu}]u(p)$
- $F_1(Q^2)$ and $F_2(Q^2)$, known as Dirac and Pauli Form Factors, are the only unknowns in nucleon transition current equation.
- Internal structure of the nucleon can be parameterized using $F_1(Q^2)$ and $F_2(Q^2)$ which are scalar functions of $Q^2(= -q^2)$.
- Sach's form factors : Fourier transforms of the electric and magnetic moments distributions in the Breit frame
    - electric form factor : $G_E = F_1 - (\kappa Q^2/4M^2)F_2$
    - magnetic form factor : $G_M = F_1 + \kappa F_2$

# Measurement of Proton Form Factor Ratio at high $Q^2$

Rosenbluth Separation and polarization transfer methods are two method to measure Proton Form Factor ratio

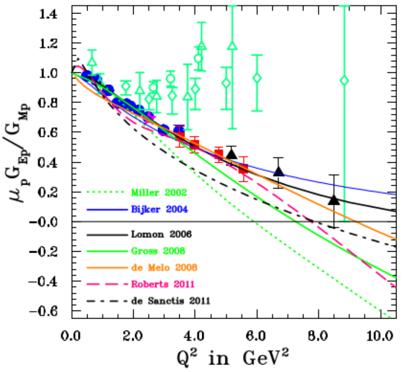



Figure: Filled symbols: The ratio $\mu_p G_E^p/G_M^p$ in polarization transfer experiments. Empty symbols: Rosenbluth results

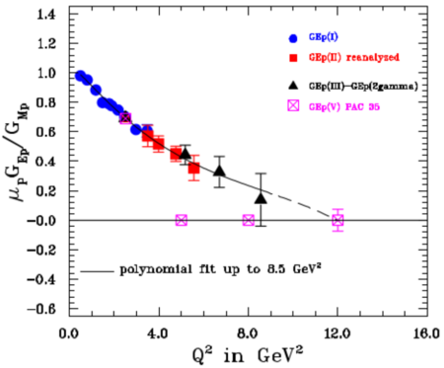
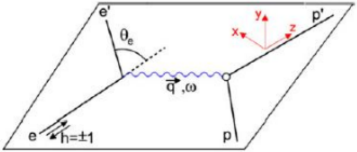



Figure: Three data points to be obtained in $G_E^p$-V. Solid line is a polynomial fit for existing data, extrapolated as dashed line.

# Polarization Transfer Method




For recoil polarization there is no normal component, two polarization components are in reaction plane

$$hP_e P_t I_0 = -2hP_e \sqrt{\tau(1+\tau)} G_E^p G_M^p tan(\frac{\theta_e}{2})$$
$$hP_e P_l I_0 = hP_e \frac{1}{m_p}(E + E'_e)\sqrt{\tau(\tau+1)}(G_M^p)^2 tan^2(\frac{\theta_e}{2})$$

Here $\tau = Q^2/4m_p^2$ ; $E_e$ Initial electron energy ; $E'_e$ Final electron energy ; $\theta_e$ scattering angle and $I_0 \sim (G_E^p)^2 + \frac{\tau}{\epsilon}(G_M^p)^2$

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

Form factor ratio is obtained without measuring the actual cross section and without changing the beam energy or detector angle ⇒ reduce sources of systematic uncertainties.

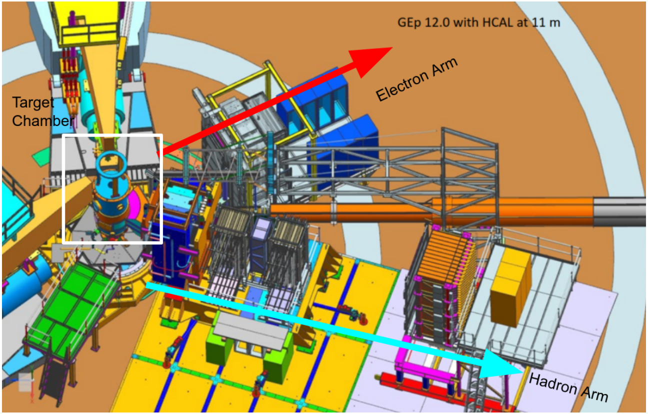



Figure: 3-D view of the Super Bigbite Spectrometer in $G_E^p$-V configuration

- Large solid angle acceptance of 75 msr for BigBite Spectrometer
- High background rate ($500 kHz/cm^2$) capable tracking detectors

