Two-Photon Exchange Contribution to the Electron-Neutron Elastic Scattering Cross Section and Data Calibrations for Gas Electron Multiplier Tracking Detectors

Ezekiel W. Wertz

October 28, 2022

Jefferson Lab
Exploring the Nature of Matter

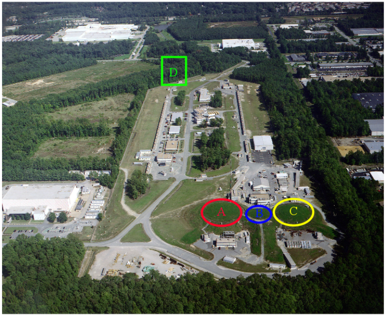
SUPER BIGBITE SPECTROMETER

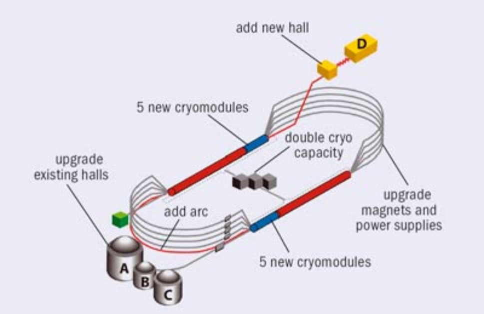
WILLIAM & MARY
CHARTERED 1693

NSF

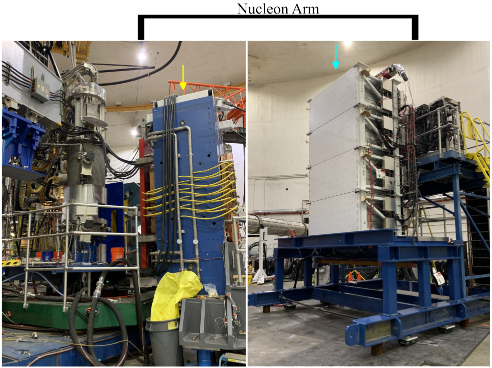
Jefferson Lab

- 12 GeV Electron Accelerator capable of conducting experiments simultaneously in 4 different Halls, located in Newport News Virginia and run by the Department of Energy
- Performed in Hall A

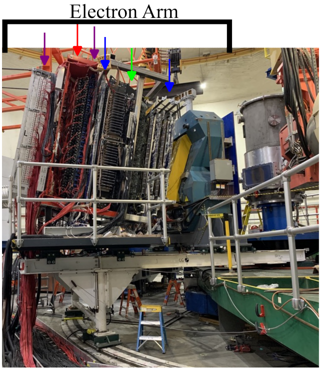




The Super BigBite Apparatus and Experiment Program



Super BigBite Spectrometer including Super BigBite Magnet and Hadron Calorimeter (HCal)

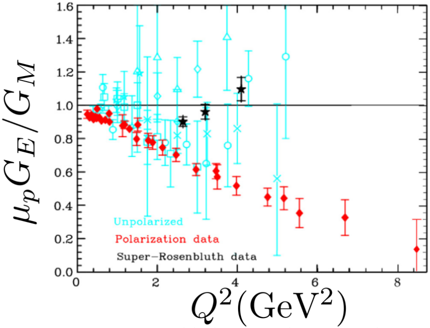


BigBite Spectrometer including GEMs, GRINCH, Calorimeters, and Timing Hodoscope

Completed Experiments: G_M^n, **neutron Two-Photon Exchange (nTPE)**

Future Experiments: G_E^n, G_E^n-RP, Pion A_{LL}, $G_E^p(5)$, and SIDIS

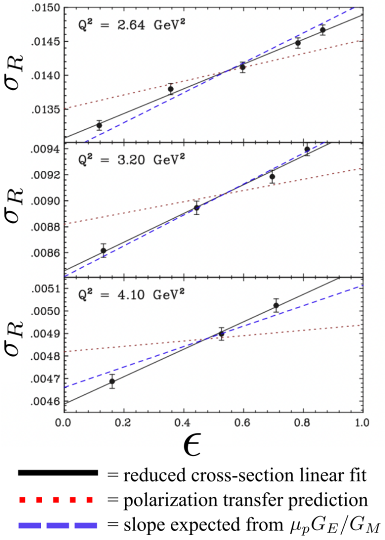
Proton Form Factor Ratio and Proton Two-Photon Exchange (pTPE)



Cyan = Rosenbluth Separation Extraction
Red = Polarization Transfer Measurements
Black = Super Rosenbluth

- Nucleon Form Factors (G_E, G_M) are fundamental observables describing the structure of the nucleon
- G_E/G_M as measured using cross-section data "Rosenbluth Separation" with a value of 1.0
- G_E/G_M as measured using polarization technique disagrees, especially at high Q^2 (3-4 sigma)
- Rosenbluth Separation is sensitive to TPE, while polarization technique is mostly insensitive. TPE could explain discrepancy
- Understanding TPE effects would provide a more complete characterization of G_E and G_M

