Triple-GEM based Polarimeter Tracker for the High-Q^2 Proton Form Factor Measurement (GEp-V) at Jefferson Lab

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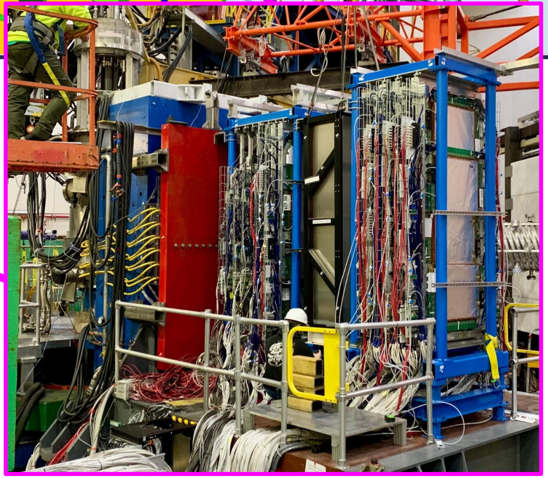
Overview

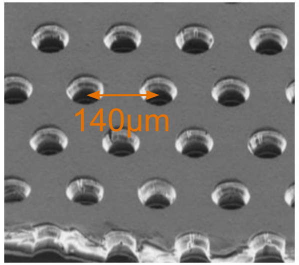
- Super Bigbite Spectrometer(SBS) GEp-V experiment and motivation for GEM based tracking detectors.
- Introduction to Triple-GEM based tracking detectors.
- Triple-GEM based polarimeter tracker for GEp-V.
- Detector Performance during the experiment.
- Recoil Proton Polarimetry and the role of GEM-based tracker.

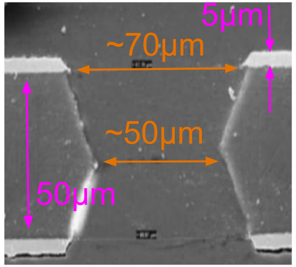
SBS GEp-V Experiment and Motivation for GEM Tracking

- The SBS GEp-V experiment will provide precision results for proton electromagnetic form factor ratio G_E^p/G_M^p up to 11 GeV^2.
- Recorded data for two kinematic points.
  - Q^2 = 5.7 GeV^2 and Q^2 = 11.1 GeV^2.
- High momentum transfer in the scattering requires the tracking detectors to have.
  - Large solid angle acceptance.
  - High-rate withstanding capabilities up to ~500kHz/cm^2.
  - Excellent spatial and timing resolution.
- Gas Electron Multiplier (GEM) detectors provide an effective solution.
  - They can handle high rates up to few MHz/cm^2.
  - Intrinsic spatial resolution < 70 μm.
  - Intrinsic timing resolution < 10 ns.
  - Large area coverage capability.
  - Low thickness minimizing the multiple scattering.