# GEMs in Super Bigbite Spectrometer

## UVA built GEMs in SBS

- Front tracker: 8 GEM layers, 6 of active area of $150 \times 40\ cm^2$ and 2 of active area of $200 \times 60\ cm^2$
- Back tracker: 8 layers, active area of $200 \times 60\ cm^2$

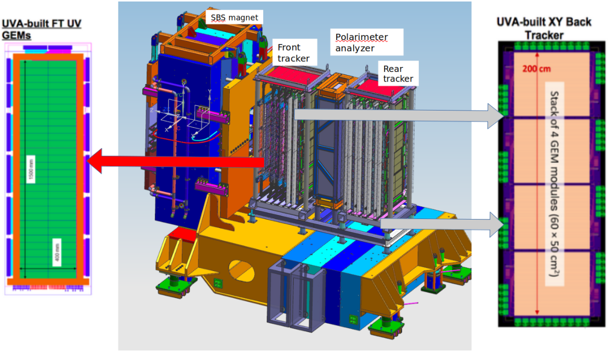



Figure: SBS in use as a proton polarimeter

- Out of 6 layers of $150 \times 40\ cm^2$ 4 are UV and 2 are XW (new)

## Triple GEM detectors

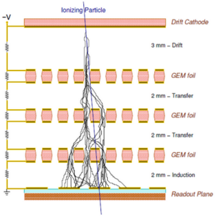



Figure: Cross section of a Triple GEM detector

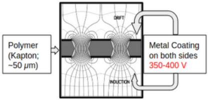



Figure: Cross section of a Triple GEM detector

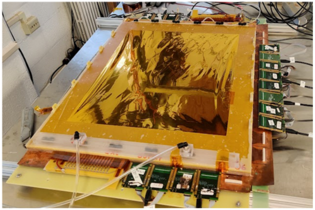


Figure: SBS 50cm x60cm module

- Using 3 GEM foils back to back to increase the gain (roughly 20 per foil $\rightarrow$20 X 20 X 20 = 8000 )
- Capabilities
  - High spatial resolution : 70 $\mu m$
  - Can handle high background rate : 500 $kHz/cm^2$
- However, HV supply uses a low cost resistive divider which is a limitation

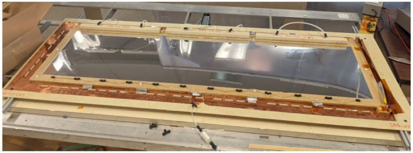
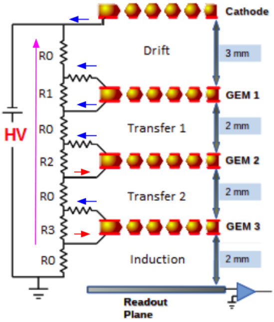


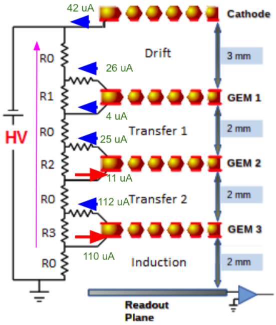
Figure: UV 40cm x 150cm module

# Difficulty in maintaining the electric field strength in the GEM

At lower rates




At higher rates




- Currents in and out of the GEM electrodes increase with the rate
- They severely alter the HV distribution at higher rates
- Voltage drops in protective resistors further weakens the electric field in GEM holes
- Reduced electric field in GEM holes directly leads to gain drop of GEM module

# Efficiency drop in $G_M^n$ Experiment

## GEM Efficiency significantly drops as beam current increasing

- At GMn the rates were 3x higher than the simulations making the efficiency drop much more severe than expected
- Having 10x more luminosity in GEp-V would be much severe

## Possible causes

- High voltage (HV) power supply using a resistive divider is limiting the appropriate field strength in multiple regions in GEM module
- High rates increase the difficulty for tracking

