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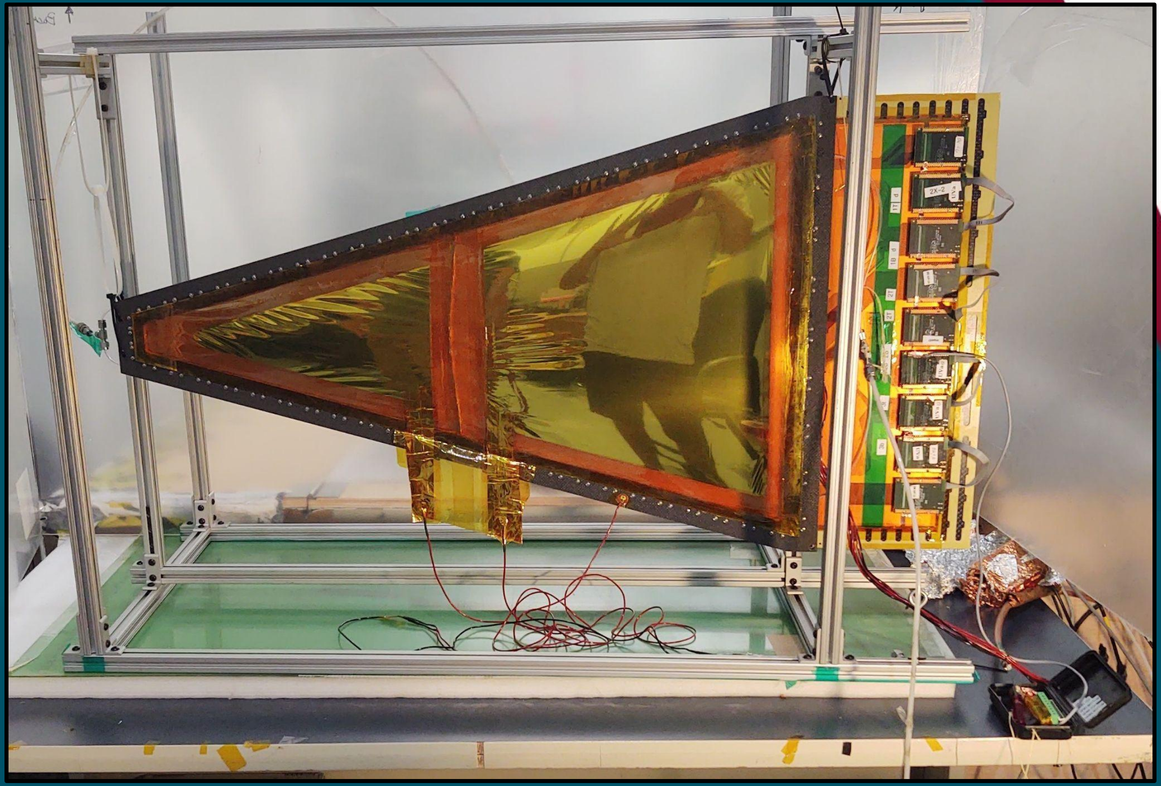


# Construction and Performance of a Large Area GEM Detector with Low Mass and Zigzag-strip Readout for the EIC


Merrick Lavinsky, Jared Hadley*, Aiwu Zhang**, and Marcus Hohlmann

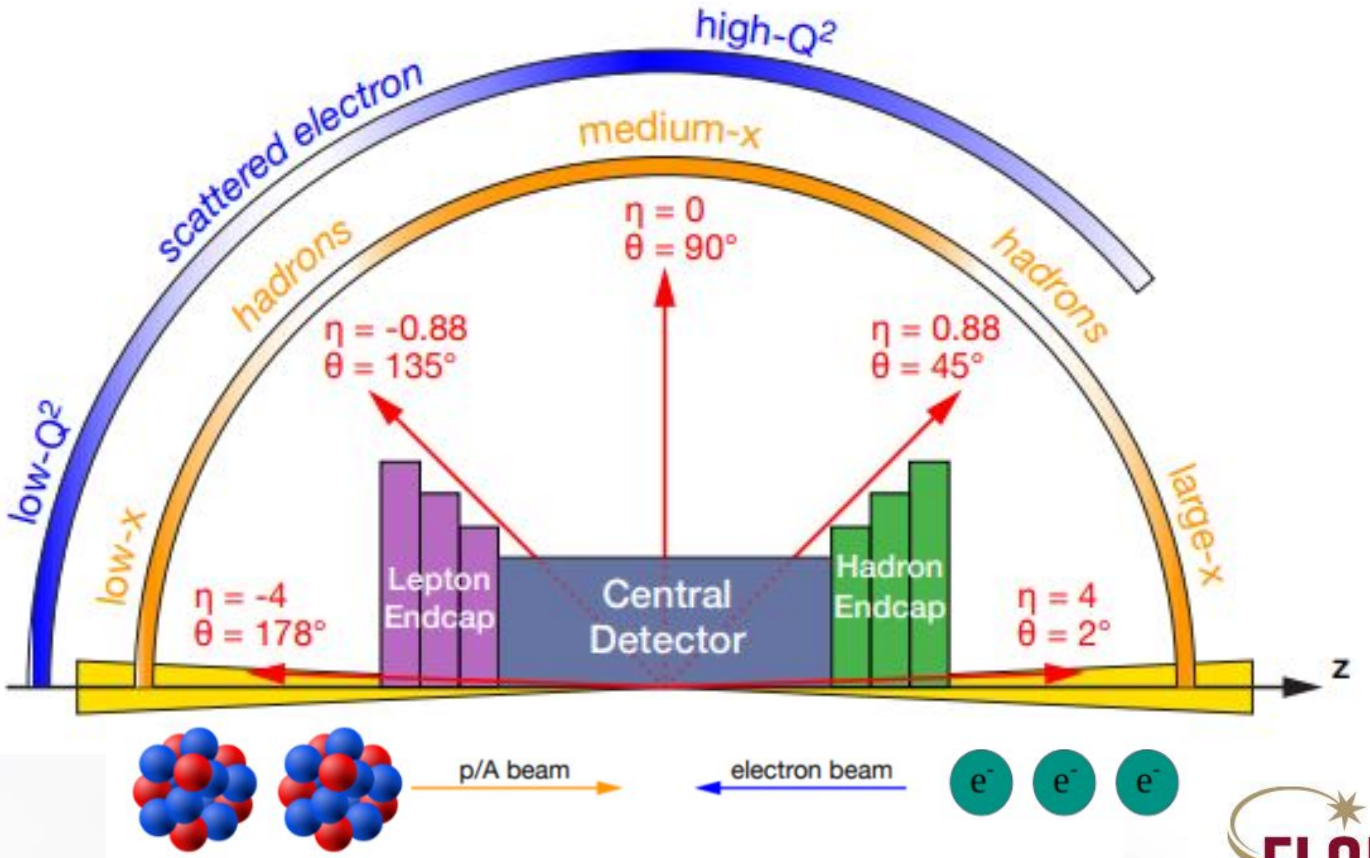
*Florida Institute of Technology*

** Now works at Swivl, CA*
*** Now works at Leidos Inc. CA*

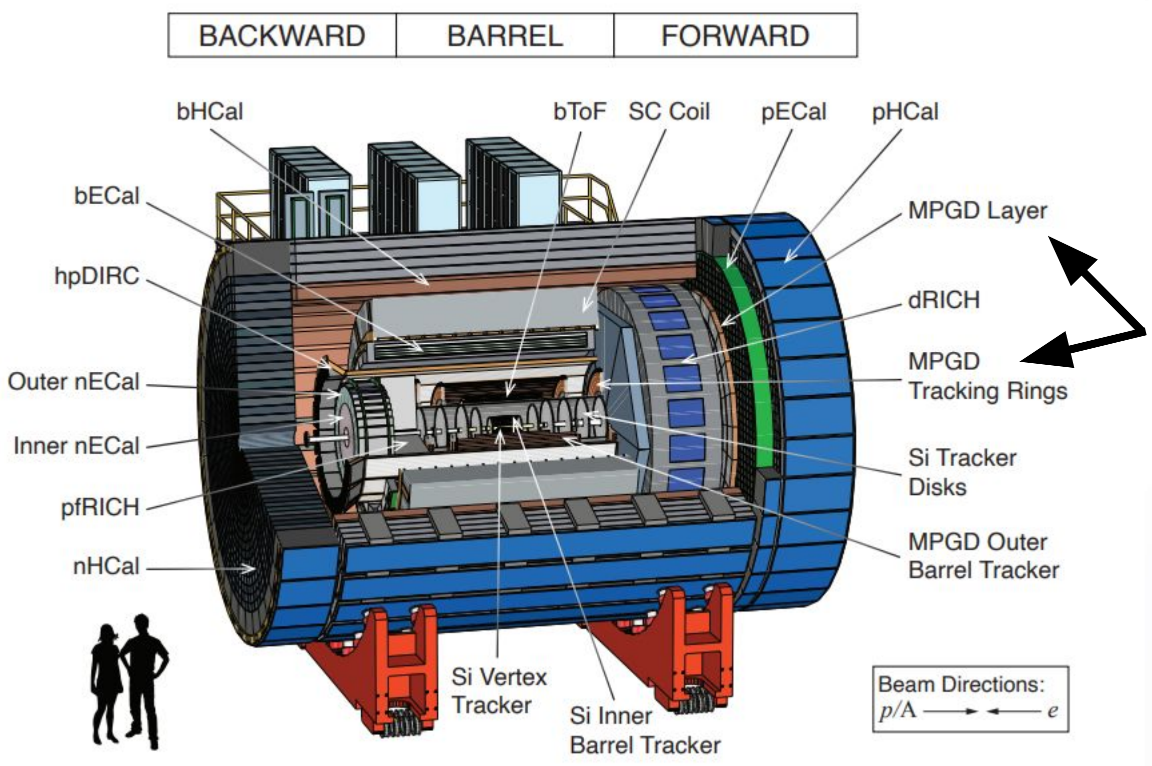
# The Future Electron Ion Collider

- Proposed to be built at BNL in NY using infrastructure from RHIC
- Collide electron beam with Protons or a variety of heavy ion beams
  - U, Pb, etc..
- Break the QCD barrier!
  - quark-gluon position and spin distribution within the nucleus
  - Understand how the nuclear force/properties of nuclear matter emerge from quark-gluon interactions

"Understand the GLUE that binds us all"



# GEM Detector Presence at the EIC and ATHENA




- A Totally Hermetic Electron-Nucleus Apparatus (ATHENA), was a previous design of the collider at that EIC facility
- This design exhibited the use of large, planar Micro Patterned Gaseous Detectors (MPGDs) for tracking in the forward or backward regions.
- ATHENA in general required trackers with Low Scattering Material and LHC quality spatial resolution



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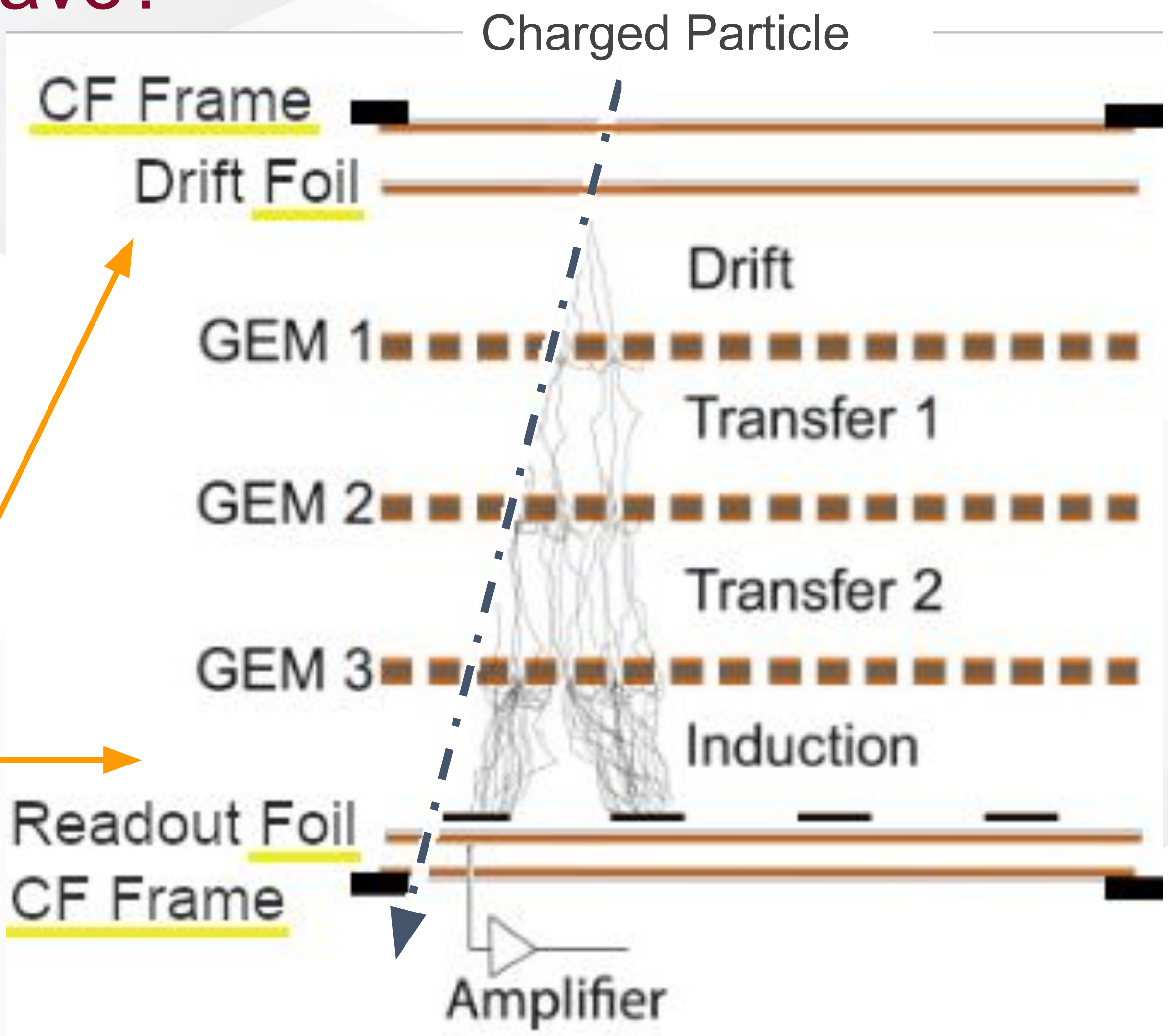
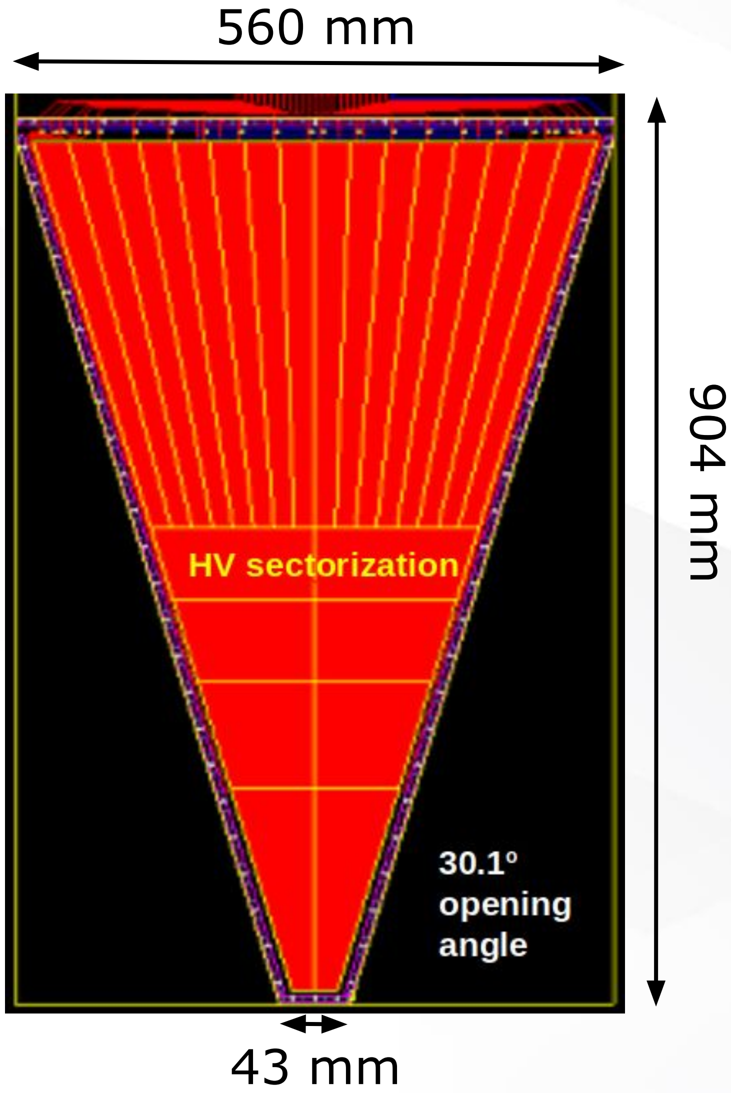
# What Advantages Does Our Design Have?