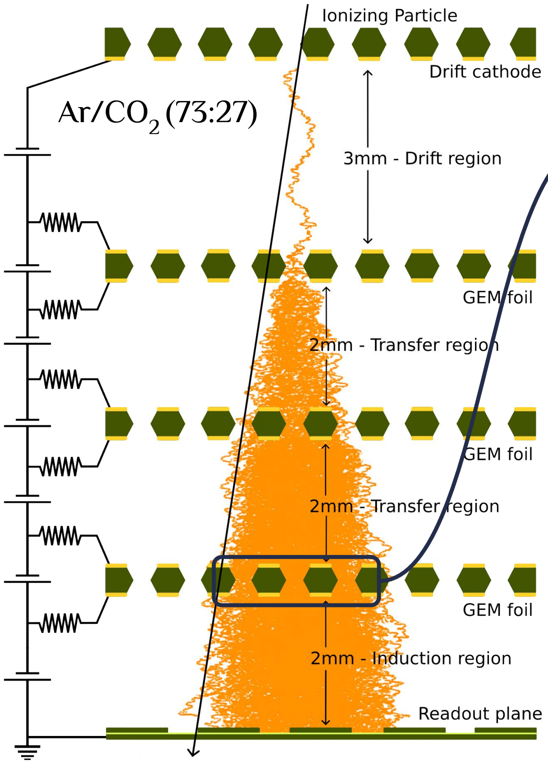


GEM Working Principle and Triple-GEM Detectors

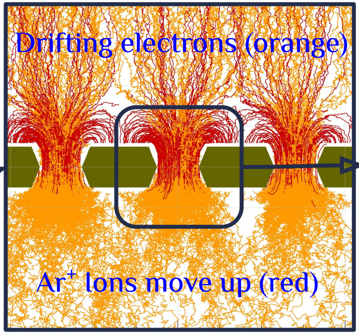


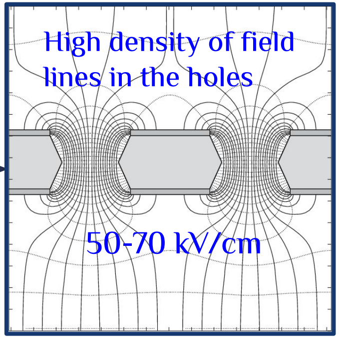


- Invented by physicist Fabio Sauli in 1997 (*Sauli, F., NIM A 386 (1997) 531*).
- A GEM foil has two copper layers separated by a Polyamide film.
- Chemically etched to produced bi-conical holes.
- High voltage applied between copper layers induces a strong electric field within the hole.



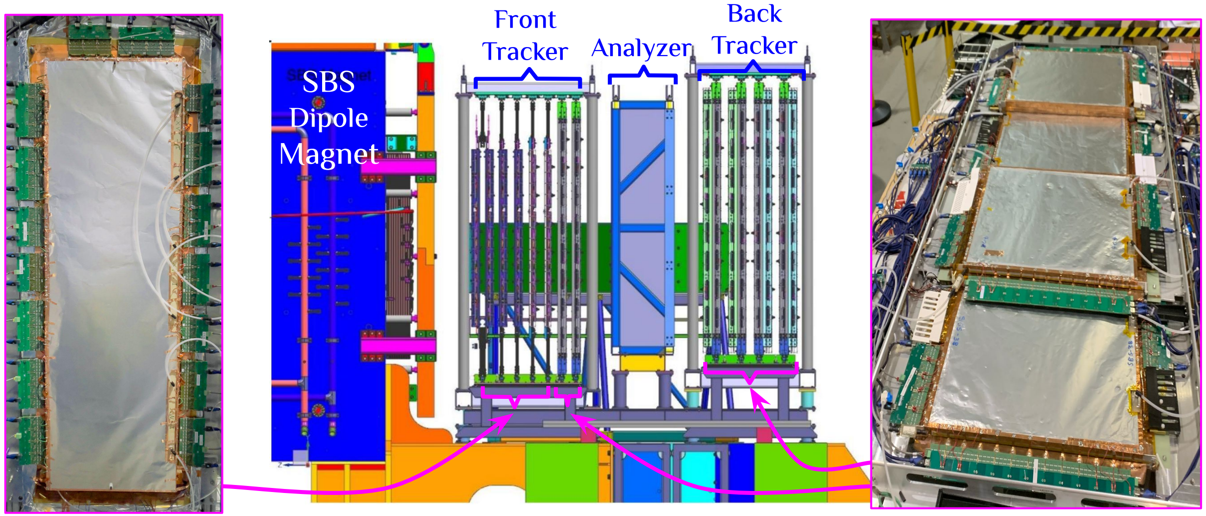
Charge amplification is separated from charge collection → Multi-stage amplification.





- Incident particle ionizes the gas in the drift region and generates primary electrons.
- Electrons moving through GEM holes are multiplied (about x20 per layer) due to strong electric field.
- An avalanche of electrons moving towards the readout plane induce a signal.
- A 2D strip readout in a GEM detector measures both X and Y coordinates of a particle hit.