Rosenbluth Separation for Nucleon Form Factors



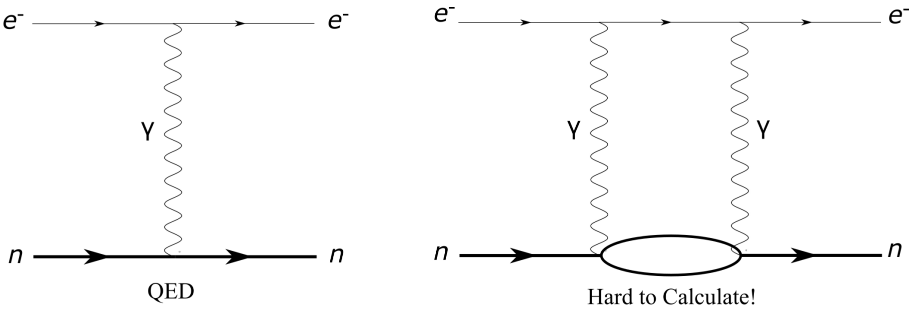
Measurement of Rosenbluth Separation used to extract proton form factors

$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha}{4MQ^2}\frac{E'}{E}\right)^2 |M_\gamma|^2$$
$$= \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left(\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right)$$
$$= \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\sigma_R$$

- $\frac{d\sigma}{d\Omega}$ is the differential Born cross-section for electron-nucleon scattering, with invariant amplitude M_γ.
- α is the fine structure constant.
- σ_{Mott} is the scattering for a point-like particle.
- ϵ is the longitudinal polarization of the virtual photon.
- $\tau \equiv \frac{Q^2}{4M^2}$. E and E' are initial and final state energies.

nTPE Cross Term Diagram

Interference of OPE and TPE diagrams contribute to the cross-section measurement and allow for extraction of TPE affects



One Photon Exchange and Two-Photon Exchange Diagram

nTPE Experiment in Hall A

- Contribution of TPE could reach 30% of the Rosenbluth Slope value at 5 $(\mathrm{GeV/c})^2$
- SBS nTPE experiment is first measurement of the Rosenbluth slope for the neutron using the ratio method
- Data taken in January & February 2022 for total of 19 days at $Q^2 = 4.5\ (\mathrm{GeV/c})^2$ and 2 different ϵ values
- Results will be limited by systematics and not statistics

Gas Electron Multiplier (GEM) detectors

- GEMs are a type of gaseous ionization detector reliant on the concept of electron avalanche and part of the subclass of detectors known as Micro-Pattern Gaseous Detectors (MPGDs)
- Used for tracking detectors, preamplification, drift chambers, time projection chambers, and radiation imaging
- Single detector gains are 10^3 or 10^4, depending on size and quality of GEM

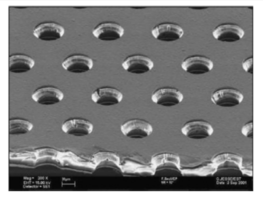


Diagram of a typical GEM electrode

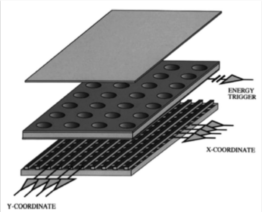
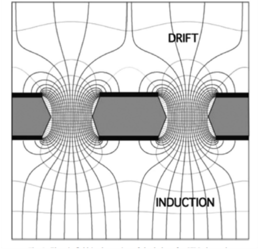
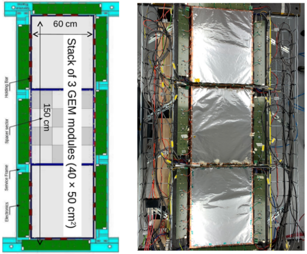


Diagram of a single GEM detector with Cartesian Readout

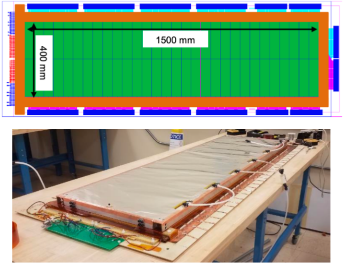


Electric Field in the region of the holes of the GEM electrode

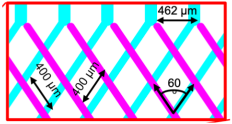
GEM Detectors for SBS Program



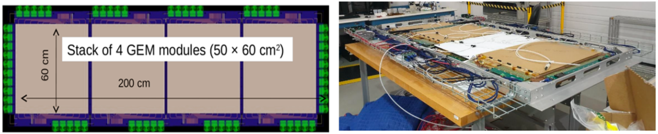
INFN XY-GEM Layer schematic and picture with RF shielding



UVA UV-GEM Layer schematic and picture with RF shielding



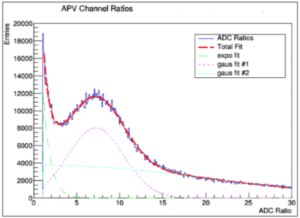
- 4 INFN XY-GEM layers prepared for SBS program
- 4 UVA UV-GEM layers prepared for SBS program
- 11 UVA XY-GEM layers prepared for SBS program
- 2 INFN GEM layers operated during nTPE
- 2 UVA UV-GEM layers operated during nTPE
- 2 more UVA UV-GEM layers moved to BigBite during nTPE



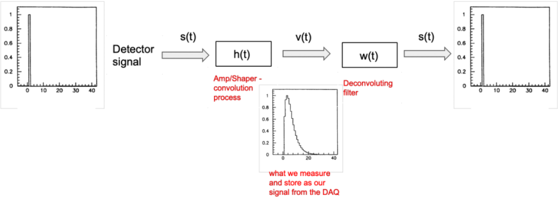
UVA XY-GEM Layer schematic and picture without RF shielding