- This talk is the finale of previous years IEEE talk, focused on the construction of this Trapezoidal GEM
  - Quick overview of design optimizations
- Ideal EIC tracking detectors have low scattering material to optimize tracking
- **Drift and readout PCB's replaced with foils**
  - Radiation length reduced from 4% to 0.59% (6.7 times less!)




GEM stack diagram with modified parts underlined in yellow

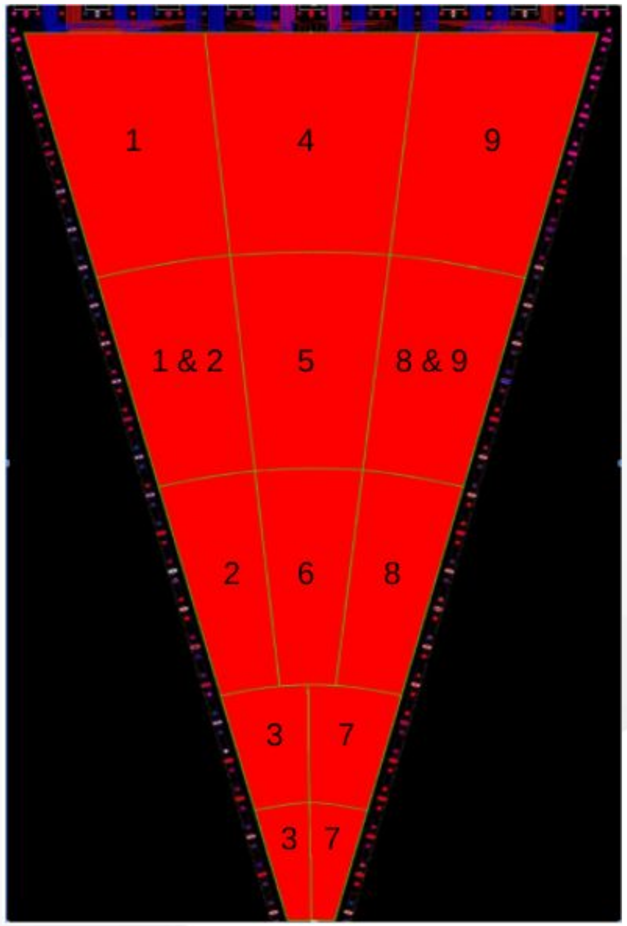
# Construction Parameters of Foil GEM




Sectorized GEM Foil

- GEM active area divided into 8 radial sectors and 18 azimuthal sectors to reduce discharging
- ~100 $cm^2$ per HV sector
- Trapezoid is 904 mm (~ 1m) long and has bases of 560 and 43 mm - which gives an opening angle of 30.1°
- Readout Foil divided into 13 sectors, instrumented with only 9 APV cards
- 3/2/2/2 mm gap spacing for reducing discharges
- Voltage is distributed to GEM foils and Drift foil via linear HV divider

Readout Foil

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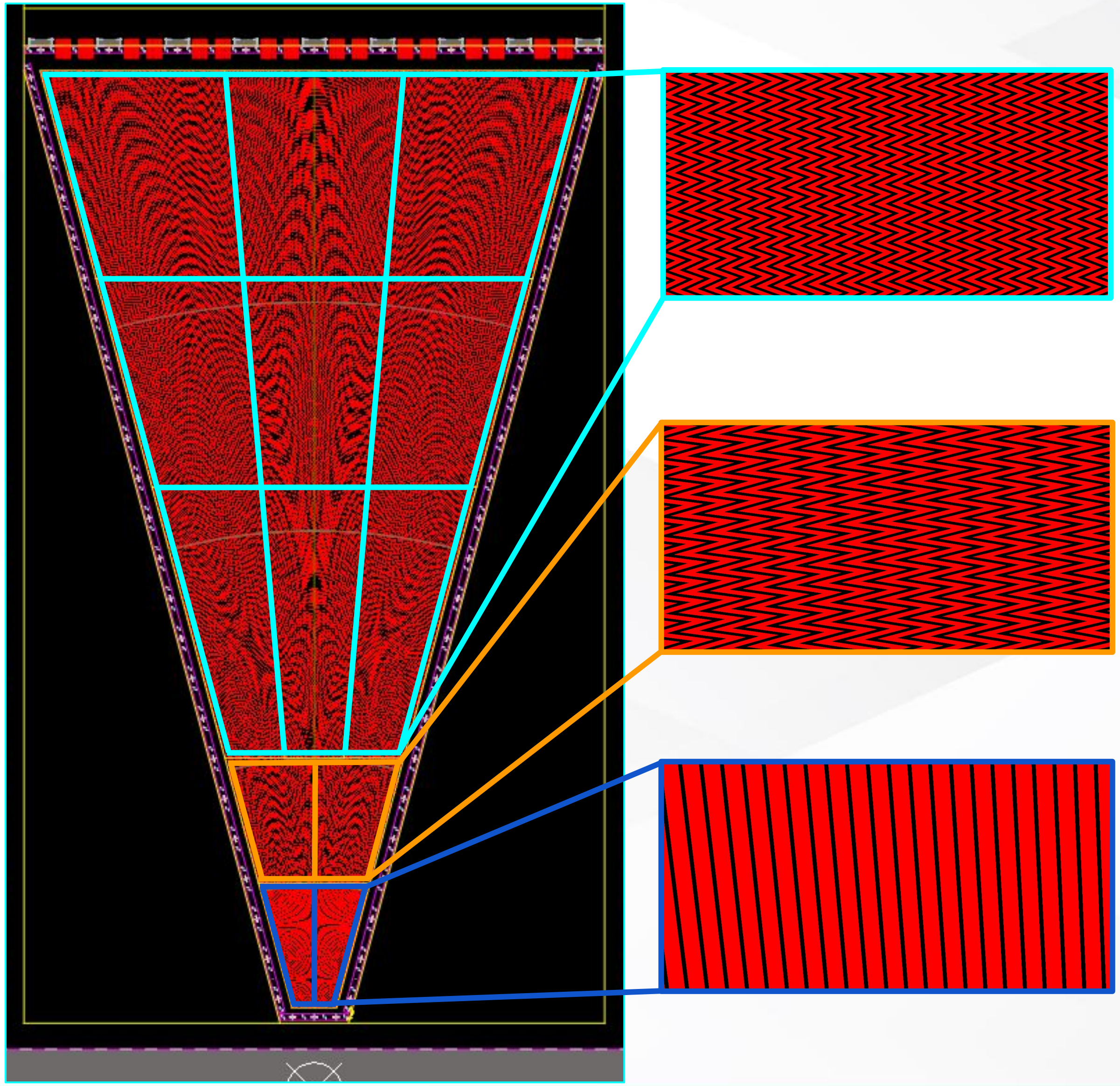
# Readout Strip Geometry



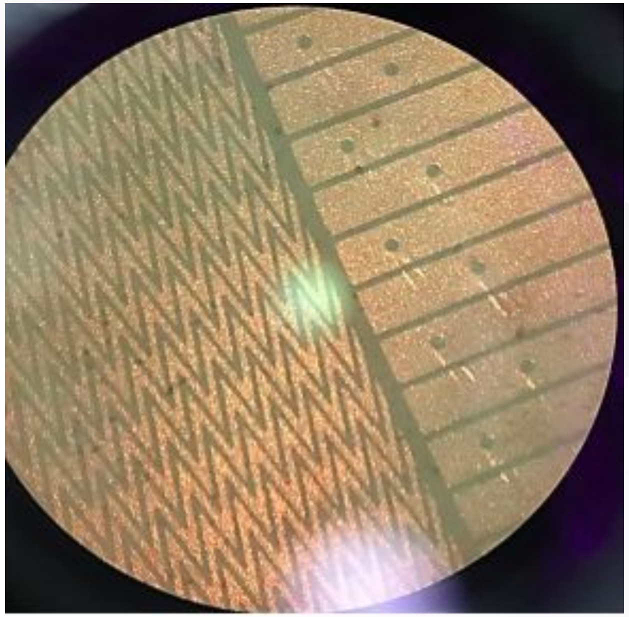
- Smaller Zigzags
- 384 (3x128) strips in each radial sector
- 1.37 mRad strip pitch  (~890 um)

- Large Zigzag geometry
- 128 strips total
- 4.14 mRad strip pitch   (~1080 um)

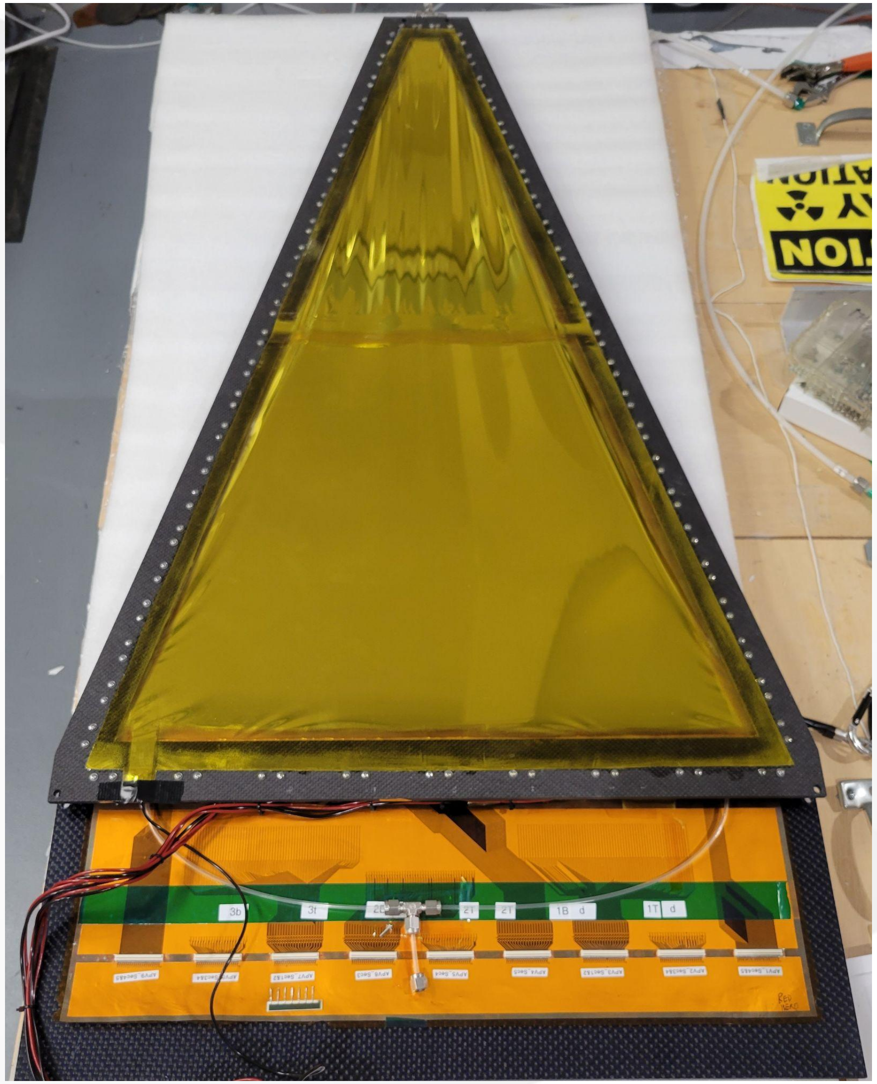
- Conventional straight strips in these two sectors
- 128 strips total
- 4.14 mRad strip pitch   (~580 um)

# What Advantages Does Our Design Have?

- The spatial resolution and manufacturing costs of a tracker can be optimized with strip geometry
- This readout uses conventional straight strips; as well as small and large zigzag readout strips
  - 66% fewer electronic channels for the readout!



Microscopic view of the zigzag strips of sector 2 next to the straight strips in sector 1 [3]



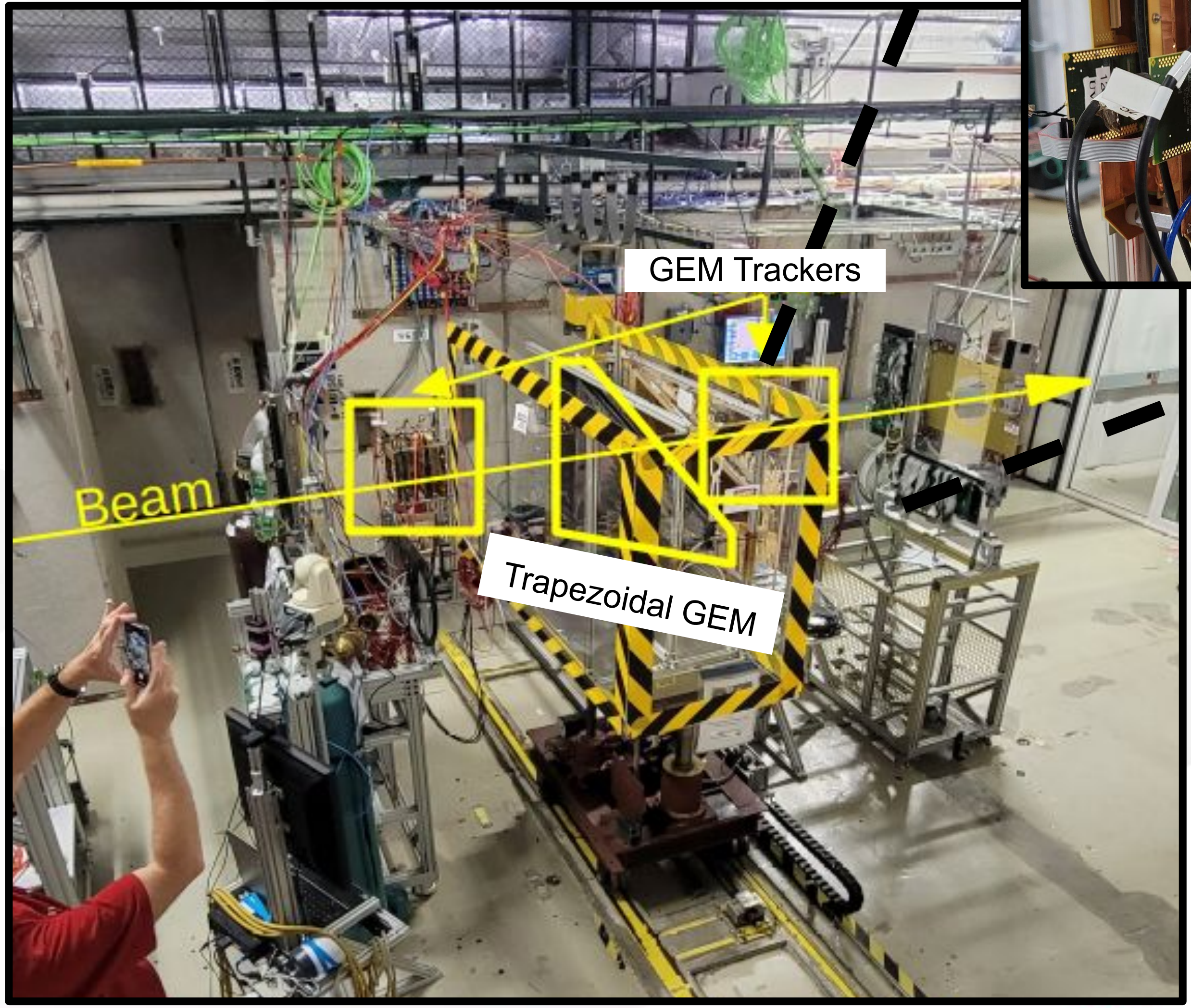
Trapezoidal GEM stack only needs 9 readout cards