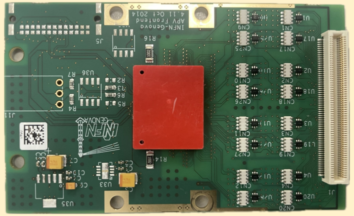
Triple-GEM Based Polarimeter Tracker



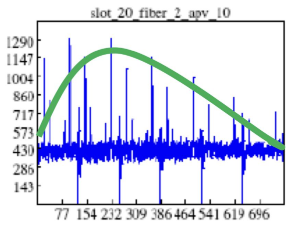
UV/XW layer
40 x 150 sq.cm
Single Modules

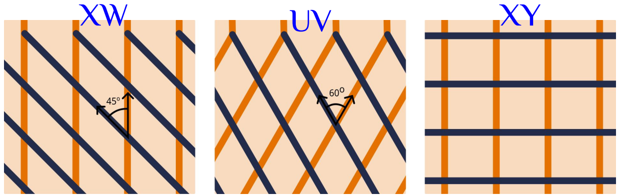
XY layer
Four Modules of
60 x 50 sq.cm each

- 46 GEM modules in Total - Designed and fabricated at UVa.
- Front Tracker:
  - 6 GEM layers of active area 40 x 150 sq.cm.
  - 2 GEM layers of active area 60 x 200 sq.cm.
- Back Tracker (Focal Plane Polarimeter)
  - 8 GEM layers of active area 60 x 200 sq.cm.
- Optimised shorter readout strip geometries in single modules to minimize signal degradation.



- APV25 based front-end readout electronics.
- 6 times samples.
- 150ns sampling window.

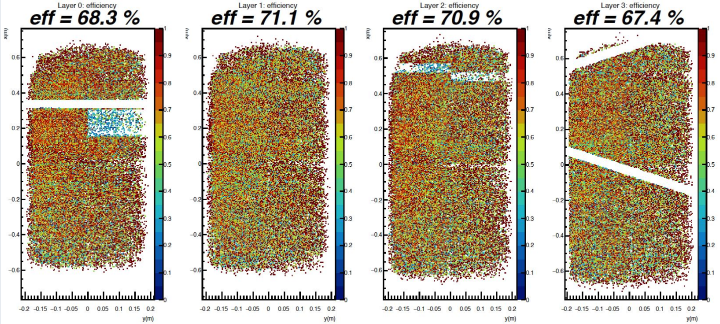




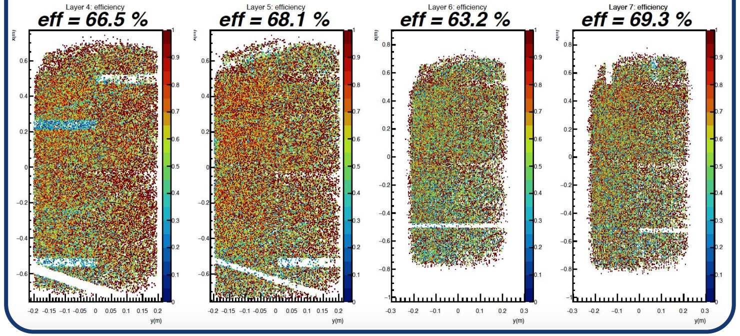
Readout Strip Orientations

GEM Detector Performance during SBS GEp-V Experiment

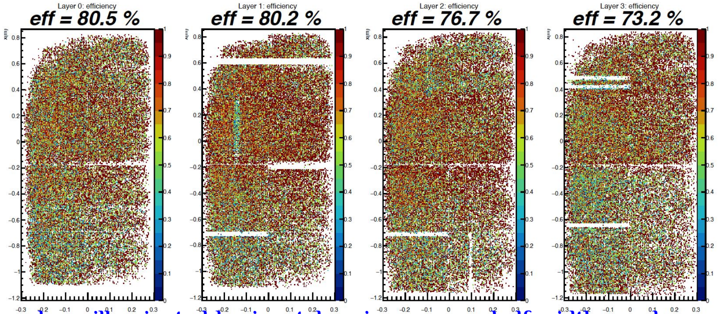
Front Tracker efficiencies (Q^2 = 11.1 GeV^2)



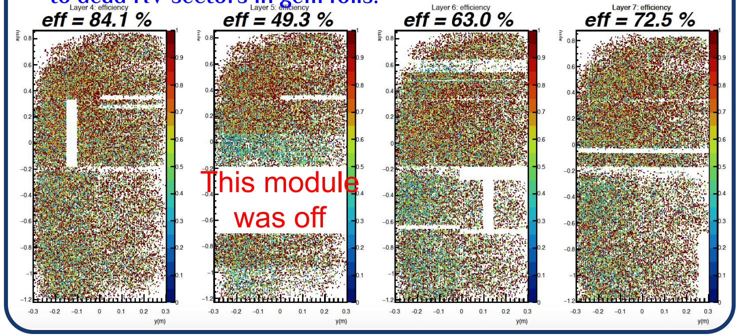
Empty regions are due to readout electronic malfunctions.