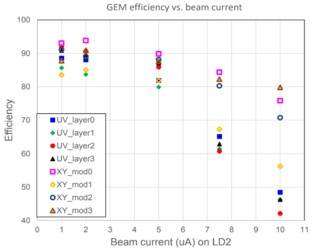
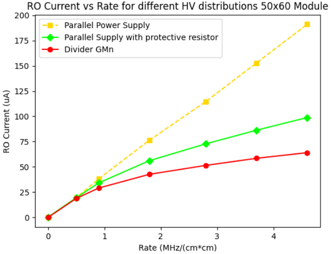


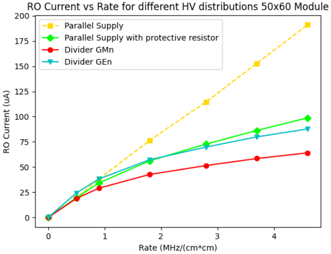

Figure: Efficiency drop with the beam current (GMn data)

## Solutions to restore the Field

- use of individual power channels (expensive)
- modify dividers
- an active HV divider

- Individual Power Channels (Parallel power supply) (CAEN DT1415ET)
  - Inefficiency of the divider is lifted. Only the effect of protective resistors remain
- Modified Resistive Divider (Divider GEn)
  - Reduce the resistance by a factor of two to reduce the ratio between currents in and out for the electrodes and the main current through the divider
  - 10 percent increase across GEM3 to compensate for the voltage drop
- Gain of the detector is proportional to the gradient of the graph




| Resistive Divider | | |
|---|---|---|
| Resistor (Ohm) | Divider GMn | Divider GEn |
| R0 | 850 | 425 |
| R1 | 550 | 275 |
| R2 | 500 | 250 |
| R3 | 450 | 250 |

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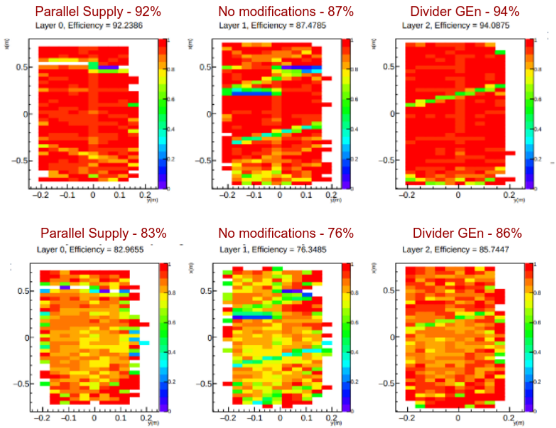
# Efficiency maps at JLab

Low beam current on Carbon foil target

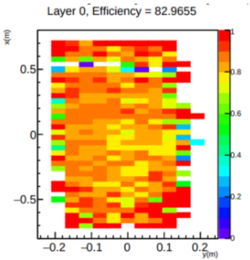
30 $\mu A$ of beam current on $^3He$ target



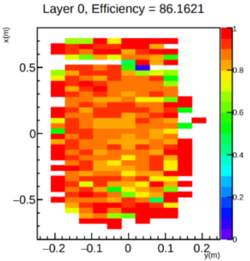

- During GMn front layers dropped below 60 percent efficiency at a beam current of 10$\mu A$ on Liquid Deuterium
- No HV modification on layer 1 - largest efficiency drop
- Layer 0 is the front most layer - on parallel power supply
- Layer 2 uses the modified divider

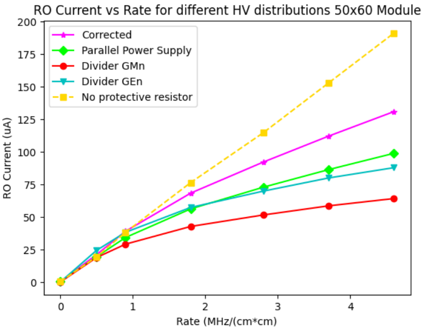
# Combining parallel power supply and corrections

before




after




- Applying the corrections help to recover some of the efficiency lost
- Efficiency maps are for $30\mu A$ of beam current on $^3He$ target
- Luminosity scans are required to further study the behaviour