# Beam Test Detector Setup at Fermilab

- FNAL Test Beam Facility (FTBF)
  - 120 GeV Protons (10s pulse / Minute)

- Install detector in beam, between 2 sets of calibrated GEM trackers


Fermilab National Laboratory



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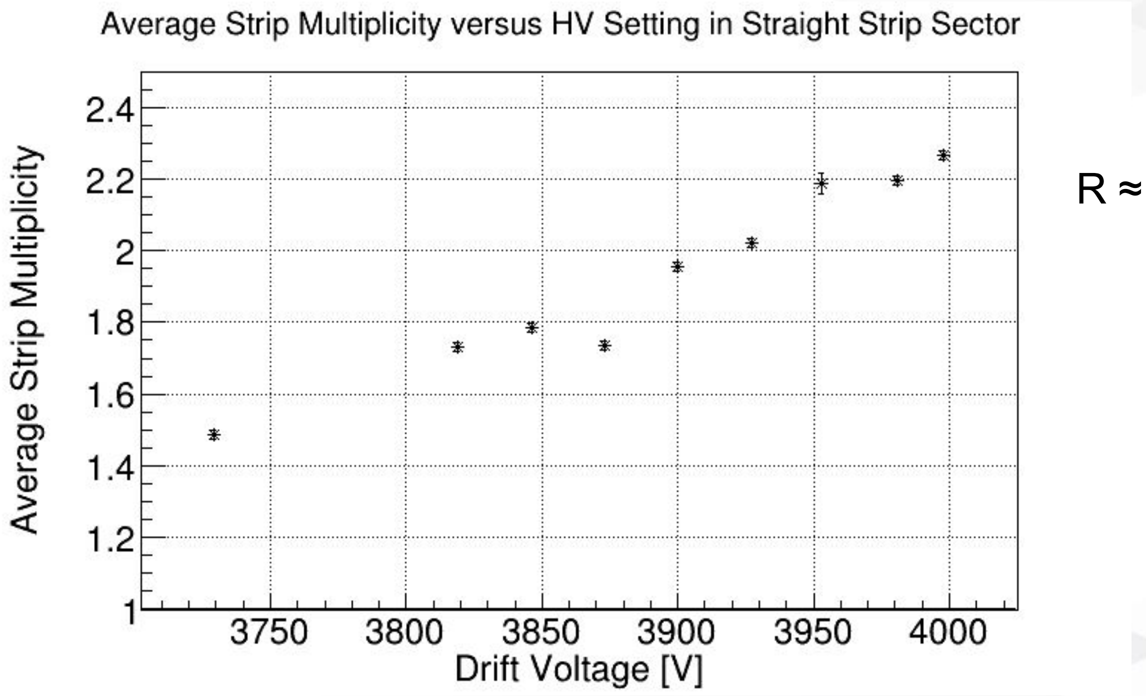
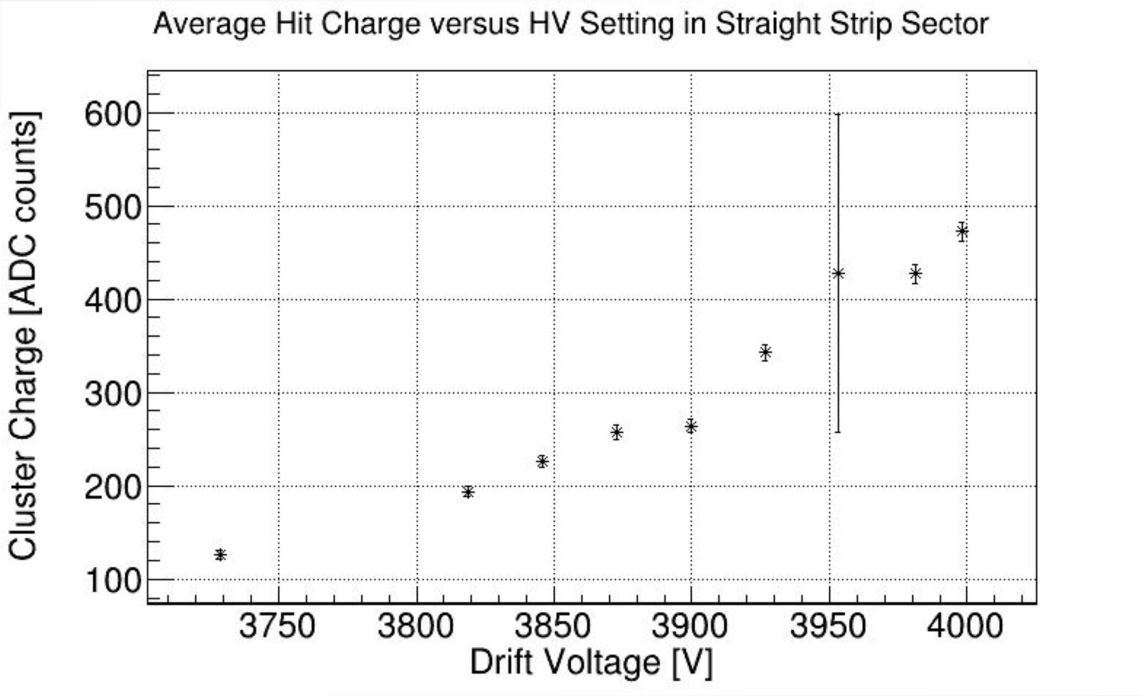
# High Voltage Scan Results




R ≈ 103 mm




Increased voltage supplied to the GEM detector leads to increased gain, which leads to more electrons being produced.

1. Wider signal pulses
2. More charge induced on the readout



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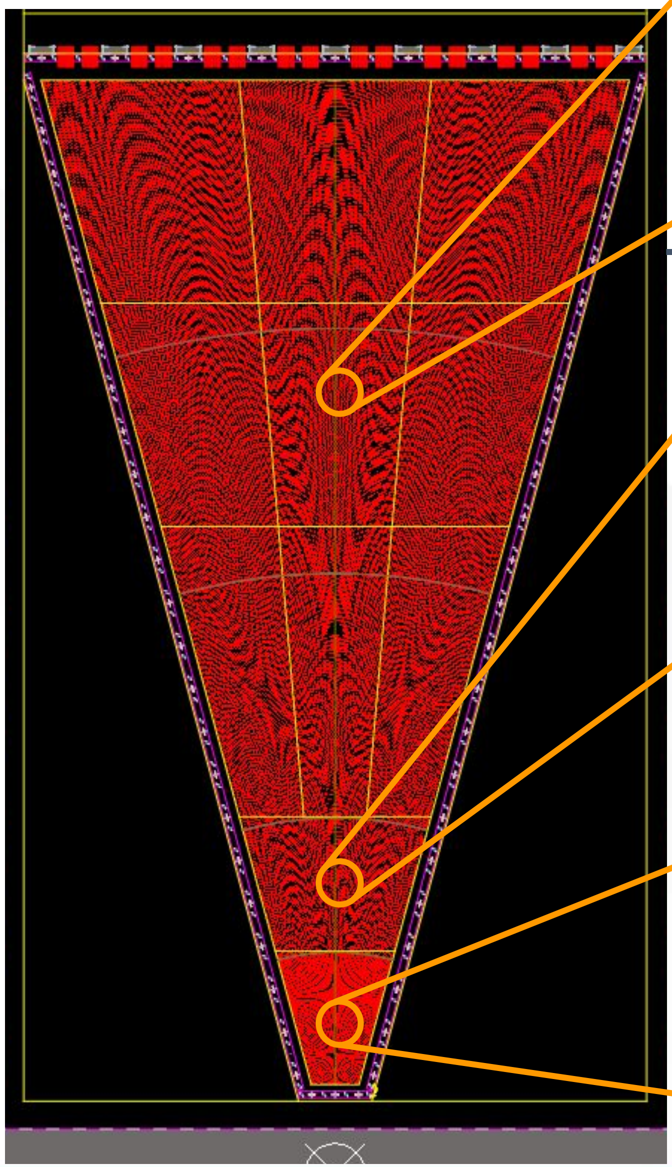
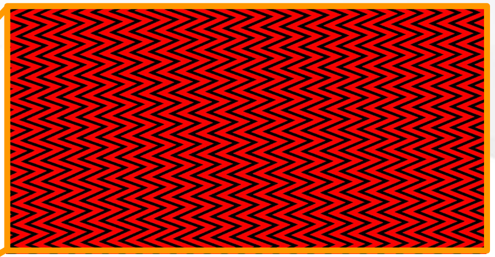
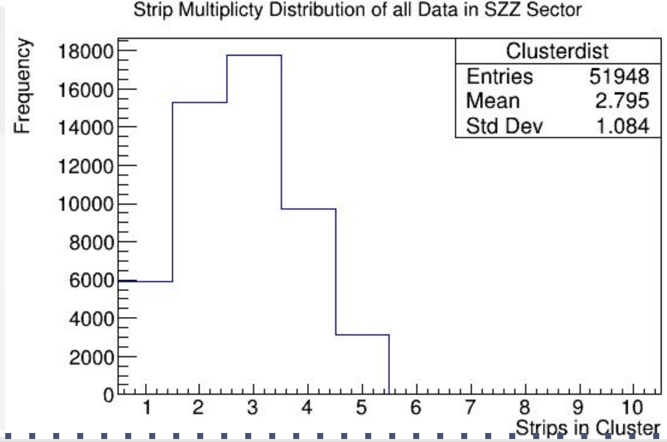
# Strip Multiplicity Results in Different Strip Geometries



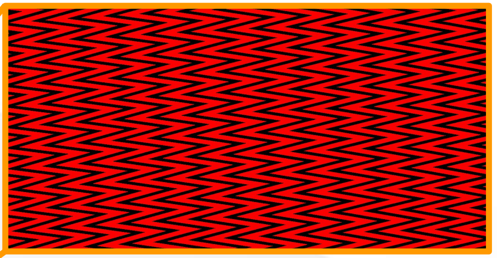
Strip Pitch: 1.37 mRad    320 < R < 904 mm