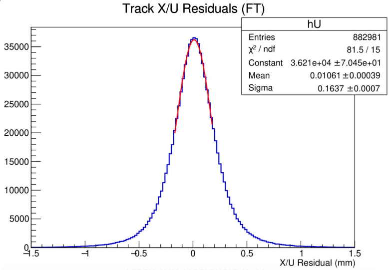


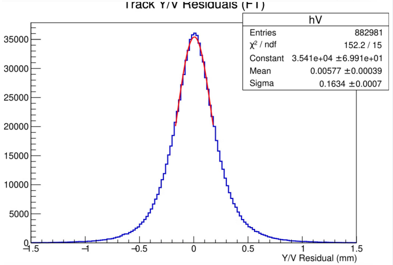
Back Tracker efficiencies (Q^2 = 11.1 GeV^2)



Less illuminated horizontal regions across half width are due to dead HV sectors in gem foils.







Intrinsic track residuals for the FT (Q^2 = 11.1 GeV^2)

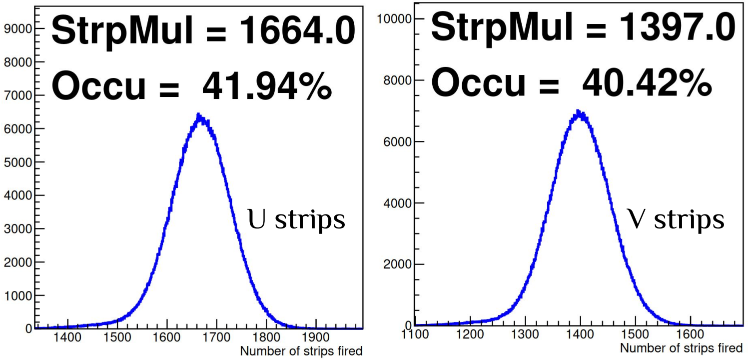
(σ_x, σ_y) ~ 164μm, 163μm

- Plots above show the first look into to the track-based efficiencies of the both front and back trackers.
- Proton tracks used here have passed a series of coincident ECal and HCal timing cuts, GEM track quality cuts, and calorimeter energy and position matching cuts, in order to select elastic *ep* events.

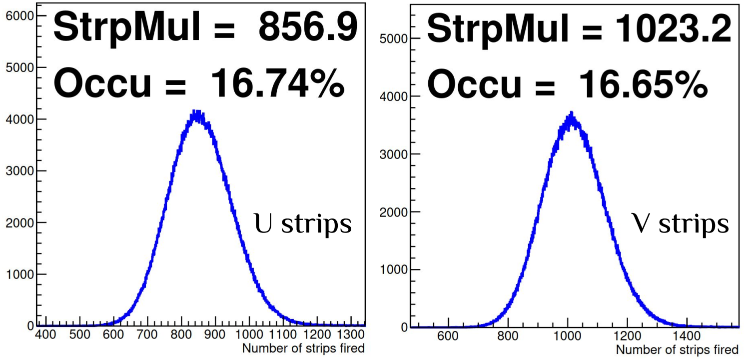
Tracking is a Challenge

- High raw strip occupancy in FT due to soft photon background of rate ~500 kHz/cm^2
- Partially overlapping background with primary hits make tracking harder.