UVA = University of Virginia, INFN = Istituto Nazionale Fisica Nucleare

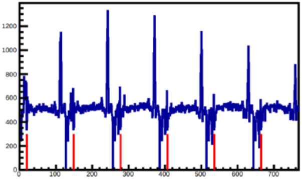
GEM Data Calibrations



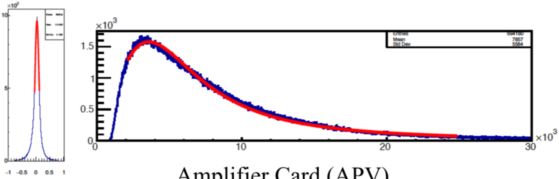
Crosstalk
Plot Credit: John Boyd
DJ.00001



Time Deconvolution
Plot Credit: Anuruddha Rathnayake
GJ.00004



Common Mode Fluctuation
Negative Pulse
Plot Credit: Sean Jeffas

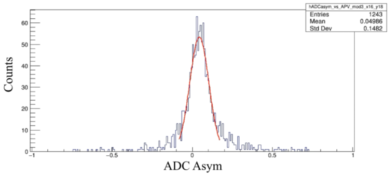


Amplifier Card (APV)
Gain Match
This Talk

Gain Match Pt 1

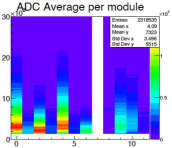
Goal of Gain Match: Compare signal amplitudes from amplifier cards (APV). Correct amplitude variations for each amplifier card by generating gain coefficients. Applying gain coefficients should improve the GEM track-based efficiency and detector resolution.

Compare 1 amplitude from different amplifier cards (sets of strips). For every event with a 'good' track, create a histogram for the ADC asymmetry ($\frac{ADC_{U/X}-ADC_{V/Y}}{ADC_{U/X}+ADC_{V/Y}}$) between every U/X and V/Y APV combination on a GEM module.

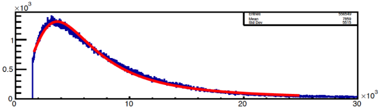


Gain Match Pt 2

For all events with a 'good' track ,on each module determine and plot the ADC Average $\left(\frac{ADCHit_{U/X}+ADCHit_{V/Y}}{2}\right)$

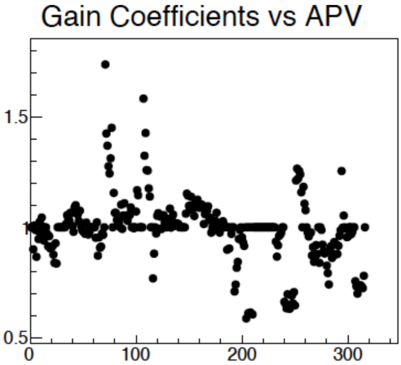


Generate ADC distributions for all hits and ADC distributions per module and apply Landua fit

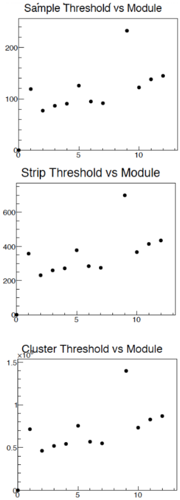


Determine the Target ADC value from the Mean Peak Value (MPV).Target ADC value will be used to determine the reference amplifier card and for determining coefficients.

Determine the APV in the U/X direction with the most statistics, use as a reference. Using a χ^2 minimization iteratively determine the relative iternal gain coefficients for each APV from the ADC asymmetries and the Target ADC value. Gain Coefficients vary from 0.5 to 2.0



Gain Match Pt 3



For each module, determine an average gain, sample, strip, and cluster thresholds.

Pipeline coefficients and thresholds to replay to see affect on GEM signals, Track Based Efficiencies, and resolution.
Initial Result: Track-Based efficiency improves by 2-4% from Gain Match

Gain Match

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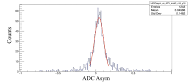

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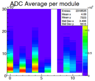
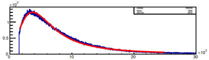


Generate ADC distributions for all hits and ADC distributions per module and apply Landau fit



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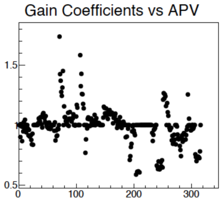

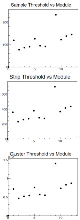

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Initial Result: Track-Based efficiency improves by 2-4% from Gain Match

Takeaway:

nTPE Summary:

- First measurement of Rosenbluth slope on the neutron. Sensitive to TPE effects.
- Data analysis is ongoing, first-pass underway
- nTPE measurement provides further understanding about nucleon form factors

GEM Gain Match Future Work:

- Finish first-pass creation of gain coefficients for GMn/nTPE data set
- Evaluate gain coefficients at different particle rates through the GEMs
- Evaluate gain coefficient stability over time
- Preliminary: Gain matching GEM signals increases Track-Based Efficiency by 2-4%

Acknowledgments

Funding: NSF, JSA Graduate Fellowship

Jefferson Lab Hall A Technicians and Staff

SBS Collaboration:

- Graduate Students and Post-Docs
- Core Group of Shifters
- INFN GEM group
- UVA GEM group
- SBS Spokespeople

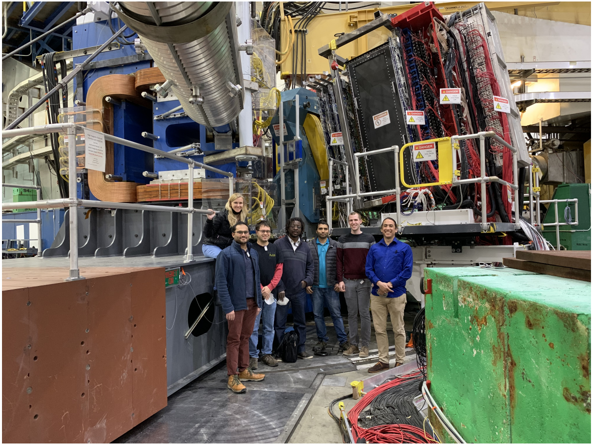
W&M Parity Group:

Advisor: David Armstrong

Graduate Students:

- Victoria Owen
- Ezekiel Wertz
- Kate Evans

Thank You!
Questions?