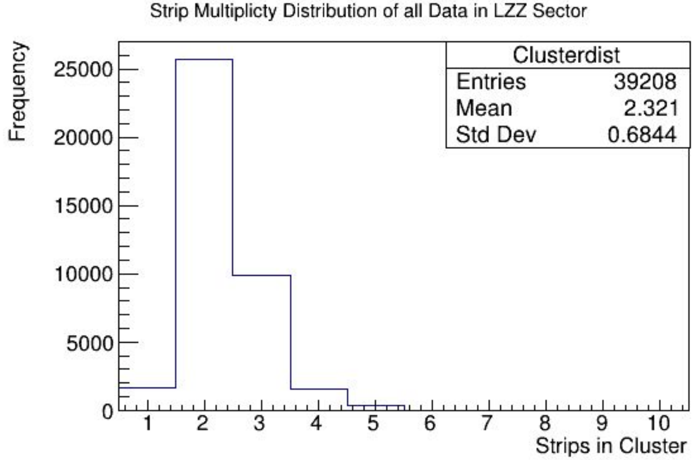
Small Zig Zag Strips



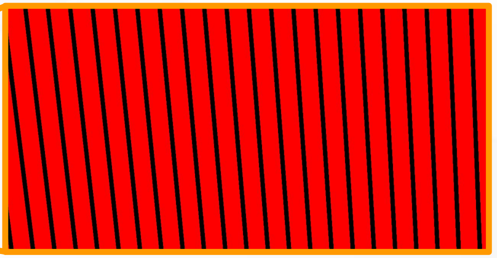

Strip Pitch: 4.14 mRad   200 < R < 320 mm



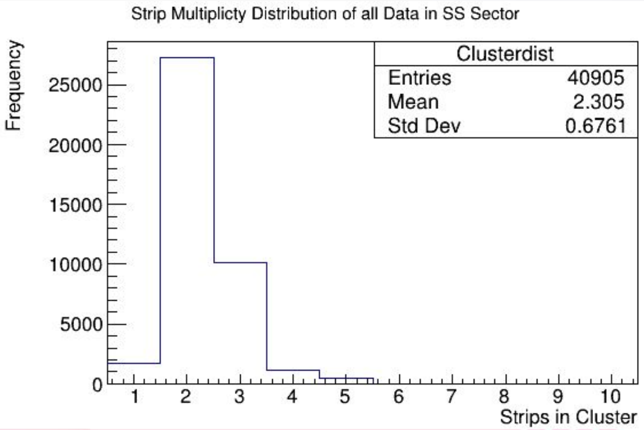
Large Zig Zag Strips




Strip Pitch: 4.14 mRad    80 < R < 200 mm



Straight Strips

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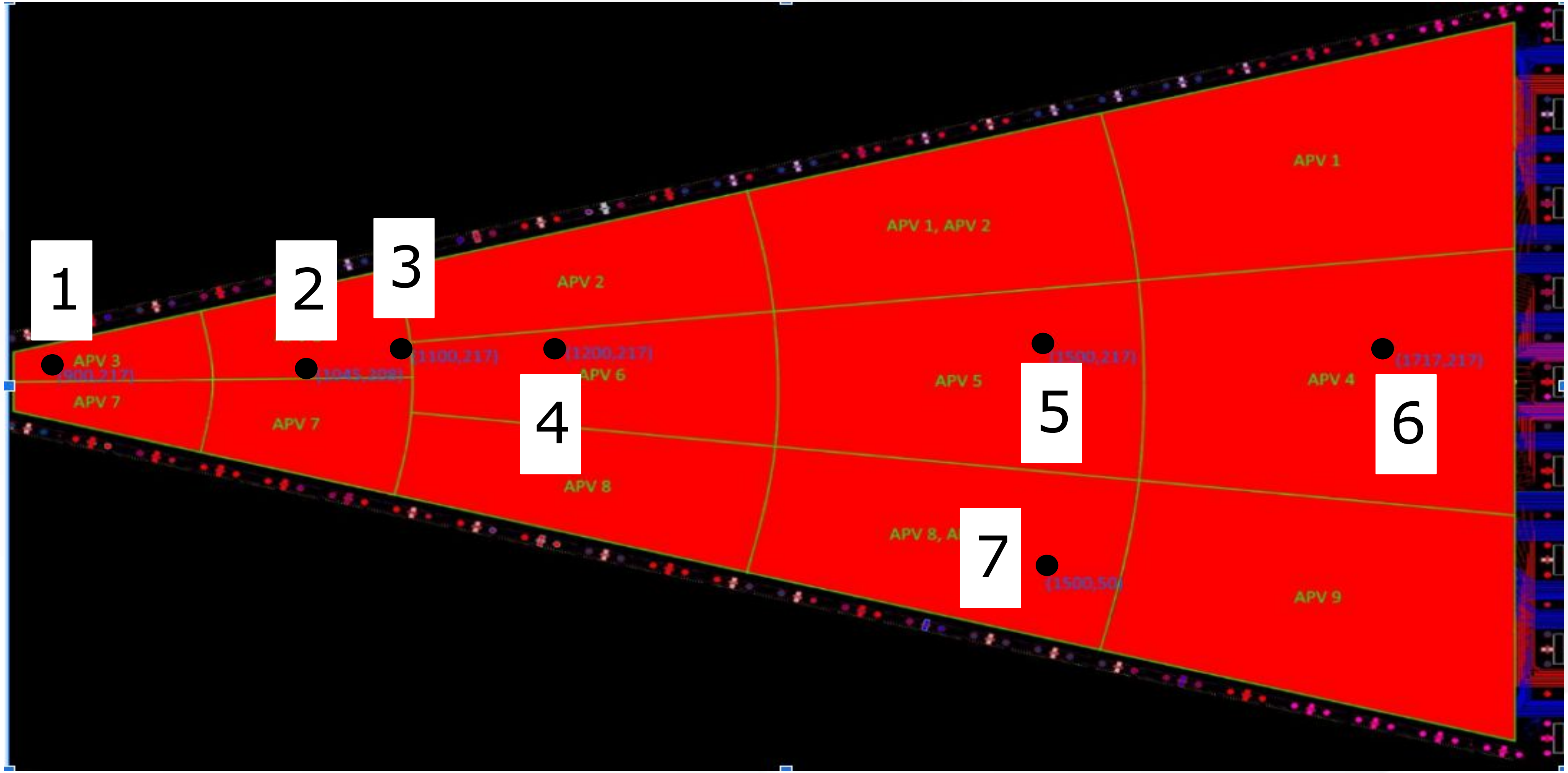
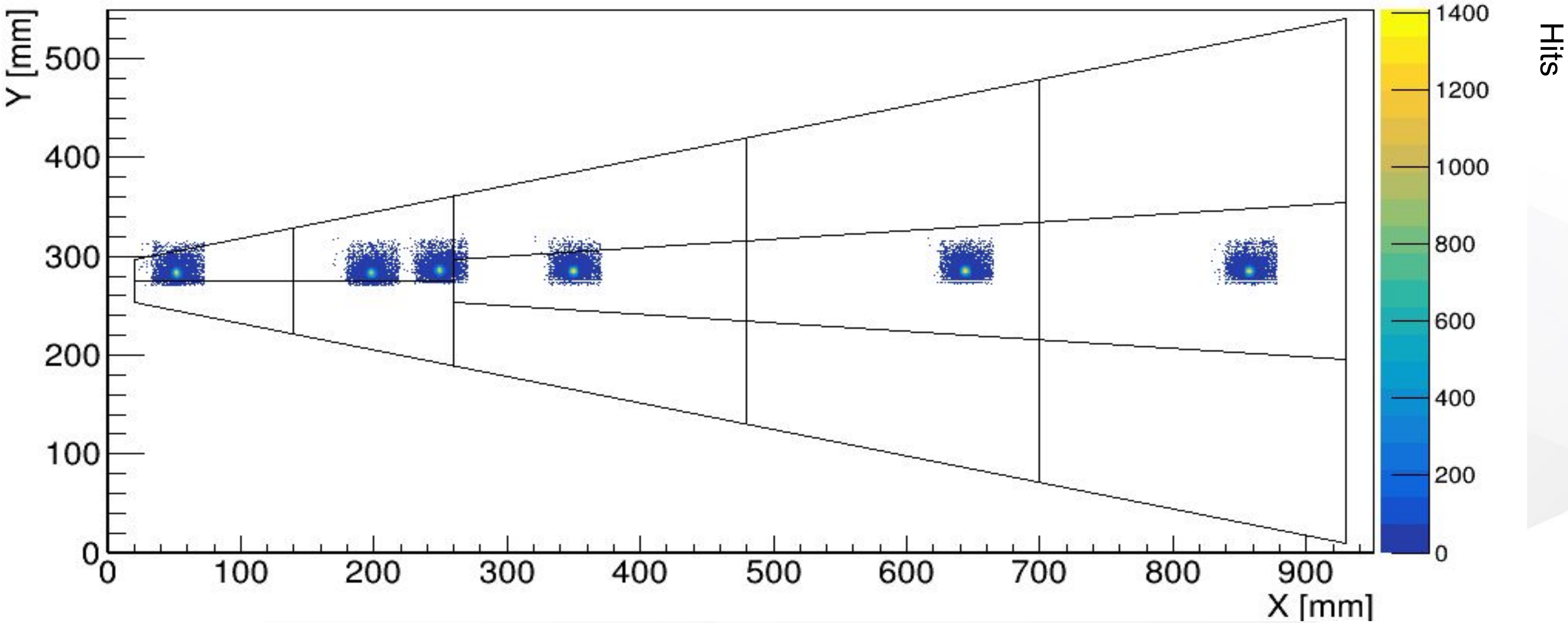
# Data Taking Locations



# Data Taking Locations (Tracker Beam Spots)



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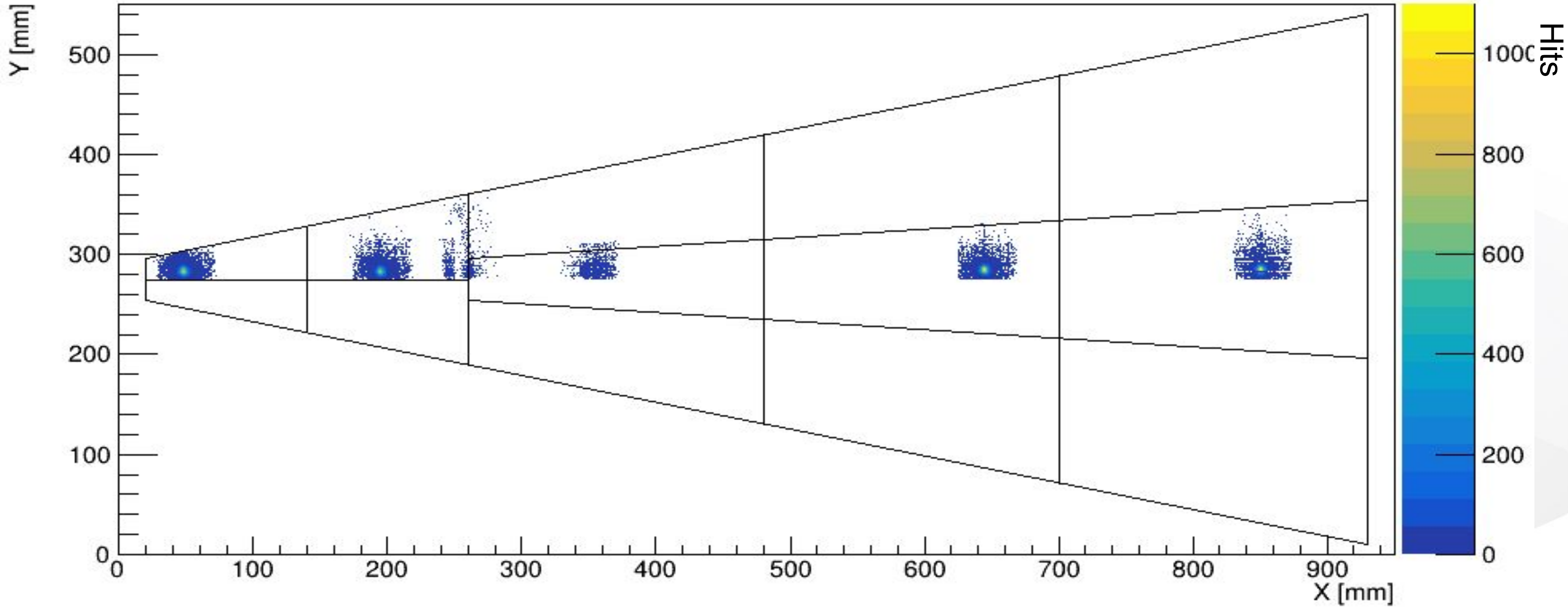
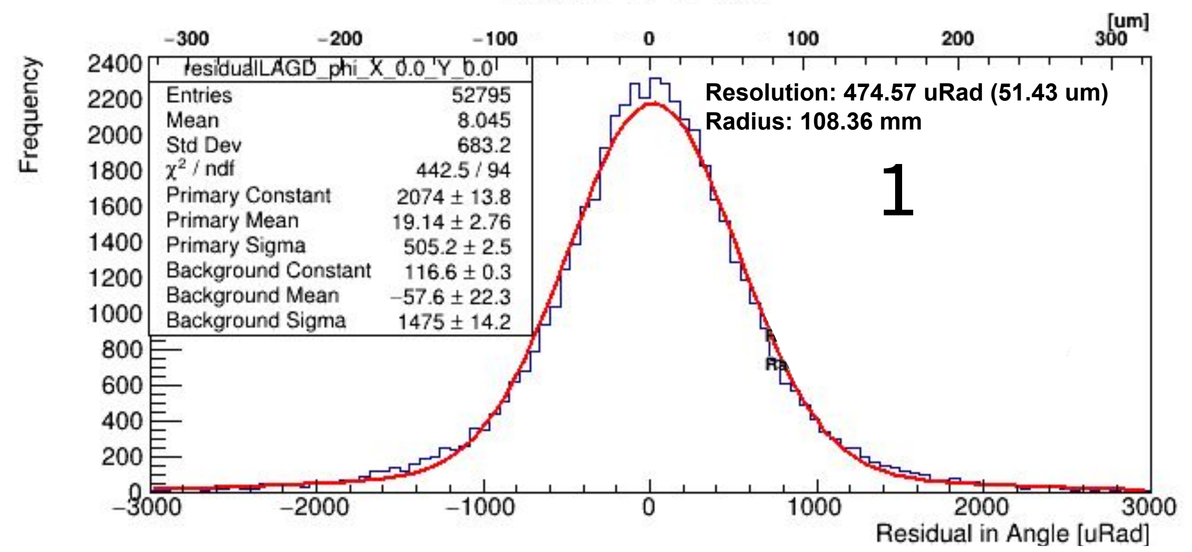
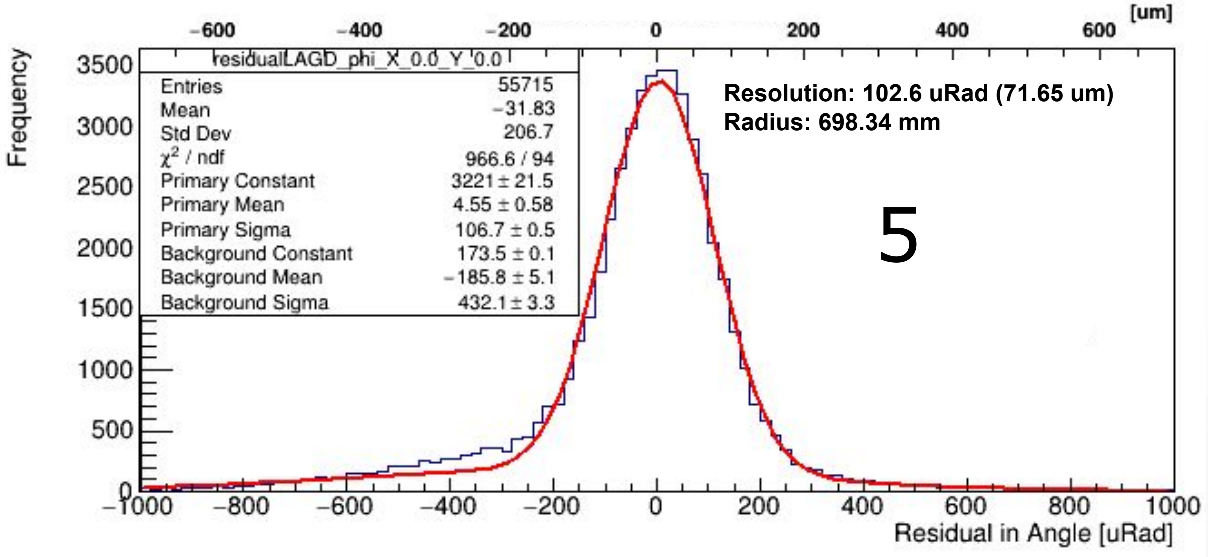
# Data Taking Locations (As seen on Trapezoidal GEM)




*X coordinate is from Trackers and Y coordinate is from Foil GEM angle with interpolated tracker radius

# Initial Resolution Measurements




$$\text{Resolution} = \sqrt{\sigma^2_{LAGDRes} - \sigma^2_{TrackerError}}$$

| Location | Strip Type | Resolution (uRad) | Resolution (um) | Local Strip Pitch (um) |
|---|---|---|---|---|
| 1 | Straight Strips | 475 +/- 3 | 51.4 +/- 0.3 | 447 |
| 2 | Large ZZ | 267 +/- 1 | 68 +/- 1 | 1041 |
| 3 | Large ZZ | 671 +/- 35 | 207 +/- 11 | 1258 |
| 4 | Small ZZ | 273 +/- 7 | 112 +/- 3 | 570 |
| 5 | Small ZZ | 103 +/- 1 | 71.7 +/- 0.4 | 956 |
| 6 | Small ZZ | 101 +/- 1 | 93 +/- 1 | 1266 |



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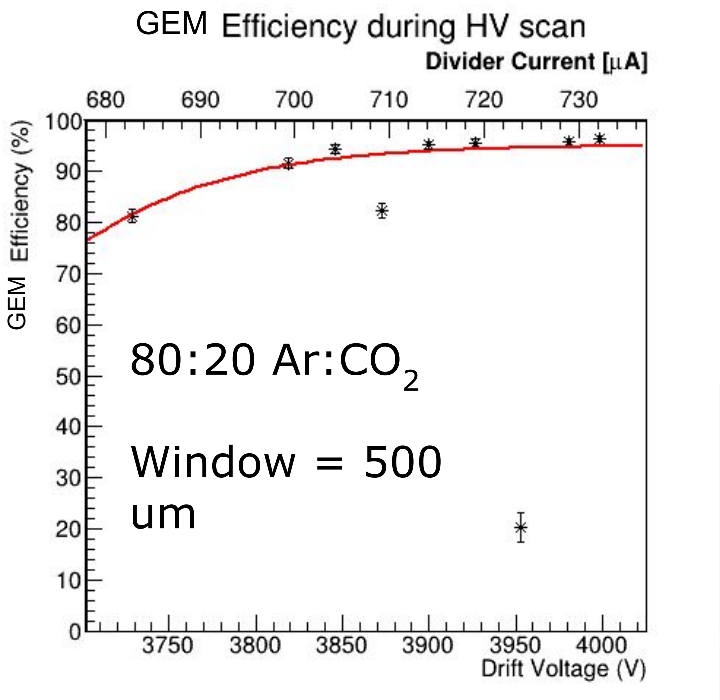
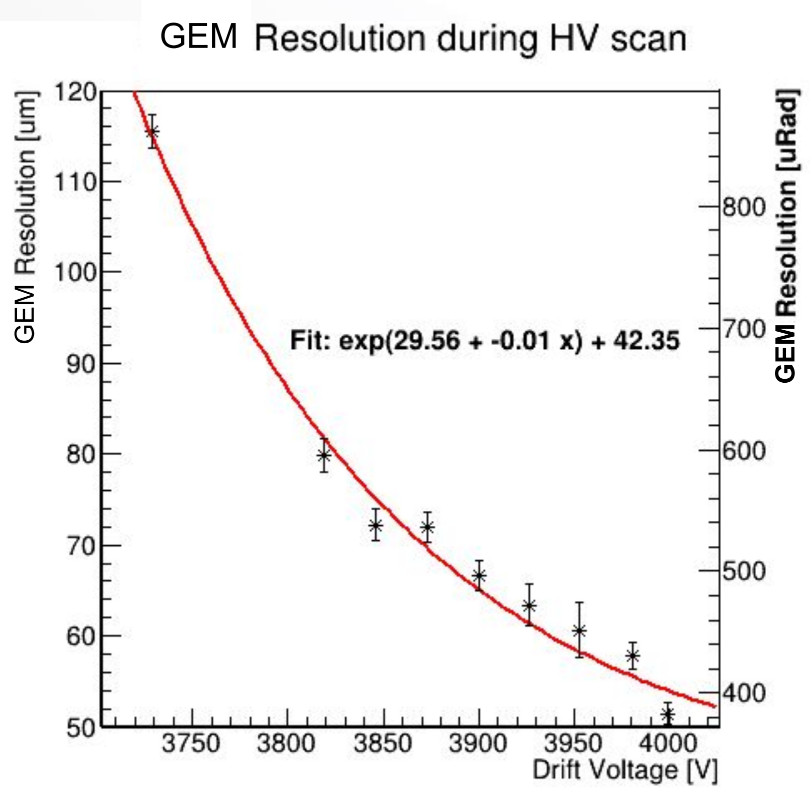
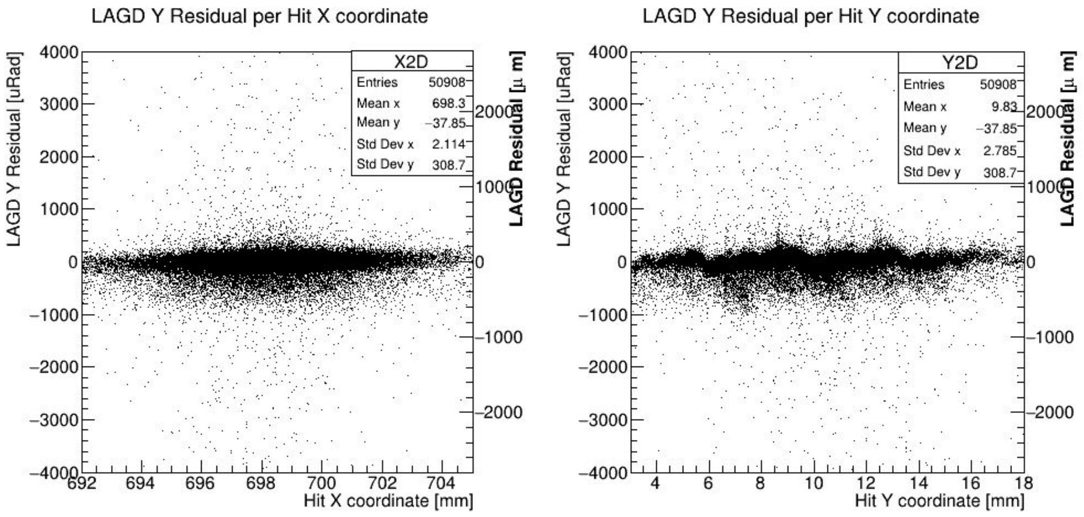
# HV Scan For Efficiency and Resolution