# Summary and Future Work

- High rate studies
  - GEMs lose efficiency when exposed to high rates
  - All the solutions tested at UVA were implemented at $G_E^n$ Experiment
  - Hopefully we are in good shape for $G_E^p$-V
- Finish tracking detector commissioning work for $G_E^n$-RP and $G_E^p$-V
- Start working on physics analysis and simulation to investigate the rate mismatch

- Our UVA group members : Nilanga Liyanage, Huong Nguyen, Xinzhan Bai, Siyu Jian, John Boyd, Sean Jeffas, Bhashitha Thuthimal Dharmasena and Minh Dao
- SBS collaboration
- Jlab staff for continuous support
- US Department of Energy, Office of science, Office of Nuclear physics award number DE-FG02-03ER41240

# Backup Slides

# Test Setup at UVA to simulate high rates environment

- 10x10 $cm^2$ chamber is placed 40 $cm$ away from the xray source
- 50x60 $cm^2$ chamber is placed 70 $cm$ away from the xray source
- Both these chambers possess XY type readouts
- X-ray generator specifications
  - Photon energy range: up to 50 $keV$
  - Output flux: 56 $MHz/cm^2$ on the surface of GEM (50 $keV/1\ \mu A$)
- 0.5 percent of x-rays are converted into MIPs
- Charge deposition equivalent to MIP rate of 20 $MHz/cm^2$ can be reached
- Measurements :
  - Readout current which is analogous to the gain
  - Voltage at each electrode

Figure: X-ray gun pointed at a module

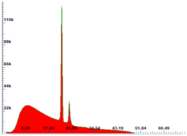



Figure: X-ray spectrum

# Estimated Rates

| particle and threshold | front chamber at 325 $cm$ | first rear chamber at 457 $cm$ | second rear chamber at 556 $cm$ |
|---|---|---|---|
| $\gamma$, 100 $KeV$ | 80,000 | 6,700 | 1,800 |
| $\gamma$, 300 $MeV$ | 140 | 12 | 5.5 |
| $e^-$ ,1 $GeV$ | 0.3 | 0.05 | 0.02 |
| $e^+$ ,1 $GeV$ | 0.2 | 0.03 | 0.01 |
| $\pi^-$ ,1 $GeV$ | 8 | 1.2 | 0.54 |
| $\pi^+$ ,1 $GeV$ | 14 | 2.1 | 0.95 |

Table 1: Estimated rates in $kHz$ per $cm^2$ at different distances from the target for different particles integrated above the given thresholds; for 40 $cm$ LH target and 75 $\mu A$

Figure: GEp-V rates

Table 8: Predicted coincidence rates (counts per hour)

| $Q^2$ (GeV/c)$^2$ | 3.5 | 4.5 | 6.0 | 8.5 | 10. | 12. | 13.5 | 16. | 18. |
|---|---|---|---|---|---|---|---|---|---|
| $d(e,e'p)$ | 40700 | 26600 | 3110 | 1345 | 1240 | 244 | 56.7 | 47.0 | 7.9 |
| $d(e,e'n)$ | 17600 | 12000 | 1600 | 627 | 580 | 114 | 26.5 | 22.0 | 3.72 |
| $p(e,e'p)$ | 273000 | 82000 | 9300 | 4400 | 5000 | 850 | 200 | 175 | 30 |
| $p(\gamma,\pi^+n)$ | 2920 | 4030 | 13500 | — | — | — | — | — | — |

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Figure: GMn rates

# Current GEM tracking layer commissioning at Jefferson Lab

- Last two side polarimeter layers for the $G_E^n$-RP is being commissioned
- All the side polarimeter layers will be moved to the Hall during the summer
- Most of the high voltage upgrade will happen before the second run of $G_E^n$-II
- Tracking inefficiencies caused due to hardware issues will be mitigated

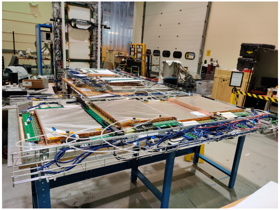


Figure: Completed layer

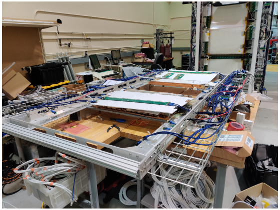


Figure: Layer in the work

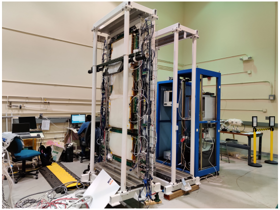
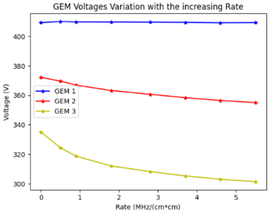