References I

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Measurement of the Two-Photon Exchange contribution to the electron-neutron elastic scattering cross section.
Jefferson Lab experiment proposal PR12-20-010, 2020.

[2] Fabio Sauli.
The gas electron multiplier (GEM): Operating principles and applications.
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 805:2–24, 2016.

[3] V Bellini et al.
GEM tracker for high luminosity experiments at the JLab Hall A.
Journal of Instrumentation, 7(05):C05013, 2012.

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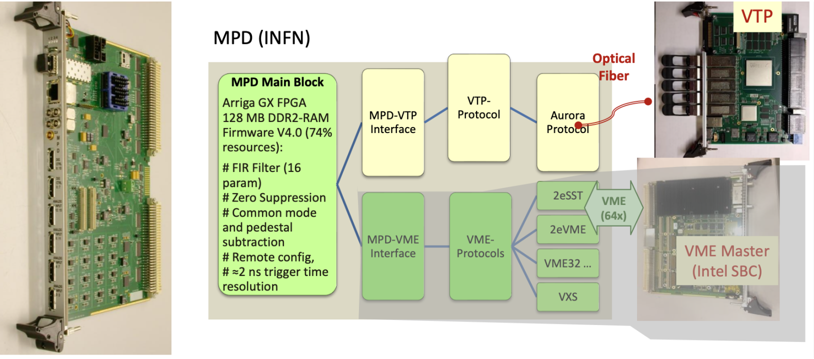
[4] S Bachmann et al.
Charge amplification and transfer processes in the gas electron multiplier.
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 438(2-3):376–408, 1999.

[5] Kondo Gnanvo et al.
Large size GEM for Super Bigbite Spectrometer (SBS) polarimeter for Hall A 12 GeV program at JLAB.
Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 782:77–86, 2015.

References III

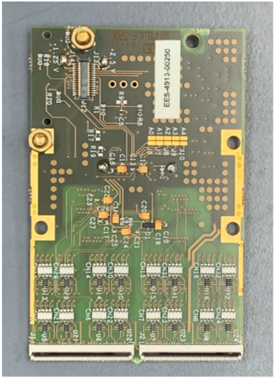
[6] A Afanasev, PG Blunden, D Hasell, and BA Raue.
Two-photon exchange in elastic electron–proton scattering.
Progress in Particle and Nuclear Physics, 95:245–278, 2017.

GEM Electronics Readout



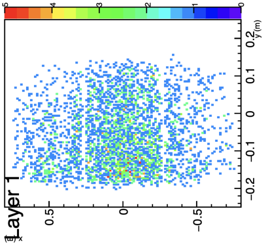
GEM Readout Electronics

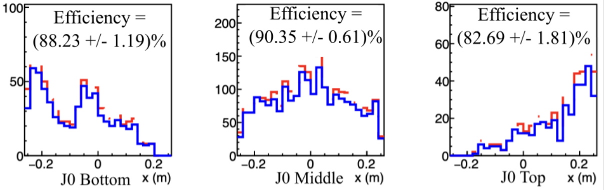
APV25 Card



APV25 Card, 128 Channels, 3.4 μs trigger latency, capable of sampling signal at 40 MHz, 100 kHz readout rate

INFN GEM Performance with Liquid Hydrogen (LH2) Target

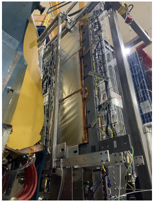




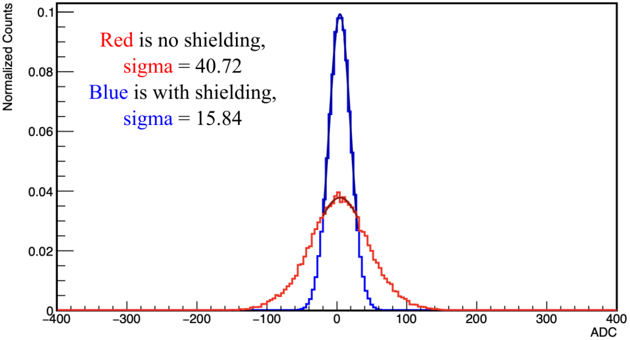
Red = Expected Hit
Blue = Observed Hit

Top: Two-Dimensional Cluster Map for layer J0 on LH2 at 1 μAmp beam current. Bottom: Track-Based Efficiencies on LH2 at 1 μAmp beam current

RF Shielding and Pedestal Improvement



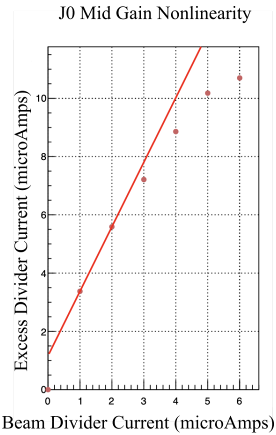
Top: INFN GEM layer no shielding. Bot: INFN GEM layer with shielding.