- Efficiency tops out at 96%
  - Two outliers have 100+ missing events
- Resolution drops exponentially with Drift voltage in Straight strips
  - Fit shows minimum at 42 um Resolution

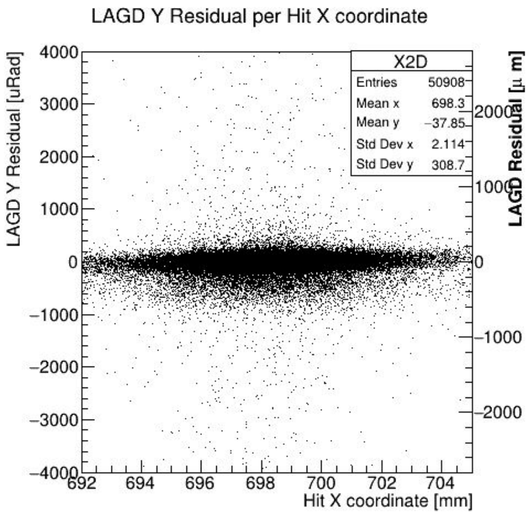


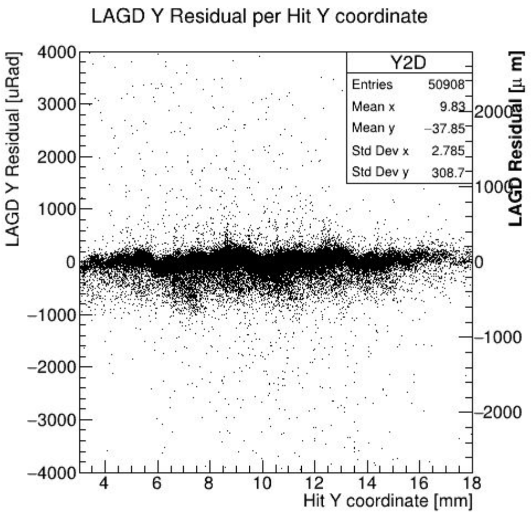
# Residual Scan Across Beam spot

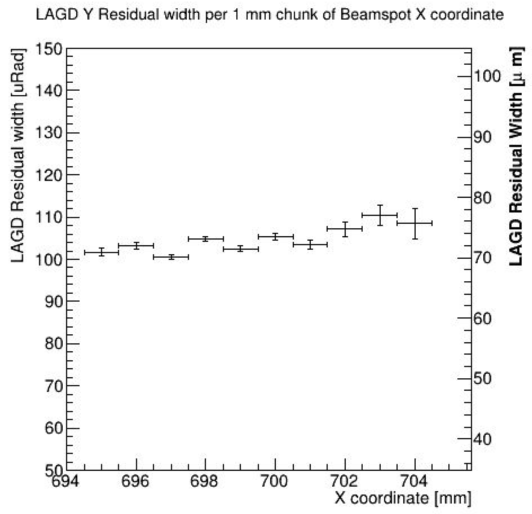


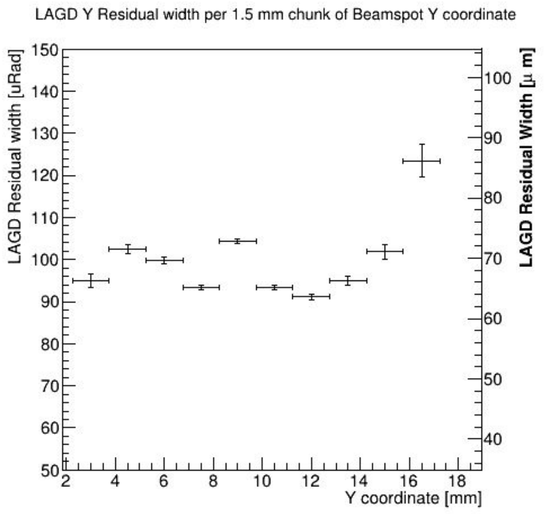

- Compare the Residuals with each X and Y coordinate
  - Coordinates Determined from the Trackers
- Constant residual in X, Non-linear effects seen in Y
- Zigzag strips have a non-constant induction across the width of the strip, which biases the cluster location towards the edges

# Residual Scan Across Beam spot



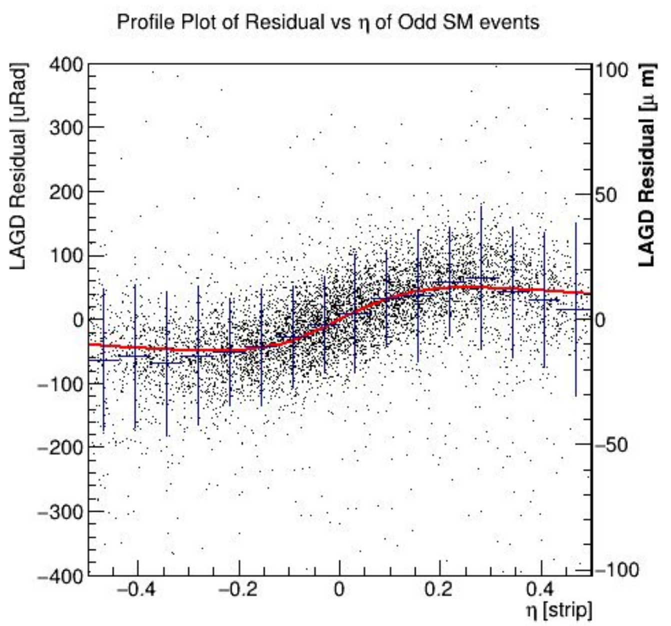



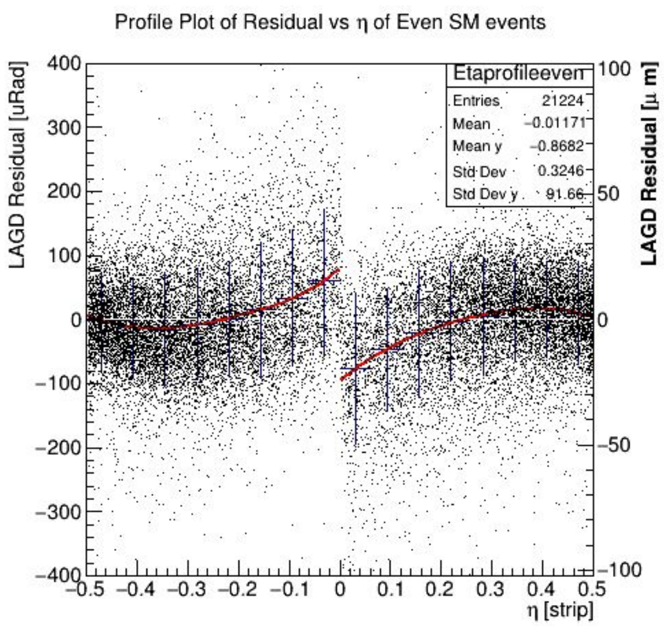



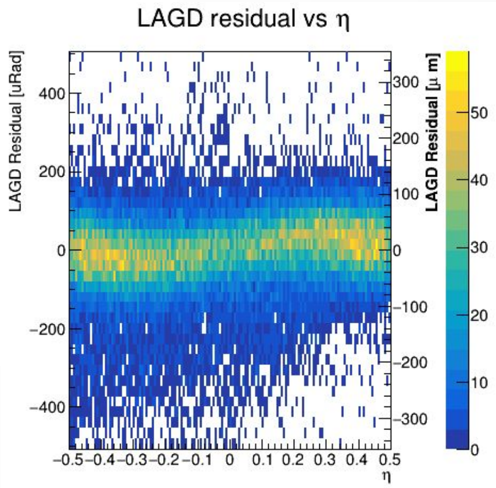

- Compare the Residuals with each X and Y coordinate
    - Coordinates Determined from the Trackers
- Constant residual in X, Non-linear effects seen in Y
- Zigzag strips have a non-constant induction across the width of the strip, which biases the cluster location towards the edges
- Top Plots show average residual stays constant at 0
- Bottom plots show Standard Deviations are lowest at the center of the beam spot

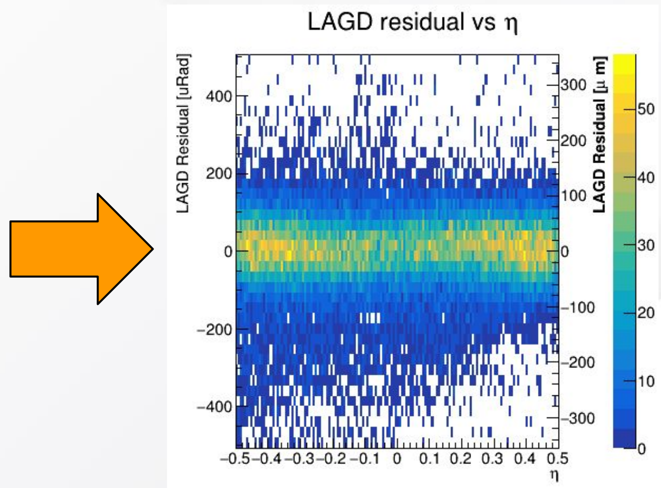
# Correction of Non-Linear ZigZag Residual Bias

- Define a new variable (η):
  - $\eta = S_{Most\ Q} - S_{Cluster}$
- Different behavior in Even and Odd SM clusters
- Fit with specific functions and use to reduce the residual of clusters

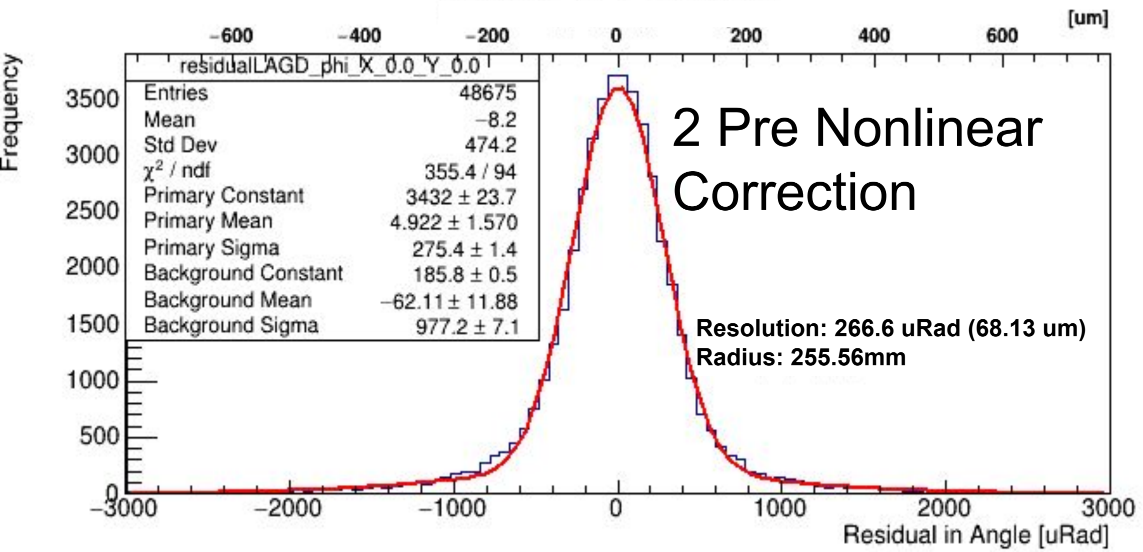


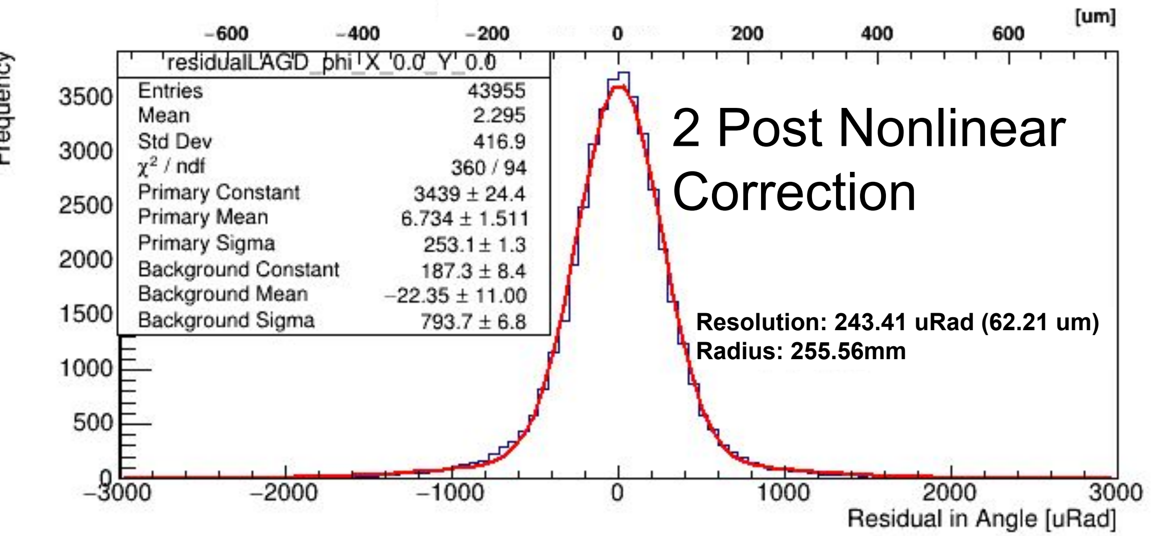



# Corrected ZigZag Resolutions




| Location | Strip Type | Resolution (uRad) | Resolution (um) | Percent Improvement |
|---|---|---|---|---|
| 2 | Large ZZ | 243 +/- 1 | 62 +/- 1 | 8.7% |
| 3* | Large ZZ | N/A | N/A | 0% |
| 4* | Small ZZ | N/A | N/A | 0% |
| 5 | Small ZZ | 96 +/- 1 | 67 +/- 1 | 6.1% |
| 6 | Small ZZ | 94 +/- 1 | 86 +/- 1 | 7.2% |