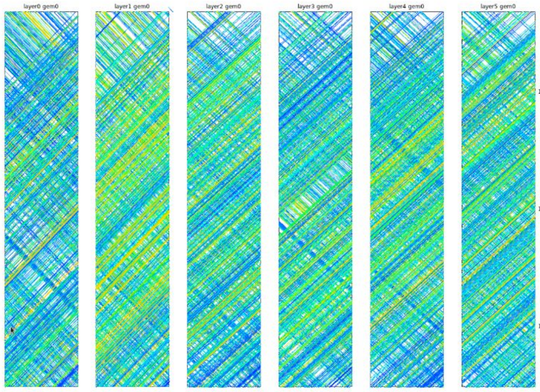
Raw strip occupancies of FT Layer 1

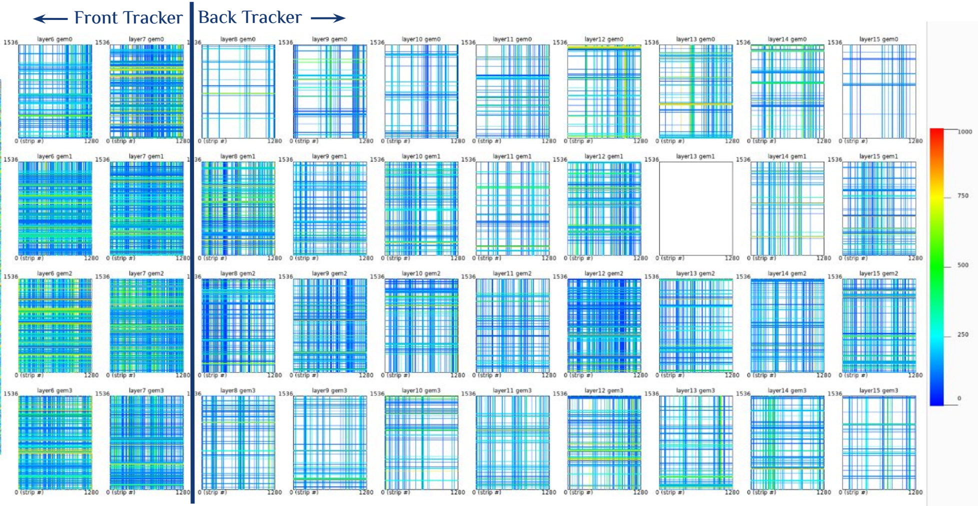


Raw strip occupancies of FPP Layer 1



Illuminated lines are strips fired during single 150ns sample window.





Anu will talk about tracking in detail!

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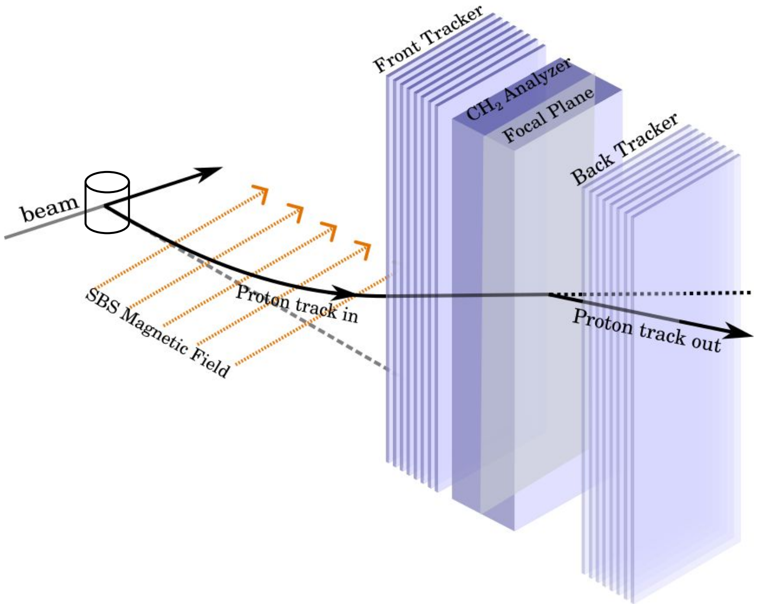
Why do we need two separate precision GEM Trackers?



- A longitudinally polarized electron beam scattered off an unpolarized liquid Hydrogen target.

- Eight GEM layers in the Front Tracker:
  - Reconstruct the proton's momentum after the deflection in the SBS magnetic field.
  - Front tracking defines the incident trajectory at the Focal Plane.

- Secondary scattering in CH_2 analyzer.

- Eight GEM layers in the Back Tracker (FPP):
  - Measure the proton's trajectory after secondary scattering in the CH_2 analyzer.

- Front and back tracks define polar and azimuthal angles of the secondary scattering.