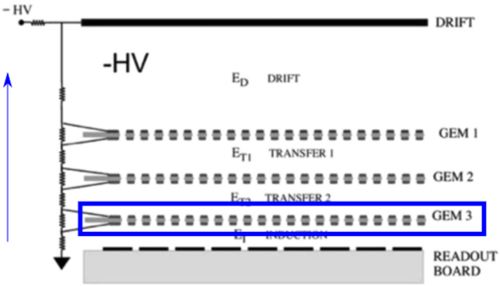


Example comparison of Common Mode baseline fluctuation, when in experimental Hall.

Installing RF aluminum shielding is critical as it reduced the common mode baseline fluctuation, that provides an acceptable detector signal to noise ratio.

INFN GEM Linearity Studies





High Voltage Diagram

- Nonlinear detector high voltage is caused by divider scheme. The divider moves current away from the 3rd GEM foil causing a sag in gain.
- GEM particle rates were high during G_M^n run period.

Lessons Learned for INFN GEMs

Improvements Made:

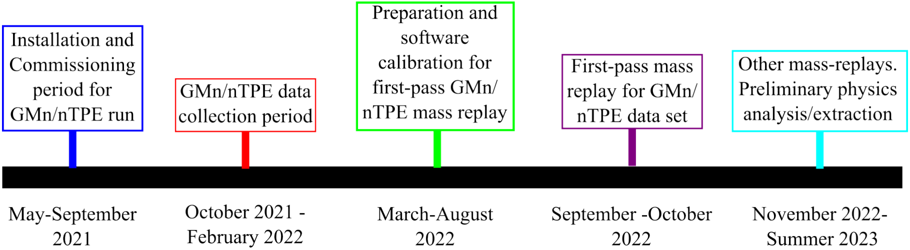
- RF (Aluminum) Shielding is important to reduce pedestal noise (common-mode corrections) and provide operable signal-noise detector conditions.

Future Improvements:

- To handle high particle rates the High Voltage divider will need to be designed for higher currents. This will reduce gain sagging effects.

Overall 5 out of the 6 INFN GEM modules had some sort of challenge during the G_M^n run period. So these occurrences need to be better understood for the remaining SBS program

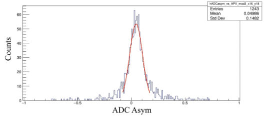
G_M^n/nTPE Timeline



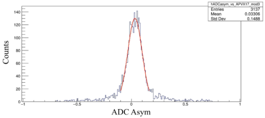
Gain Match Zoom 1

Start:

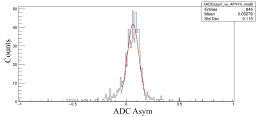
For every event with a 'good' track, create a histogram for the ADC asymmetry $\left(\frac{ADC_{U/X} - ADC_{V/Y}}{ADC_{U/X} + ADC_{V/Y}}\right)$ for:
Every U/X and V/Y APV combination on a GEM module.



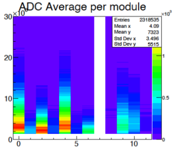
The ADC asymmetry for each U/X APV and all APVs on a GEM module.



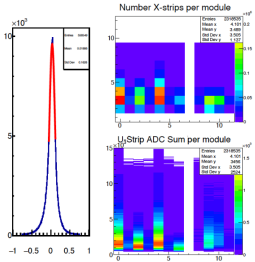
The ADC asymmetry for each V/Y APV and all APVs on a GEM module.



For all events with a 'good' track on each module determine and plot the ADC Average $\left(\frac{ADCHit_{U/X} + ADCHit_{V/Y}}{2}\right)$

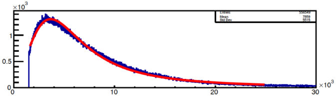


ADC asymmetry per module and other ADC Diagnostic Plots:

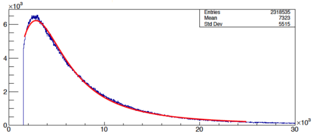


Gain Match Zoom 2

Generate ADC distributions for all hits and ADC distributions per module and apply Landua fit

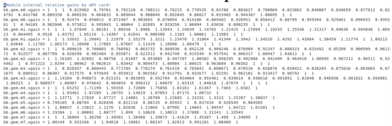


Determine the Target ADC value from the Mean Peak Value (MPV) of the Landau fit of the ADC Distribution for all hits..

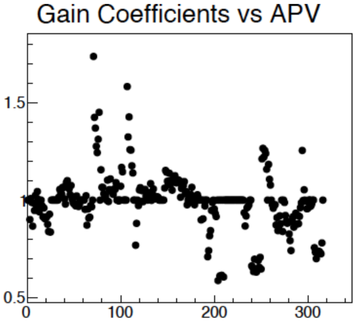


Determine the APV in the U/X direction with the most statistics, use as a reference. Using a χ^2 minimization iteratively determine the relative iternal gain coefficients for each APV from the ADC asymmetries and the Target ADC value.