*Not enough good hits to correct NL effects :(



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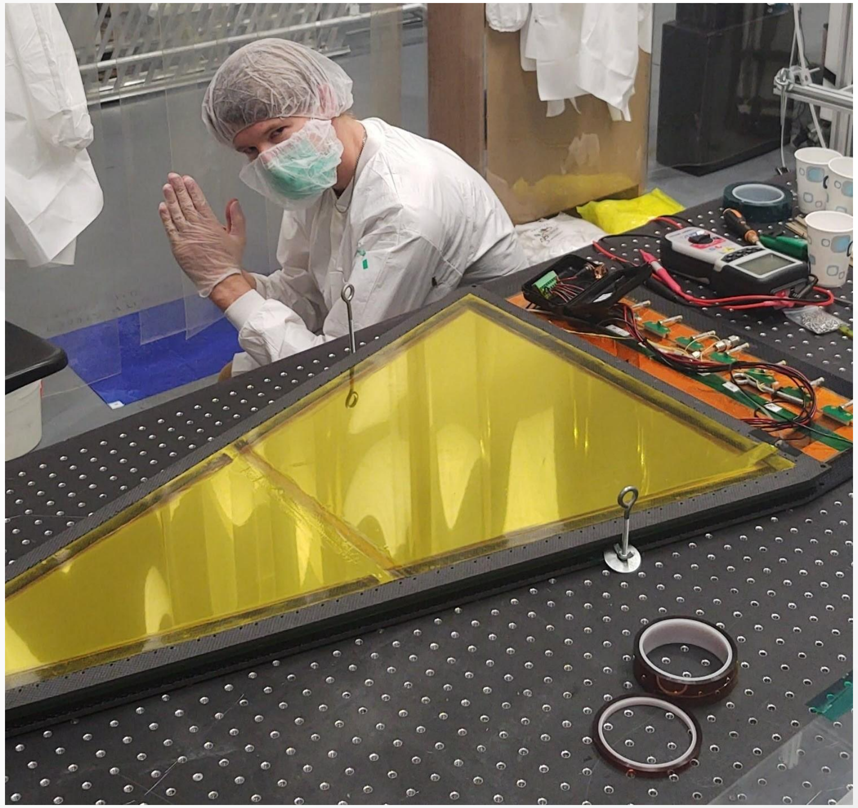
# Conclusions

- Designed, assembled, and successfully took data with a low-mass, large-area GEM detector!
- Detector characterization and HV scans show a max detection efficiency of 96% and similar behavior to conventional GEMs
- The best resolutions found for each strip type is: Straight strips at 51 +/- 1 um, Large ZZ at 62 +/- 1 um, and Small ZZ with 67 +/- 1 um.



Undergrad Jared beside the trapezoidal GEM after our first successful assembly

In Progress:

- Characterize noise in GEM
- HV Gain Curve
- Gain Uniformity of Readout Foil



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# Questions?




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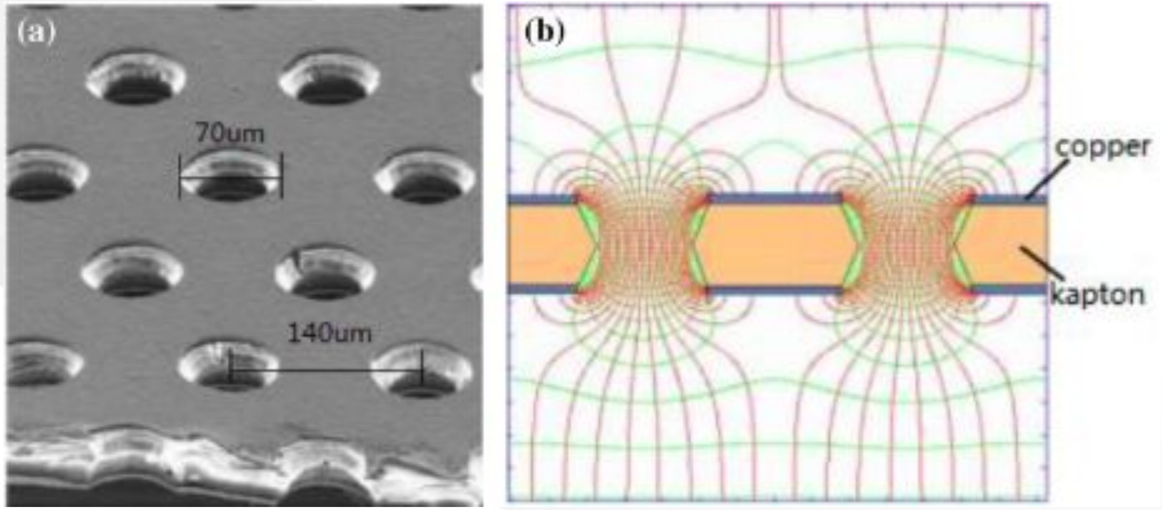
# Backup Slides

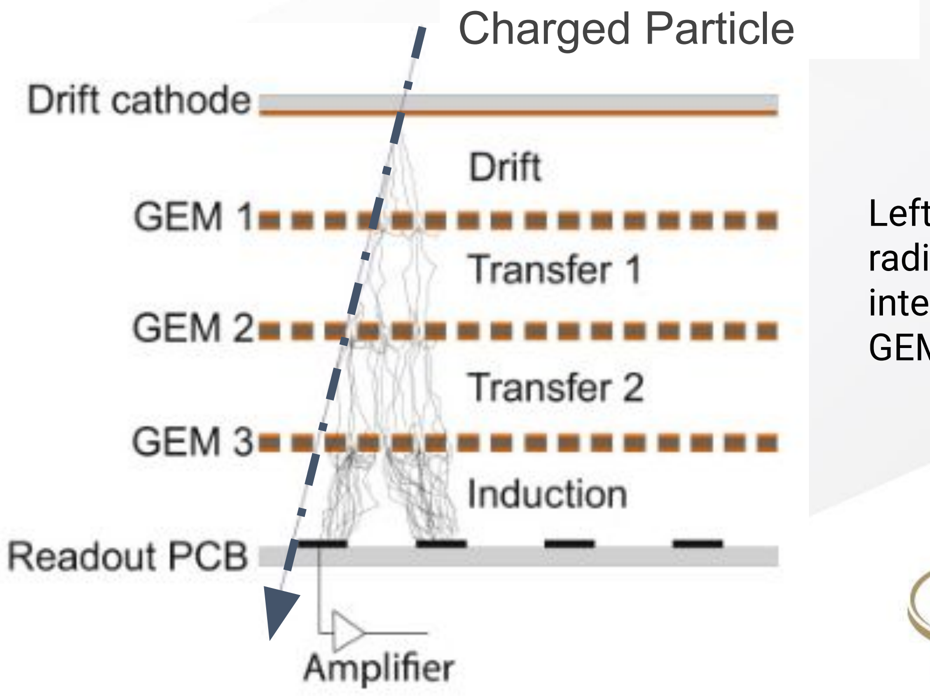
# How GEM Detectors Work

Gas Electron Multiplier foils amplify the signal within gaseous radiation detectors




Left: Close up of GEM foil [5]. Right: Electric field pinching in GEM foil pores [5]

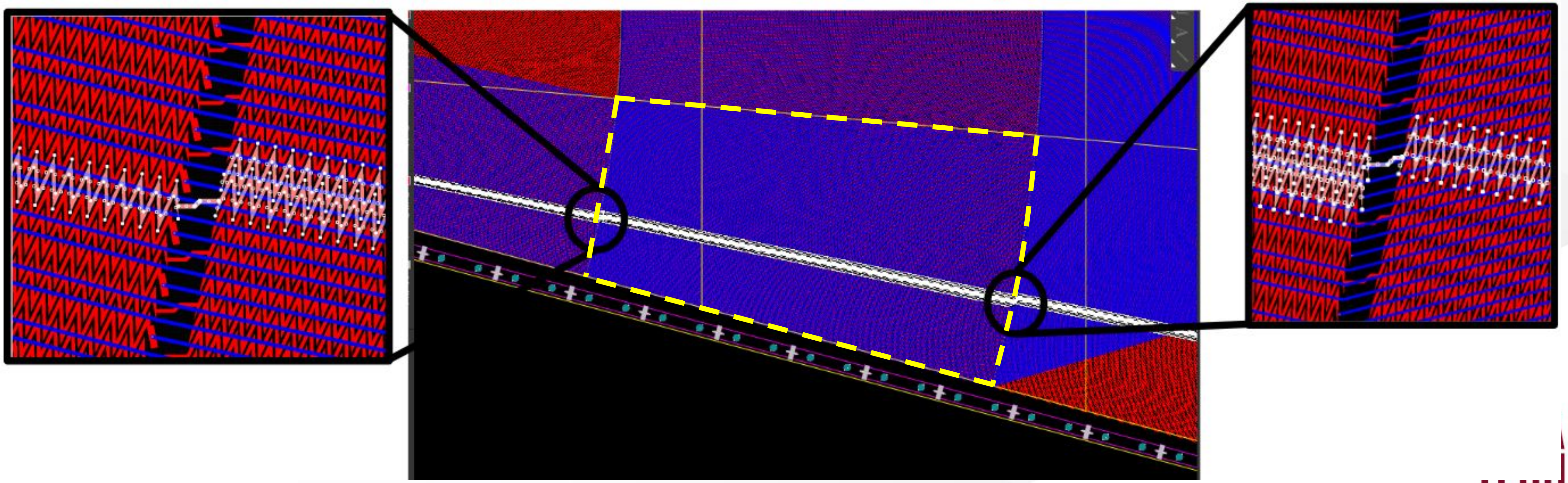
1. Charged Radiation particle enters detector
2. Ionizes gas, releasing electrons
3. Electrons forced towards readout and through GEM foils via electric fields
4. Readout signal induced on strips by electron showers




Left: Side view of radiation particle interacting with a GEM detector [4]

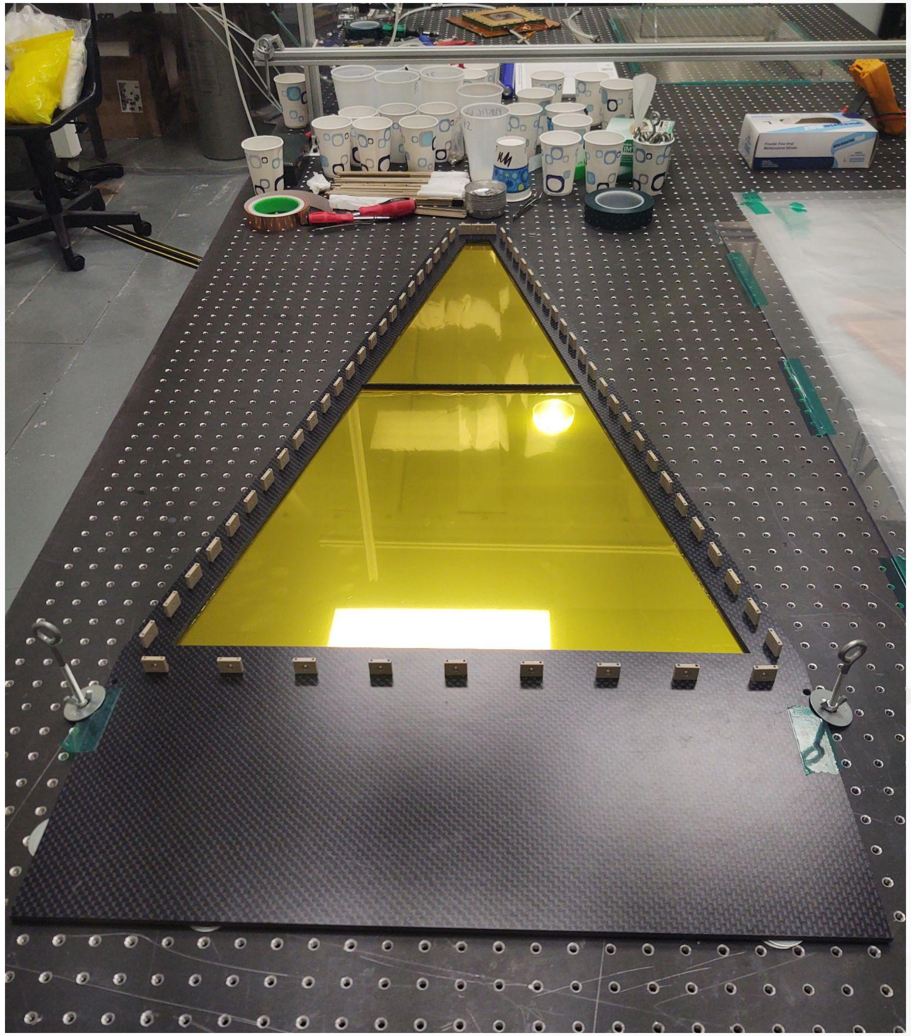
# What Advantages Does Our Design Have?

- Detector readouts sectorized for stability and rough radial information
  - Our detector measures **Angle** only
- Interweave adjacent sectors to make a middle sector
- Further reduces number of electronics needed - easier to instrument



# How this GEM Detector was Assembled

- Drift/GEMs/Readout spacing of 3/2/2/2 mm
- Pullout posts attached to bottom CF frame



Bottom CF frame with pullout posts attached



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# How this GEM Detector was Assembled

Modified GEM stack in the assembly process

- Drift/GEMs/Readout spacing of 3/2/2/2 mm
- Pullout posts attached to bottom CF frame
- GEM stack is assembled as follows:
  a. Foil placed on stack and stretched with tape
  b. Spacer added
  c. Foil tested for shorts
- Tighten GEM stack screws and cut tape
- Pullouts tighten entire stack



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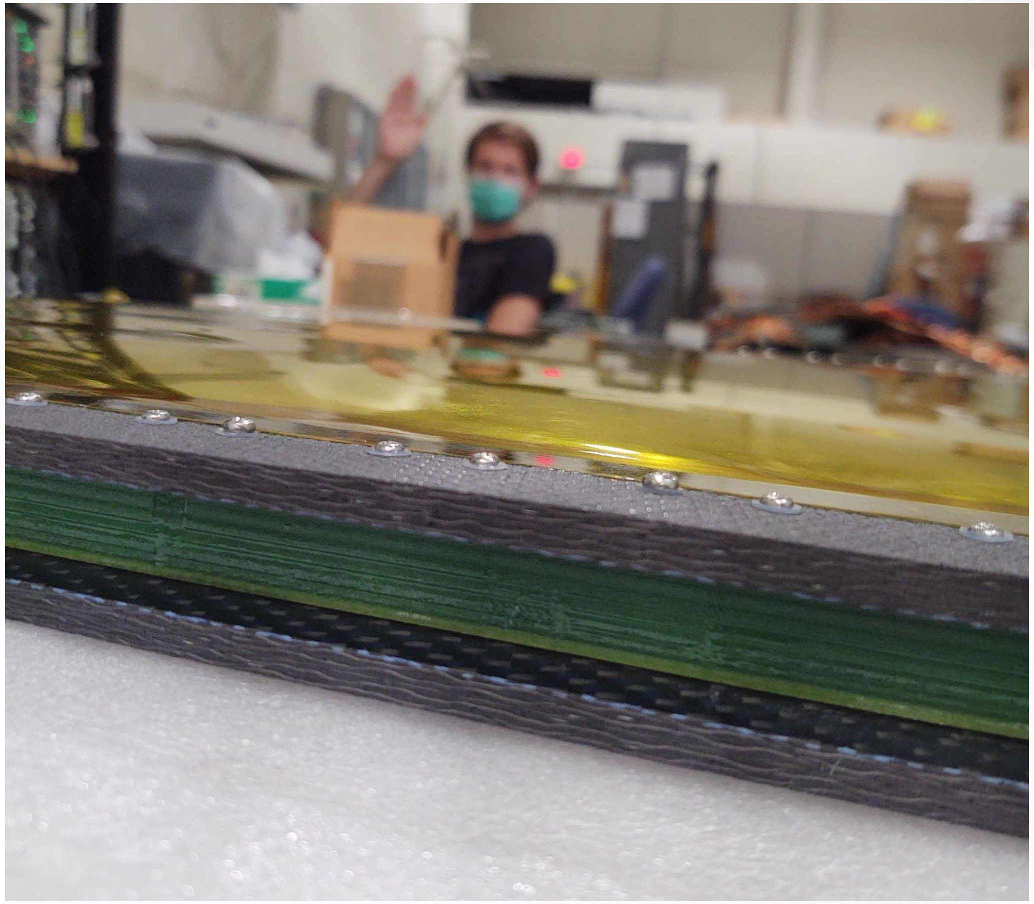
# How this GEM Detector was Assembled