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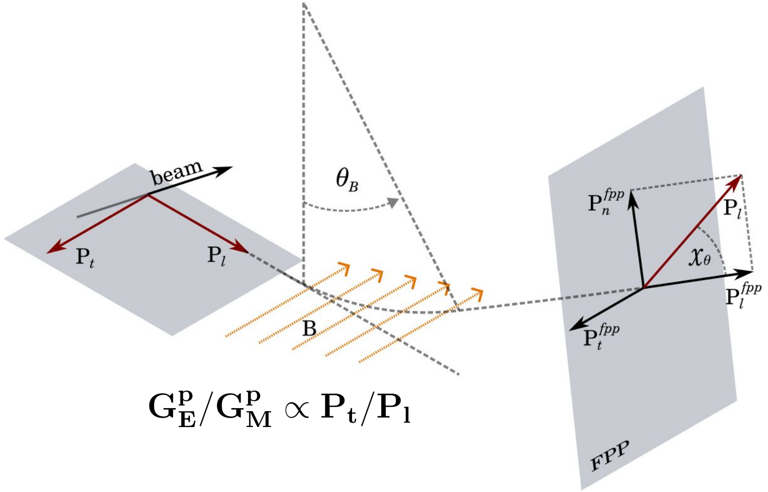
Recoil Proton Polarimetry

- Spin-polarized ensemble of electrons impart net polarization to the scattered ensemble of protons.

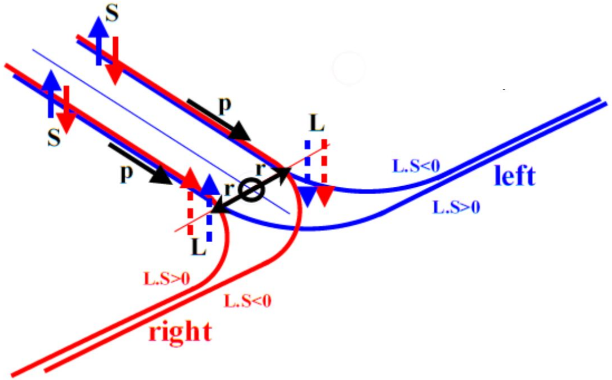


$$G_E^p/G_M^p \propto P_t/P_l$$

- Polarization component can be measured through a suitable secondary scattering.
  - The Recoil Proton Polarimetry is based on the spin-orbit coupling of the proton-nucleus in secondary scattering.

(Akhiezer & Rekalo, *Dokl. Akad. Nauk SSSR* 180 (1968))

- The spin orbit force has the form $\mathbf{L}\cdot\mathbf{S}$
  Since $\mathbf{L}\cdot\mathbf{p}=(\mathbf{r}\times\mathbf{p})\cdot\mathbf{p}=0$, spin-orbit force is insensitive to $\mathbf{P}_l$.
- Spin precession in the magnetic field of SBS rotates $\mathbf{P}_l$ to a transverse component.
- The spin-orbit force preferably deflects the proton in the direction $\mathbf{p}\times\mathbf{S}$ (parallelly or anti-parallelly based on the sign of $\mathbf{L}\cdot\mathbf{S}$).



C.F. Perdrisat et al., PSTP 2013, UVA.
https://discovery.phys.virginia.edu/research/groups/PSTP2013/Talks/PSTP2013_talk_perdrisat.pdf

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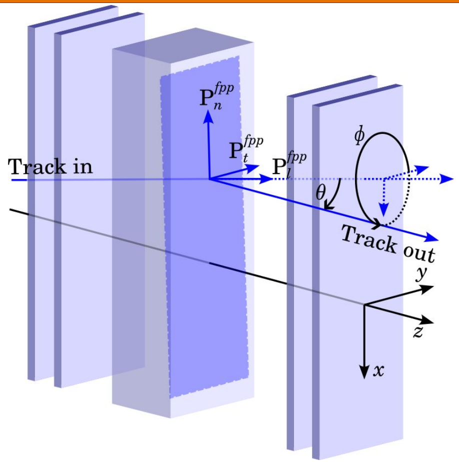
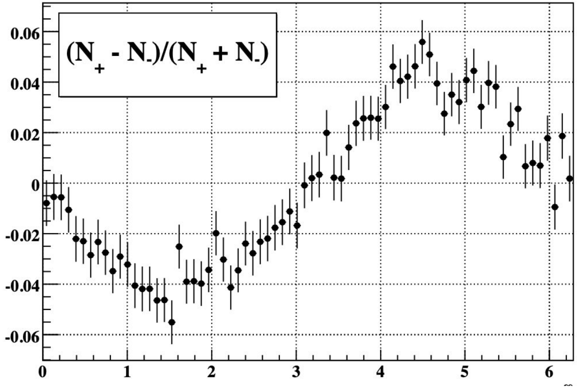
Recoil Proton Polarimetry Continued...