Print APV gain coefficients to output file and create plots

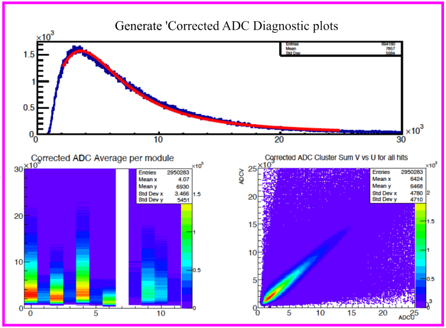


```
Module internal relative gains by APV card:
bb.gem.m0.vgain = 1  1  1  0.815962  0.79761  0.792128  0.780211  0.78215  0.778535  0.83788  0.865627  0.780869  0.823862  0.848887  0.836659  0.877812  0.82
4792  0.842708  0.889358  0.889539  0.864833  0.889844  0.900049  0.892645  0.86827  0.853985  0.944387  1.00095  1  1
bb.gem.m0.ugain = 1  1  0.92474  0.850013  0.872467  0.983683  0.870094  0.914106  0.869482  0.926951  0.856412  0.88799  0.959394  0.925861  0.898933  0.9393
81  1  0.94165  0.982046  0.973812  0.995043  1.00864  1.02895  0.929256  1.06994  1.03656  0.680235  1  1  1
bb.gem.m1.vgain = 1  1  1  1.07849  1.06161  1.08436  1.0986  1.13943  1.24639  1.14702  1.21425  1.27099  1.19335  1.25546  1.31317  0.99636  0.993848  1.084
23  0.864495  0.9526  1.03752  1.05119  1.14367  1.01641  0.980388  1.1103  1.00061  1.11983  1  1
bb.gem.m1.ugain = 1  1  1.33932  1.20941  1.21979  1.35279  1.3211  1.23478  1.31864  1.41344  1.3943  1.34529  1.4292  1.42664  1.38459  1.11774  1  1.09213
 1.03046  1.11705  1.08173  1.26998  1.17885  1.07667  1.11429  1.18908  1.08479  1  1  1
bb.gem.m2.vgain = 1  1  0.880619  0.760003  0.768502  0.863732  0.868936  0.842126  0.909246  0.876989  0.92347  0.880323  0.825492  0.85209  0.900599  0.8612
72  0.922577  0.867799  0.928299  0.982484  0.955871  0.921511  0.942749  0.915549  0.957541  0.966317  1.00947  1.04813  1  1
bb.gem.m2.ugain = 1  1.16185  1.02692  0.98758  1.01697  0.953085  0.947707  1.00502  0.956295  0.992988  0.942499  0.964918  1.00999  0.987211  0.96511  0.93
4462  1  0.971222  1.0294  1.00962  0.982615  1.03442  0.989473  1.00904  1.06615  0.963609  0.96562  1  1  1
bb.gem.m3.vgain = 1  1  0.828357  0.860443  0.771785  0.778174  0.761419  0.765041  0.808671  0.870316  0.828876  0.858422  0.830265  0.875016  0.863865  0.87
1675  0.886912  0.86487  0.917575  0.975645  0.955813  0.965562  0.912791  0.932677  1.02291  0.962101  0.913417  0.98792  1  1
bb.gem.m3.ugain = 1  1.14204  0.948873  0.815151  0.883095  0.932704  0.954064  0.955461  0.939014  0.936618  0.991091  1.01048  0.946956  0.981022  0.958981
 1.00323  1  0.980977  1.06907  0.976642  0.964054  0.999312  1.04079  1.03315  1.04018  1.07079  1  1  1  1
bb.gem.m4.vgain = 1  1  1.65252  1.71199  1.59359  1.72009  1.75056  1.83161  1.61367  1.7403  1.6501  1
bb.gem.m4.ugain = 1  1  1.03461  1.07285  1.20755  1.14819  1.07053  1.07175  1.08732  1
bb.gem.m5.vgain = 1  1.13771  1.17028  1.07727  1.14001  1.26709  1.22685  1.33291  1.3313  1.25207  1.30837  1
bb.gem.m5.ugain = 0.799165  0.80784  0.828456  0.822116  0.80135  0.85953  1  0.837434  0.920549  0.964585
bb.gem.m6.vgain = 1  1.08657  1.13812  1.1276  1.02836  1.11069  1.07995  1.14043  1.09547  1.04722  1.01581  1
bb.gem.m6.ugain = 1.19104  1  1.00091  1.08777  1.099  1.10628  1.10613  1.17888  1.21241  1.33543
bb.gem.m7.vgain = 1  1  1.36869  1.36298  1.49501  1.38468  1.39873  1.41626  1.45387  1.499  1.34099  1
bb.gem.m7.ugain = 1.00144  0.933166  1  1.04818  1.10081  1.08147  1.02913  0.991181  1.08489  1
```



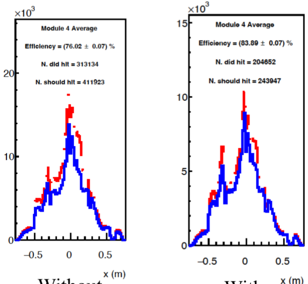
Gain Match Zoom 3

For each module, determine an average gain, sample, strip, and cluster thresholds.