Modified GEM stack in the assembly process

- Drift/GEMs/Readout spacing of 3/2/2/2 mm
- Pullout posts attached to bottom CF frame
- GEM stack is assembled as follows:
  a. Foil placed on stack and stretched with tape
  b. Spacer added
  c. Foil tested for shorts
- Tighten GEM stack screws and cut tape
- Pullouts tighten entire stack
- Add gas tight frame (green), attach top CF frame
- Modified GEM is now complete
  a. Assembled in the Physics High Bay
- Onto Quality Control Testing



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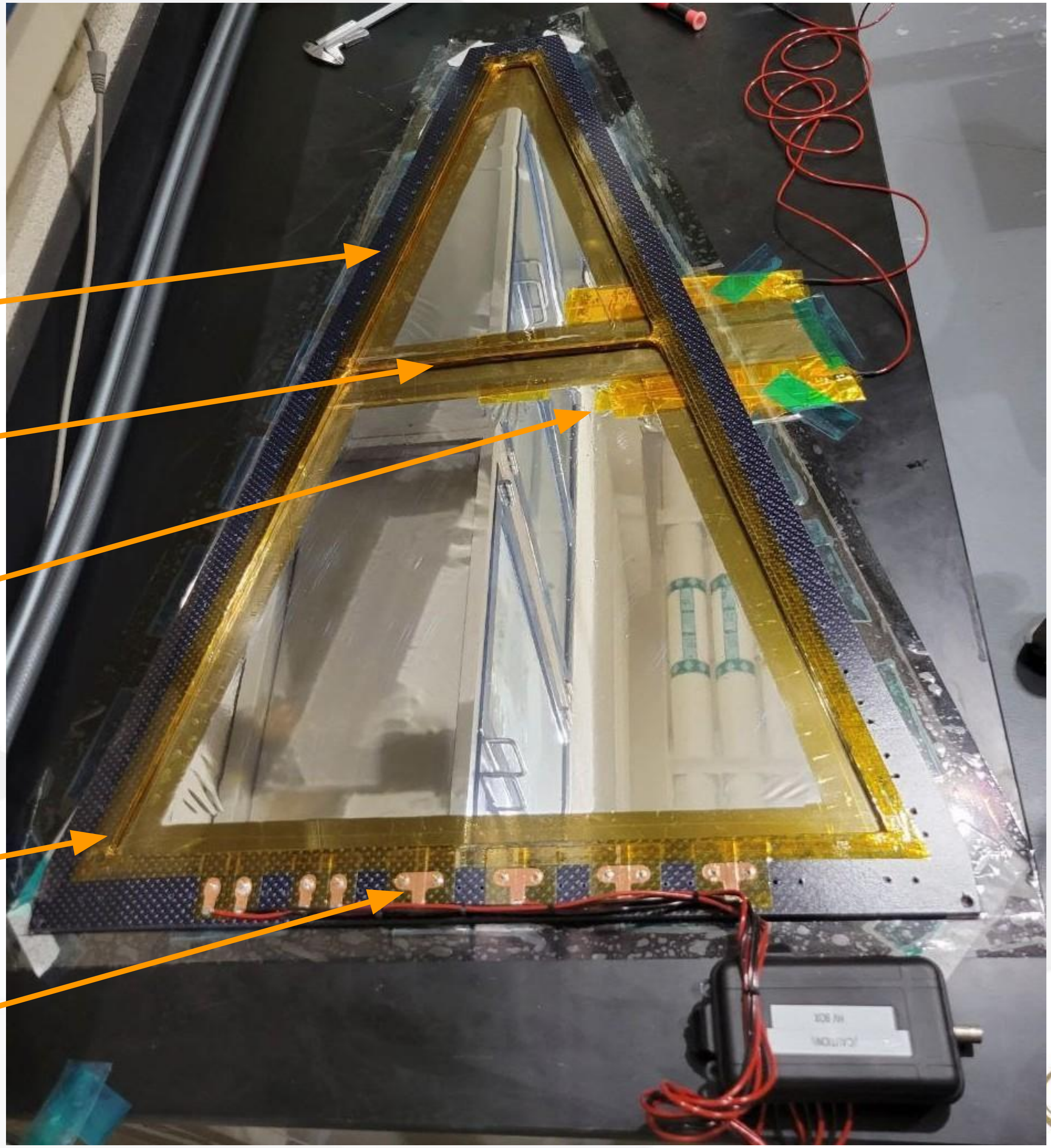
# Design of External Frames

GEM foils need a working gas to operate
- 70%Ar : 30%$CO_2$

- Carbon fiber (CF) frame with Al-Kapton windows
- Narrow rib in frame to fortify window and frame
- Voltage applied to Al side of drift window to counteract electrostatic force of drift foil
- Al removed in top frame window edges to insulate from CF Frame
- Electrical HV connections to GEM foils



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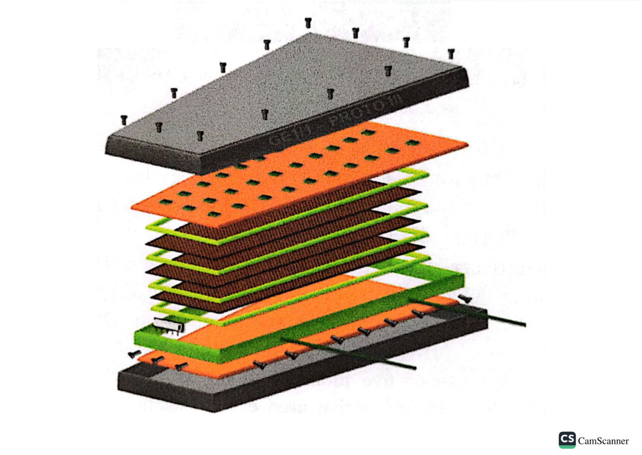
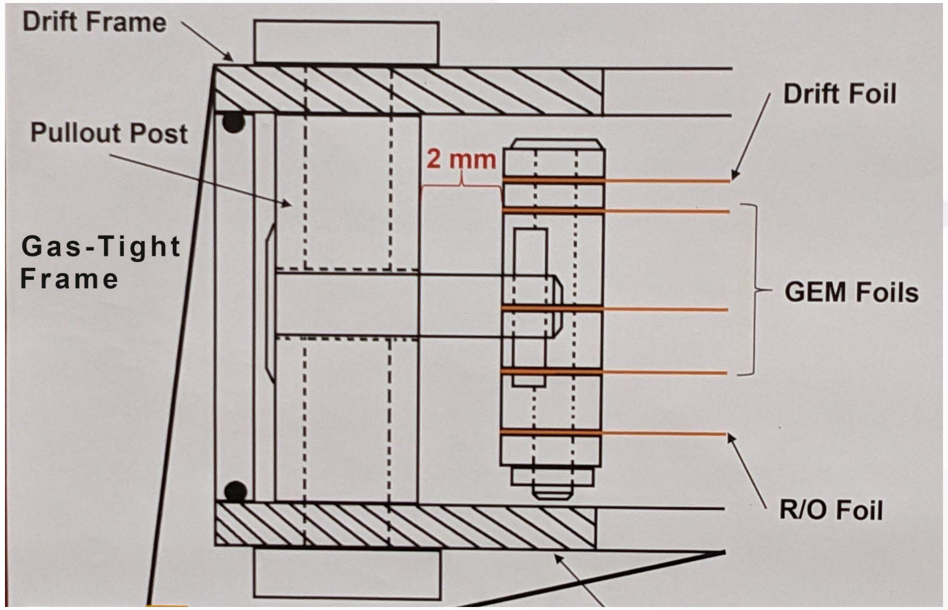
# How this GEM Detector was Assembled



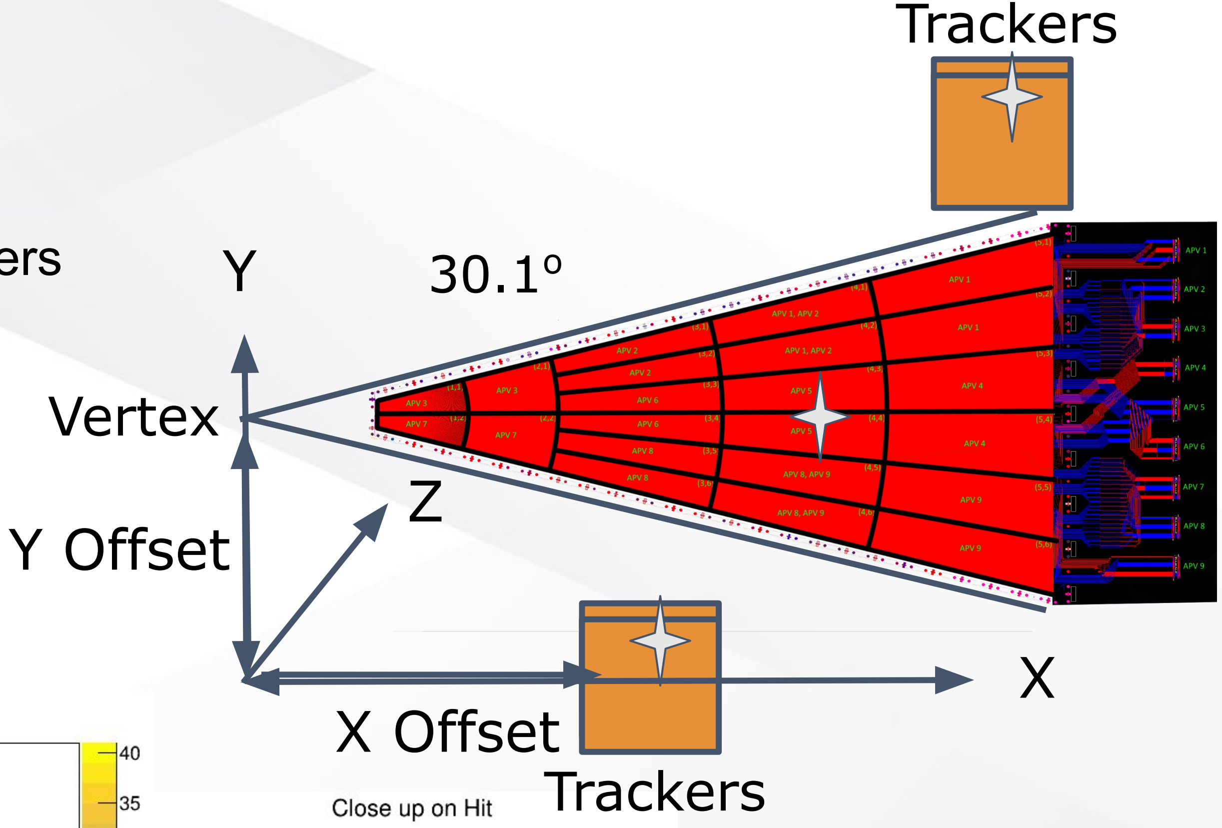


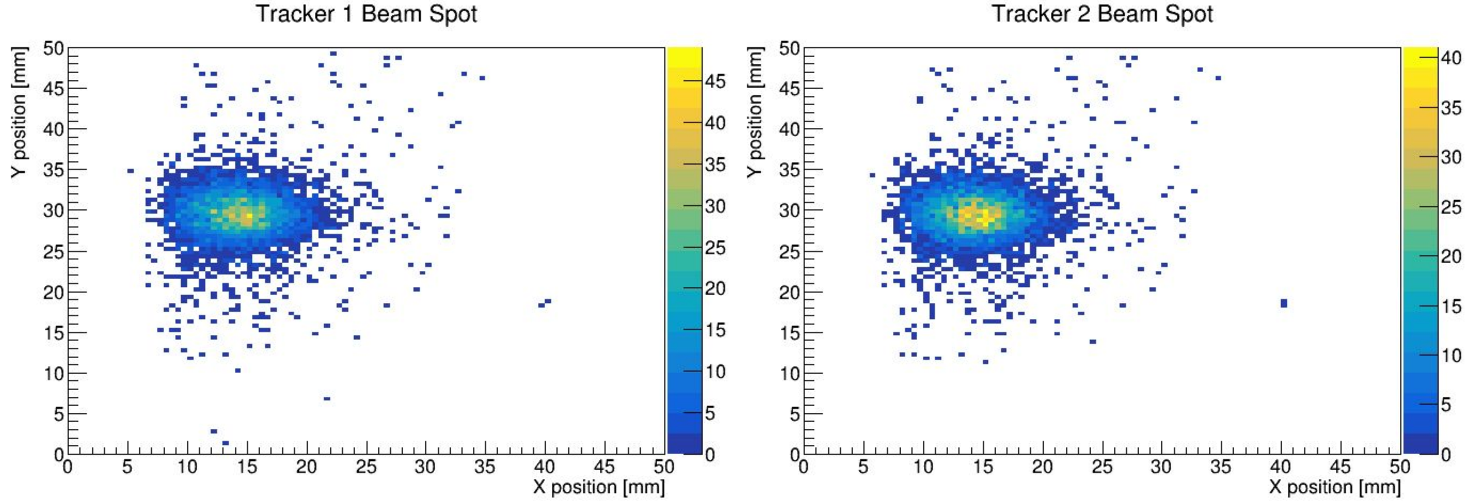

Exploded View [6] and Side Profile [] of assembled GEM stack

- Foils tested for Shorts
- GEM stack is assembled:
  - Foil placed on stack and stretched with tape
  - Spacer added
  - Foil tested for shorts
  - Repeat for all foils
- Tighten stack screws and cut tape
- GEM stack placed in bottom frame and connected to pullouts for last stretch
  - Planarity is Important for Uniform Gain
- Electrically test and add gas tight frame to seal top and bottom frames
- Screw on top frame and assembly is finished!