Example from GEp-III (Puckett, A. J. R., *arXiv:1508.01456* (2015)).

- If one spin state is dominant, this creates an asymmetry in the azimuthal angular distribution of the secondary scattering.

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

Instrumental asymmetry that describes non-uniformities in detector response

For negative and positive helicity states

Carbon analyzing power

- Fit the distribution to obtain polarization components simultaneously.

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

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

Precession angle

Fringe field correction

μ_p — proton magnetic moment, E_e — incident beam electron energy

E_e' — scattered electron energy, θ_e — electron scattering angle, M_p — proton mass

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Overview and Upcoming Work

- SBS GEp-V experiment uses the Recoil Polarization technique to obtain the proton electromagnetic form factor ratio G_E^p/G_M^p.

- The Triple GEM-based polarimeter tracker demonstrated reliable and stable performance even at unprecedented rates.

- Initial tracking efficiencies: FT layers 60%-70%, FPP layers 70%-80%; improvements anticipated with optimized reconstruction.

- Ongoing work on GEM detector calibrations and tracking reconstruction improvements.

Acknowledgements

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- US Department of Energy, Office of Science, Office of Nuclear physics award number DE-FG02-03ER41240

Thank You!

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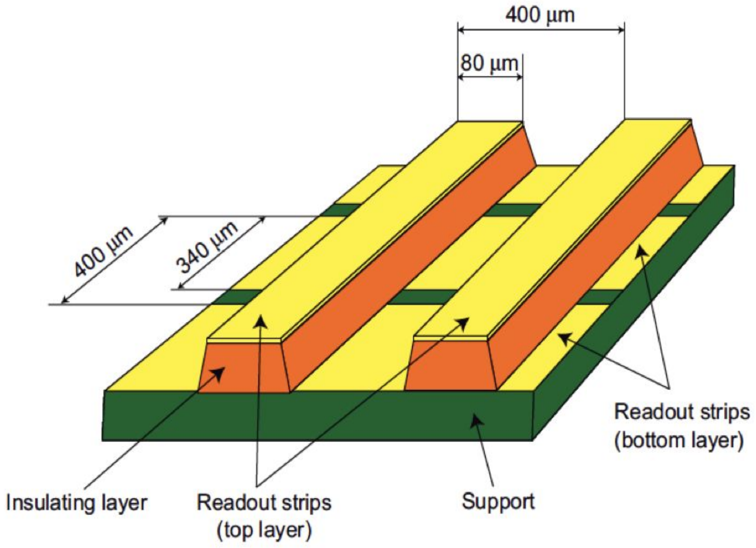
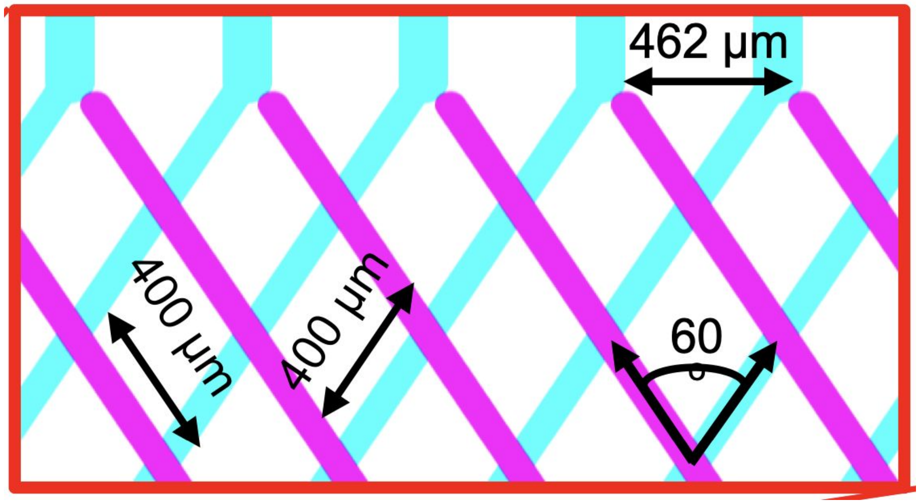
Backup Slides