Gain Match Zoom 4

Pipeline info toDatabase to see affect on ADC signals in GEM and Track Based Efficiencies



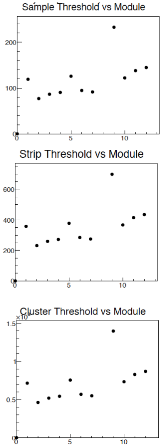
Without Coefficients

With Coefficients

Finish:

Print out module information. Create plots

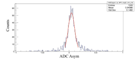
```
bb.gem.m0.modulegain = 1.00493
bb.gem.m0.threshold_sample = 119.138
bb.gem.m0.threshold_stripsum = 357.414
bb.gem.m0.threshold_clustersum = 714.828

bb.gem.m1.modulegain = 0.850227
bb.gem.m1.threshold_sample = 77.0525
bb.gem.m1.threshold_stripsum = 231.157
bb.gem.m1.threshold_clustersum = 462.315

bb.gem.m2.modulegain = 0.950809
bb.gem.m2.threshold_sample = 86.5102
bb.gem.m2.threshold_stripsum = 259.531
bb.gem.m2.threshold_clustersum = 519.061

bb.gem.m3.modulegain = 0.837287
bb.gem.m3.threshold_sample = 90.4981
bb.gem.m3.threshold_stripsum = 271.494
bb.gem.m3.threshold_clustersum = 542.989

bb.gem.m4.modulegain = 0.948182
bb.gem.m4.threshold_sample = 125.836
bb.gem.m4.threshold_stripsum = 377.507
bb.gem.m4.threshold_clustersum = 755.013

bb.gem.m5.modulegain = 1.0476
bb.gem.m5.threshold_sample = 94.7869
bb.gem.m5.threshold_stripsum = 284.361
bb.gem.m5.threshold_clustersum = 568.722
```



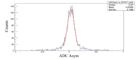
Gain Match

Start:

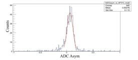
For every event with a 'good' track, create a histogram for the ADC asymmetry $\left(\frac{ADC_{U/X}-ADC_{V/Y}}{ADC_{U/X}+ADC_{V/Y}}\right)$ for:
Every U/X and V/Y APV combination on a GEM module.



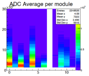
The ADC asymmetry for each U/X APV and all APVs on a GEM module.



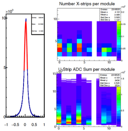
The ADC asymmetry for each V/Y APV and all APVs on a GEM module.



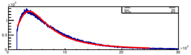
For all events with a 'good' track on each module determine and plot the ADC Average $\left(\frac{ADCHit_{U/X}+ADCHit_{V/Y}}{2}\right)$



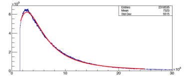
ADC asymmetry per module and other ADC Diagnostic Plots:



Generate ADC distributions for all hits and ADC distributions per module and apply Landau fit

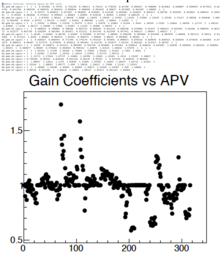


Determine the Target ADC value from the Mean Peak Value (MPV) of the Landau fit of the ADC Distribution for all hits..

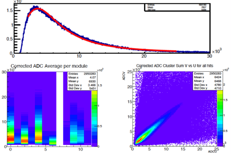


Determine the APV in the U/X direction with the most statistics, use as a reference. Using a χ^2 minimization iteratively determine the relative internal gain coefficients for each APV from the ADC asymmetries and the Target ADC value.

Print APV gain coefficients to output file and create plots



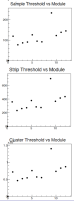
Generate 'Corrected ADC Diagnostic plots



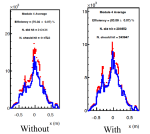
For each module, determine an average gain, sample, strip, and cluster thresholds.

Print out module information. Create plots

```
bb.gem.m0.modulegain = 1.00493
bb.gem.m0.threshold_sample = 119.138
bb.gem.m0.threshold_stripsum = 357.414
bb.gem.m0.threshold_clustersum = 714.828

bb.gem.m1.modulegain = 0.850227
bb.gem.m1.threshold_sample = 77.0525
bb.gem.m1.threshold_stripsum = 231.157
bb.gem.m1.threshold_clustersum = 462.315

bb.gem.m2.modulegain = 0.950809
bb.gem.m2.threshold_sample = 86.5102
bb.gem.m2.threshold_stripsum = 259.531
bb.gem.m2.threshold_clustersum = 519.061

bb.gem.m3.modulegain = 0.837287
bb.gem.m3.threshold_sample = 90.4981
bb.gem.m3.threshold_stripsum = 271.494
bb.gem.m3.threshold_clustersum = 542.989

bb.gem.m4.modulegain = 0.948182
bb.gem.m4.threshold_sample = 125.836
bb.gem.m4.threshold_stripsum = 377.507
bb.gem.m4.threshold_clustersum = 755.013

bb.gem.m5.modulegain = 1.0476
bb.gem.m5.threshold_sample = 94.7869
bb.gem.m5.threshold_stripsum = 284.361
bb.gem.m5.threshold_clustersum = 568.722
```



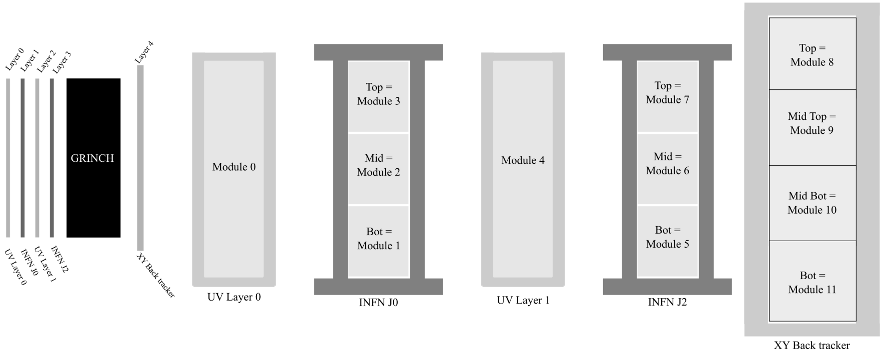
Pipeline info toDatabase to see affect on ADC signals in GEM and Track Based Efficiencies