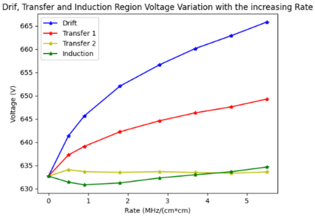
Figure: Vertically mounted layers

# Changes in voltage distribution due to the increasing Rate

## Observations

- Voltage across drift, and the first transfer region goes up noticeably
- GEM 3 loses a significant amount of voltage
- Effect is less severe in GEM 2 and GEM 1



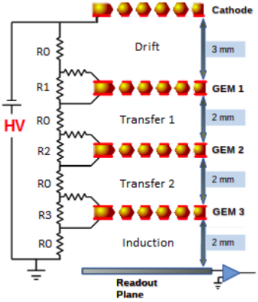
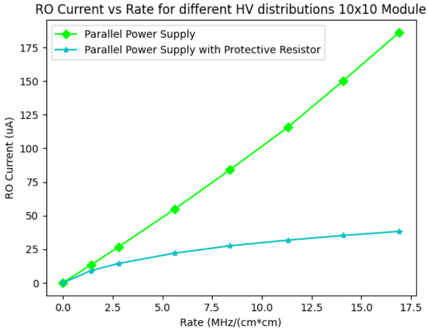
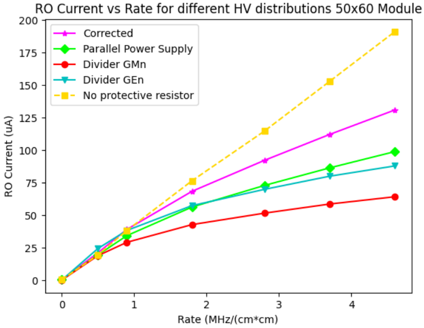




Figure: Triple GEM regions

# Impact from protective resistors




- protective resistors were bypassed when parallel power supply was used

- protective resistors were still in use when the parallel power supply was used
- even with parallel power supply still the current is not linear, but we can correct for that

# Active Divider

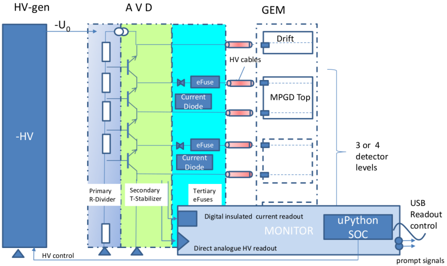



Figure: AVD Schematic

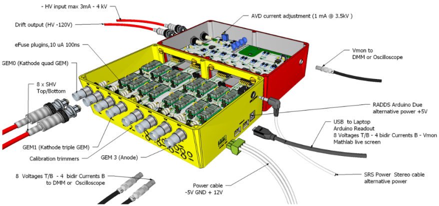
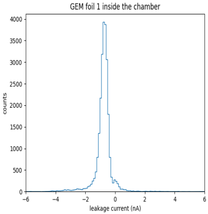


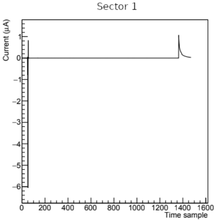

Figure: AVD Schematic

Credit : Hans Muller and his group at Cern

- we are going to give this a try too
- parallel power supply is the best solution but expensive




Leakage current distribution

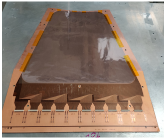



Current profile of good sector

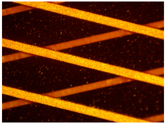
## Steps involved in building the prototype

- Visual inspection of the GEM foils and the readout
- Sector High voltage testing of the GEM foils
- Preparation of the frames
- Stretching and gluing foils to the frames
- Assembling the triple GEM detector
- Complete the high voltage distribution
- Ready for testing