COMPASS X-Y strip readout



Avalanche multiplication occurs in all gases, but effective operation needs a specific *gas mixture*.
Desired properties of a good mixture:

- Low working voltage (low ionization potential)
- Stable high-gain operation
- High rate capability (fast recovery)
- Good proportionality

Noble gases (e.g., Ar, He, Ne, Kr, Xe) are the are a good choice because they have no molecular structure. So there is no energy absorption in collisions.

Argon produces more primary ionization than He or Ne; Kr and Xe are even better but expensive.

But, pure argon is unstable at high gain due to:

- High excitation energy (11.6 eV) → emission of energetic UV photons.
- UV photons cause photoemission from the cathode → secondary avalanches.
- Leads to self-sustaining discharge (breakdown).

Adding polyatomic gases (e.g. CH_4, isobutane, CO_2) improves stability because they have many non-radiative vibrational and rotational modes that absorb energy.

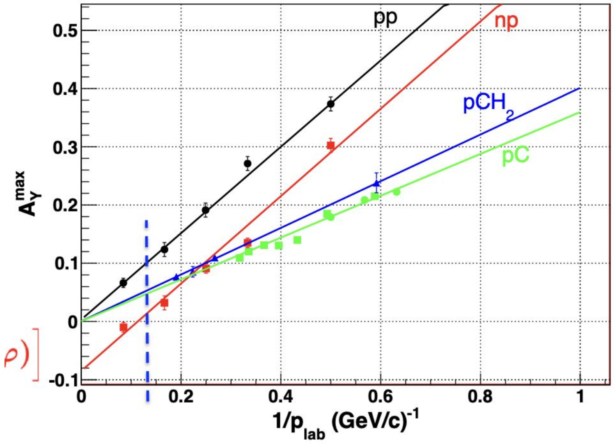
This quenches UV photon emission, preventing secondary avalanches.

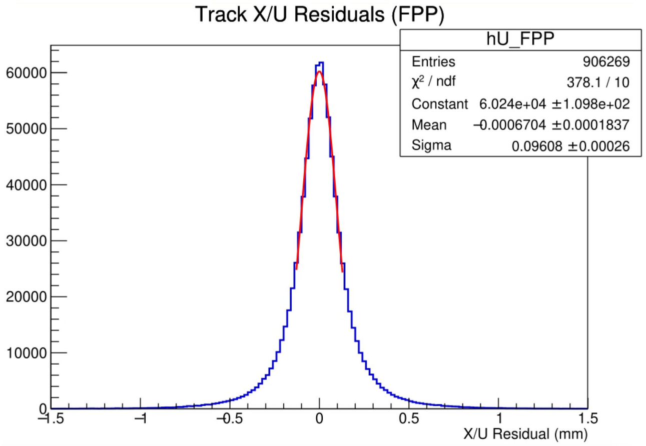
- In the Ideal Dipole Approximation:

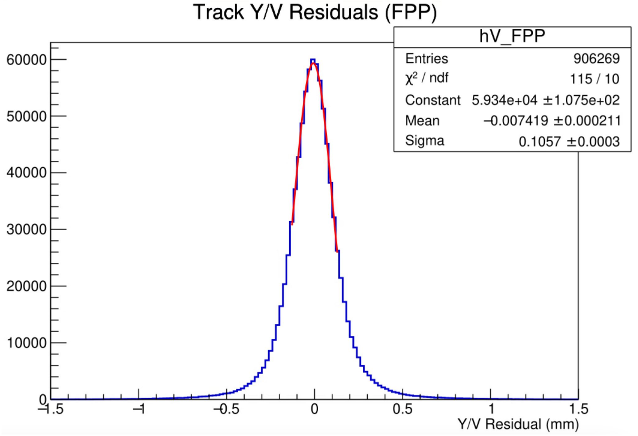
$$\chi_\theta \equiv \gamma \kappa_p \theta_{\text{bend}}$$

K_p - Proton's anomalous magnetic moment

A_Y analyzing power vs. inverse proton momentum







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