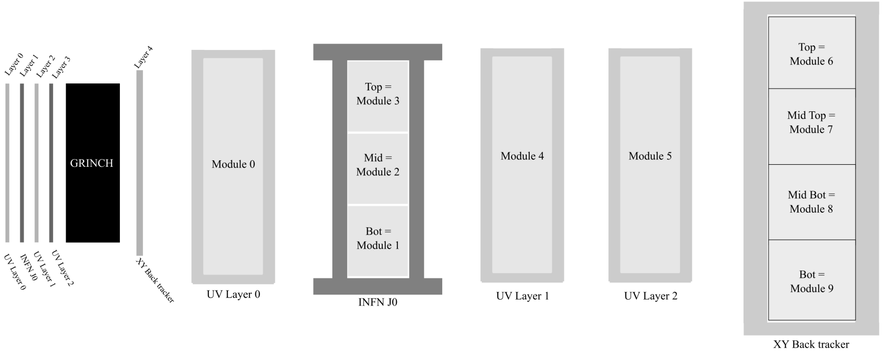
Without Coefficients | With Coefficients

Finish:

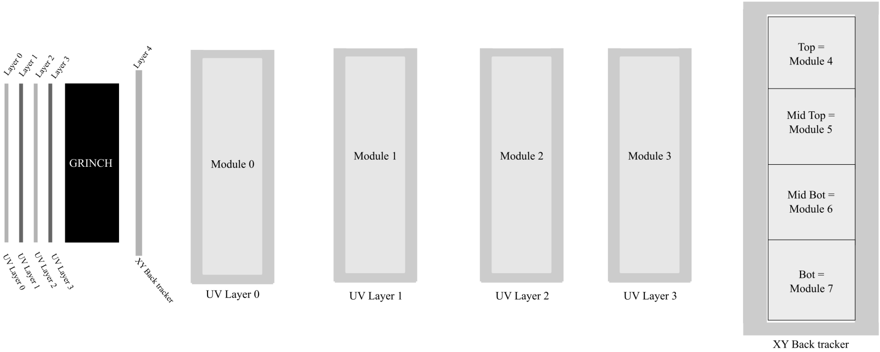
Config 1


Layer 0
Layer 1
Layer 2
Layer 3
GRINCH
Layer 4
UV Layer 0
INFN J0
UV Layer 1
INFN J2
XY Back tracker
Module 0
UV Layer 0
Top = Module 3
Mid = Module 2
Bot = Module 1
INFN J0
Module 4
UV Layer 1
Top = Module 7
Mid = Module 6
Bot = Module 5
INFN J2
Top = Module 8
Mid Top = Module 9
Mid Bot = Module 10
Bot = Module 11
XY Back tracker

Config 2


Layer 0
Layer 1
Layer 2
Layer 3
Layer 4
GRINCH
UV Layer 0
INFN J0
UV Layer 1
UV Layer 2
XY Back tracker
Module 0
UV Layer 0
Top = Module 3
Mid = Module 2
Bot = Module 1
INFN J0
Module 4
UV Layer 1
Module 5
UV Layer 2
Top = Module 6
Mid Top = Module 7
Mid Bot = Module 8
Bot = Module 9
XY Back tracker

Config 3



Layer 0
Layer 1
Layer 2
Layer 3
GRINCH
UV Layer 0
UV Layer 1
UV Layer 2
UV Layer 3
Layer 4
XY Back tracker
Module 0
UV Layer 0
Module 1
UV Layer 1
Module 2
UV Layer 2
Module 3
UV Layer 3
Top =
Module 4
Mid Top =
Module 5
Mid Bot =
Module 6
Bot =
Module 7
XY Back tracker

SBS nTPE extraction

- Big Picture: While TPE has been studied for the proton, there is essentially no TPE data for the neutron
- No free neutron targets

Start: $R_{n/p}$ is the ratio of quasi-elastic yields in scattering from a deuteron target. $N_{e,e'n}$ and $N_{e,e'p}$ are the quasi-elastic detector yields for neutrons and protons.

$$R_{n/p} \equiv R_{observed} = \frac{N_{e,e'n}}{N_{e,e'p}}$$

Apply corrections for hadron efficiencies, radiative corrections, final state effects, and re-scattering. Call this ratio $R_{corrected}$, its proportional to $\sigma_L^{n(p)}$ and $\sigma_T^{n(p)}$.

Now fix Q^2 = 4.5 $(\text{GeV/c})^2$ and consider two different kinematic points ($\epsilon_1$and ϵ_2).

Take a corrected ratio for each kinematic point, call them $R_{corrected,\epsilon_1}$and $R_{corrected,\epsilon_2}$.

Consider the ratio of the two corrected ratios and define $S_c^{n(p)} = \sigma_L^{n(p)}/\sigma_T^{n(p)}$

$$\text{A} = \frac{R_{corrected,\epsilon_1}}{R_{corrected,\epsilon_2}} = B \times \frac{1+\epsilon_1 S_c^n}{1+\epsilon_2 S_c^n} \approx B \times (1 + \Delta\epsilon \cdot S_c^n)$$

B only contains known proton information.
End: Two unknowns are σ_L^n and σ_T^n, which can be extracted.