Setting up sector HV test



MOLLER readout

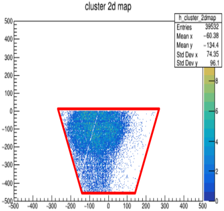


Microscopic image

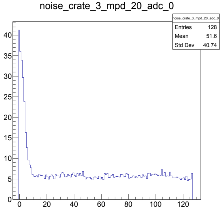
# Prototype Detector for MOLLER Experiment -Testing

Moller prototype in testing

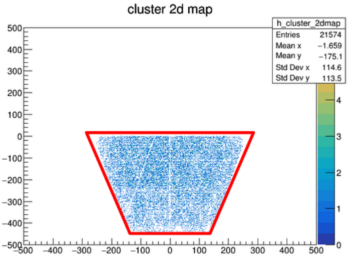
- Shielding serves the purpose of noise reduction
- Cosmic and X-Ray data to verify the functionality
- Readout design optimization to avoid noisy channels
- SRS readout was used for data acquisition



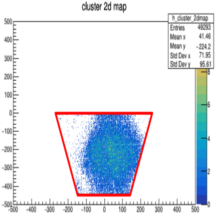

X-Ray 2-D hit map




Noisy strips




Cosmic 2-D hit map




X-Ray 2-D hit map

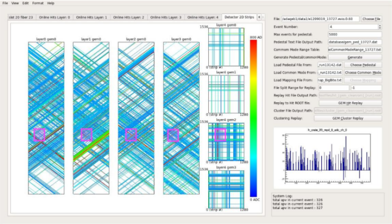
- 5 GEM layers out of electromagnetic field, high rate, large quantity of combinations

**Tracking algorithm in a nutshell:**

- Perform 1D clustering of strips along each dimension in each GEM chamber
- Form all possible 2D combinations within calorimeter-defined region
- Divide each tracking layer into a uniform 2D rectangular grid, accumulate a list of 2D hit candidates in each grid bin (bin size 1 x 1 $cm^2$)
- Loop all possible combinations from hits in outermost layers (within search region)
- Form straight-line projection
- Loop all possible combinations from each inner layer (minimum 3 layers)
- Find the hit combination with best $X^2$/ndf

Tracking algorithm credit goes to **Prof. Andrew Puckett and Dr. Weizhi Xiong**

What we're up against, II (run 13727, 12 uA LD2, $Q^2 = 4.5\ GeV^2, E = 4\ GeV$)




- This is the same event as previous slide, but requiring max ADC sample on a strip greater than 100, a typical offline threshold for cluster maxima that is higher than online threshold

□ = approximate size of calorimeter-constrained track search region at each layer

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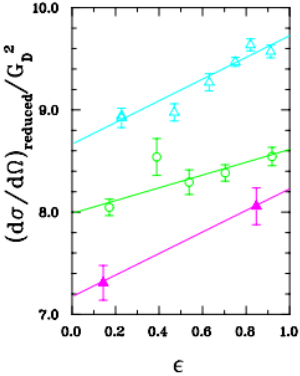
Slide courtesy of Prof. Andrew Puckett

$$\left(\frac{d\sigma}{d\Omega}\right)_{reduced} = \frac{\epsilon(1+\tau)}{\tau}\left(\frac{d\sigma}{d\Omega}\right)_{exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = G_M^2 + \frac{\epsilon}{\tau}G_E^2, \qquad (13)$$

where $(d\sigma/d\Omega)_{exp}$ is a measured cross section. A fit to several measured reduced cross section values at the same $Q^2$, but for a range of $\epsilon$-value, gives independently $\frac{1}{\tau}G_{Ep}^2$ as the slope and $G_{Mp}^2$ as the intercept, as shown in Fig. 3; the data displayed in this figure are taken from [And94].



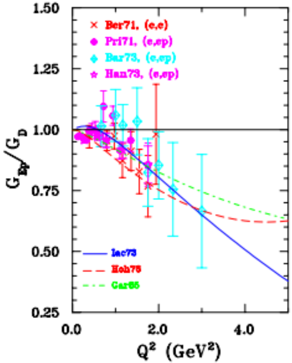




Figure 3: Demonstration of the Rosenbluth separa-

Figure 4: Early Rosenbluth separation data for $G_{...}$

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