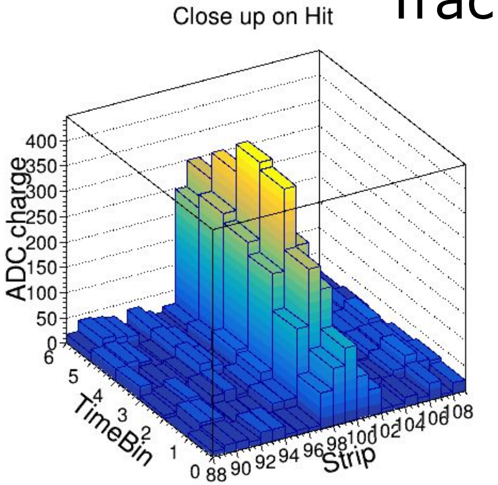
# How Adonis Analyzes the Data

- Use decoded signals from strips in GEMs and trackers
- Determine strip multiplicity and cluster charge
- Reconstruct particle track
    - Z positions were measured at FTBF
- Align trackers and GEMs (X,Y and rotational)
- Calculate reconstruction level data




Beam Spot in Trackers 1 and 2




Example Hit with Strip Multiplicity of 4



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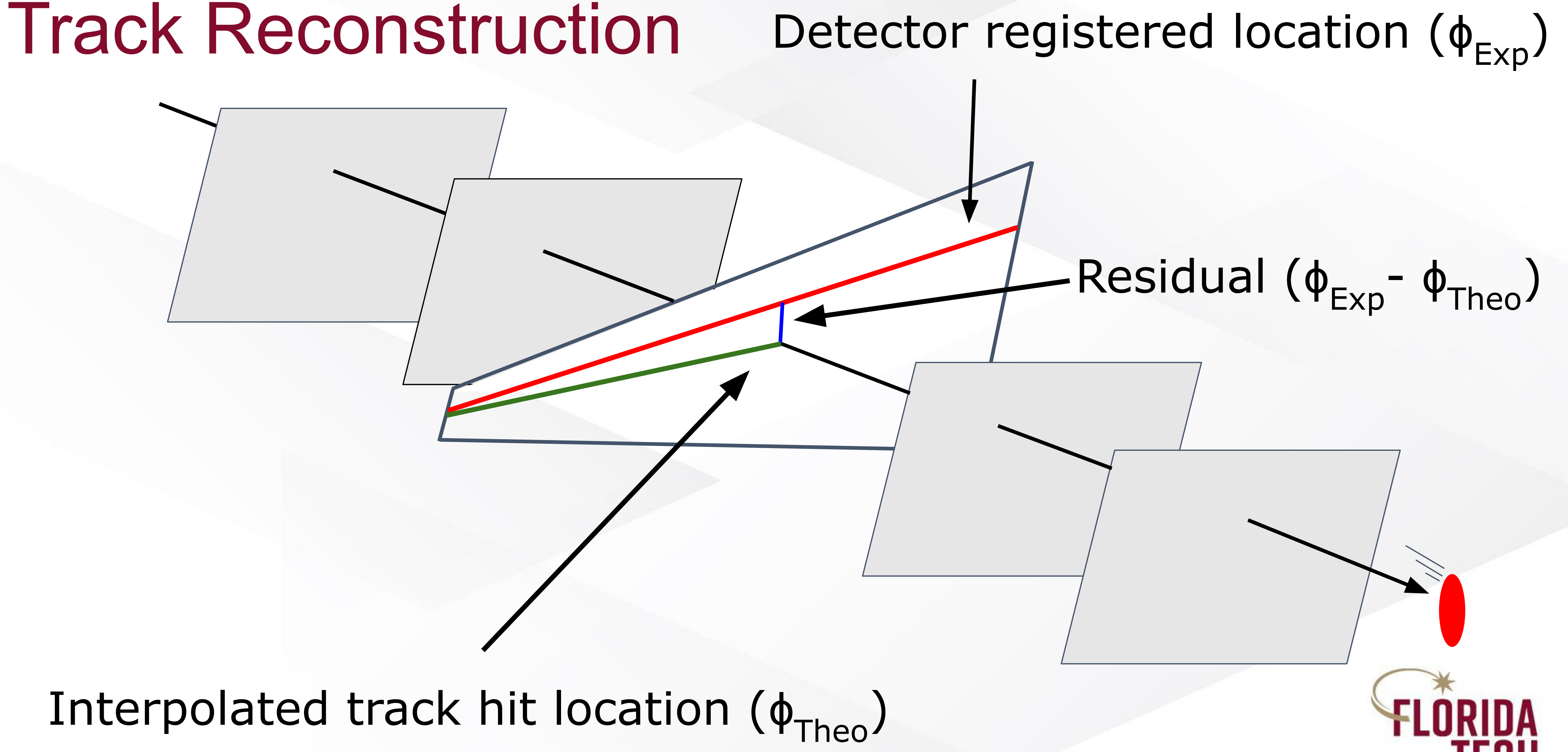
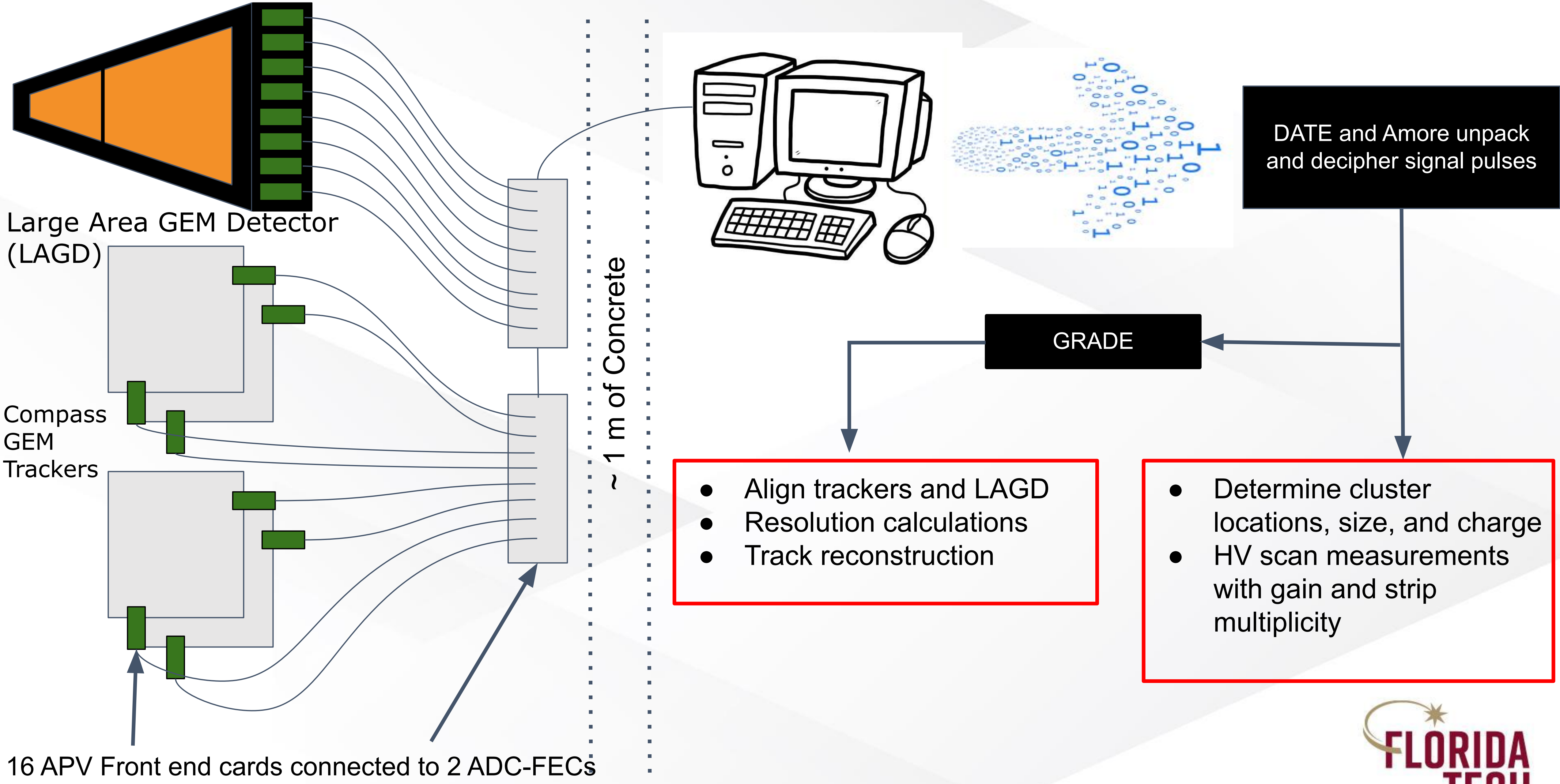
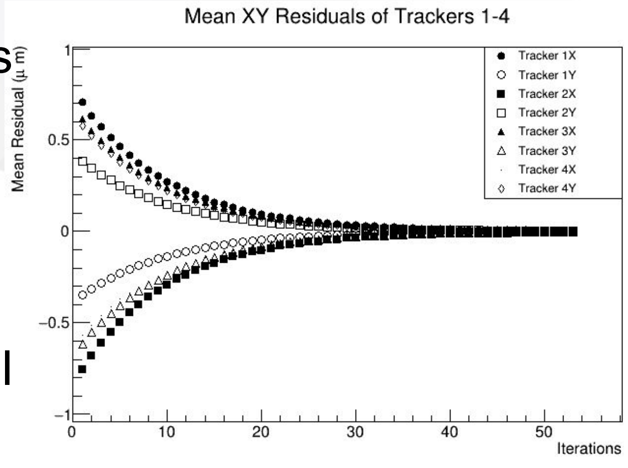
# Track Reconstruction

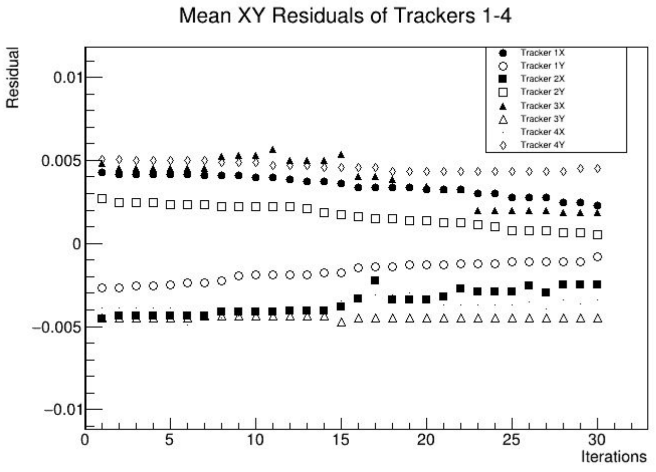


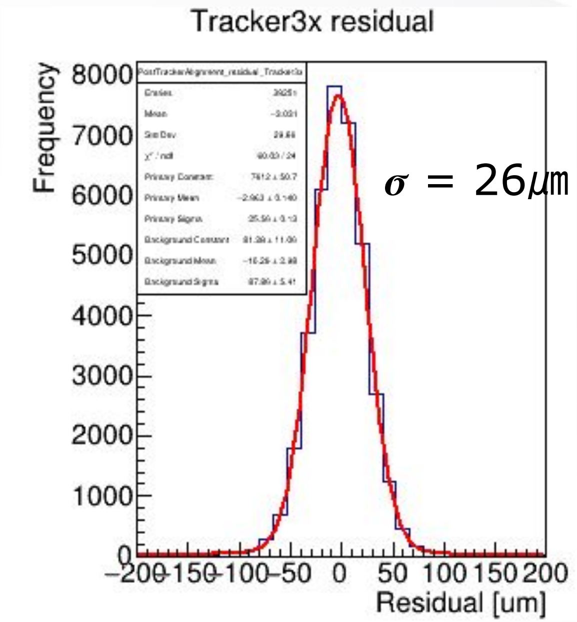

Large Area GEM Detector
(LAGD)
Compass
GEM
Trackers
~1 m of Concrete
16 APV Front end cards connected to 2 ADC-FECs
DATE and Amore unpack
and decipher signal pulses
GRADE
• Align trackers and LAGD
• Resolution calculations
• Track reconstruction
• Determine cluster locations, size, and charge
• HV scan measurements with gain and strip multiplicity

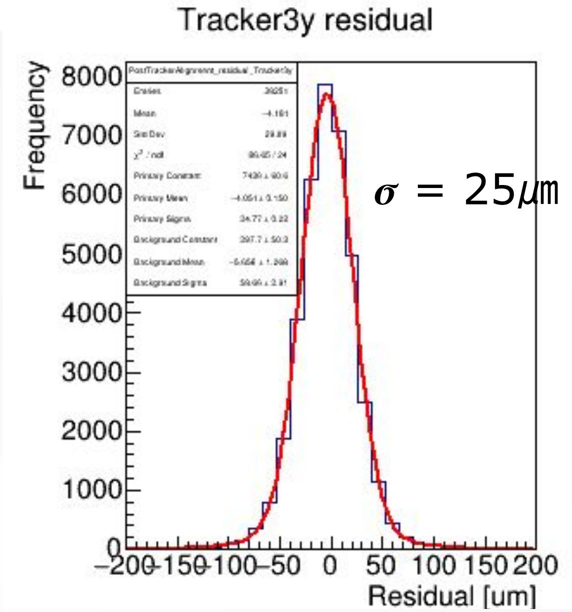
# Alignment of the Tracker GEMs

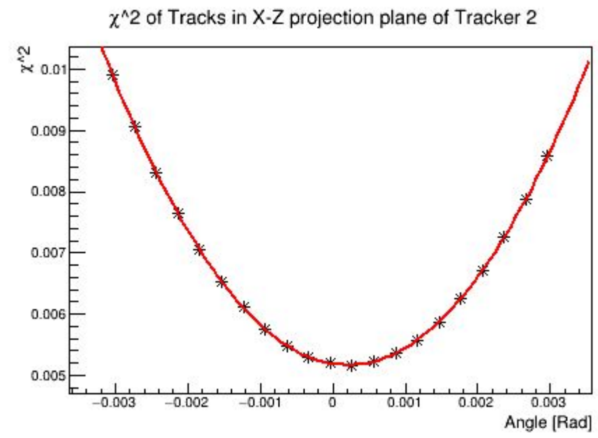
- Need trackers aligned to accurately reconstruct tracks
- 3 main alignment steps
  - Shift in X and Y
  - Shift and rotate at the same time
  - Individually rotate each tracker
- Each iteration shifts trackers by 10% of mean residual
- Trackers mean residuals aligned to within ≈25 $\mu m$

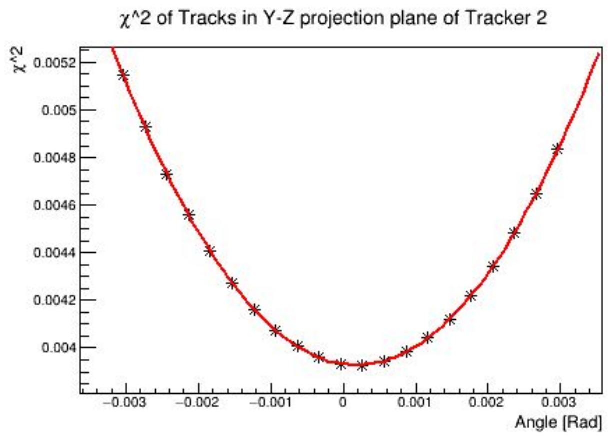
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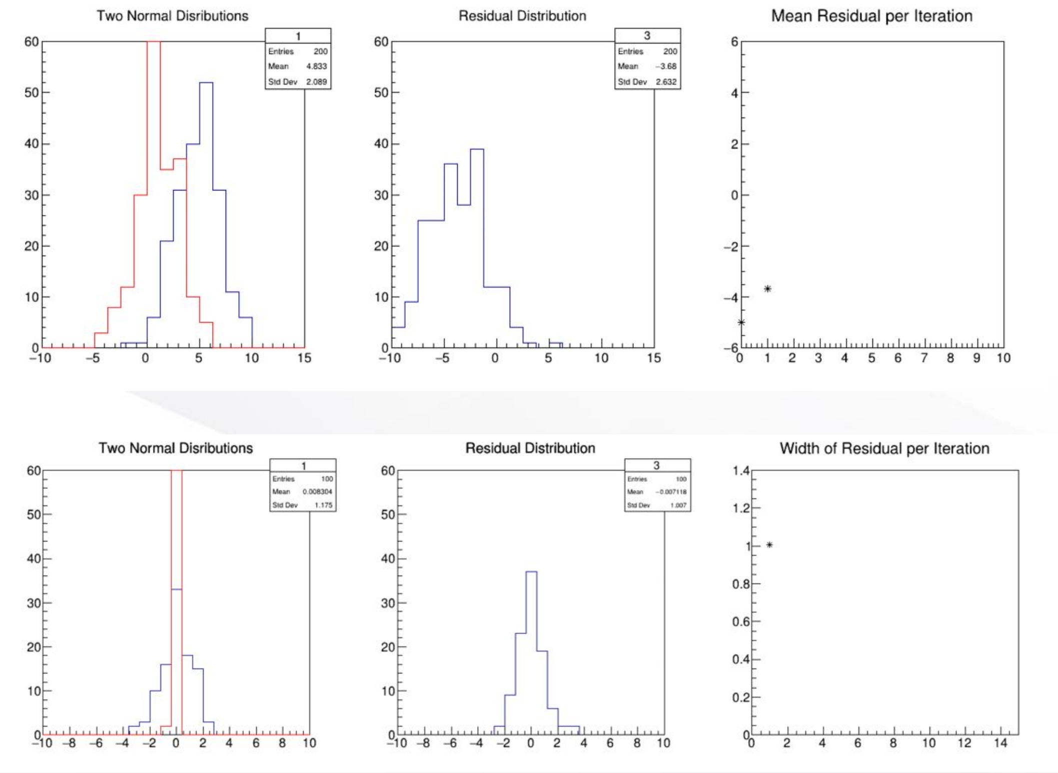
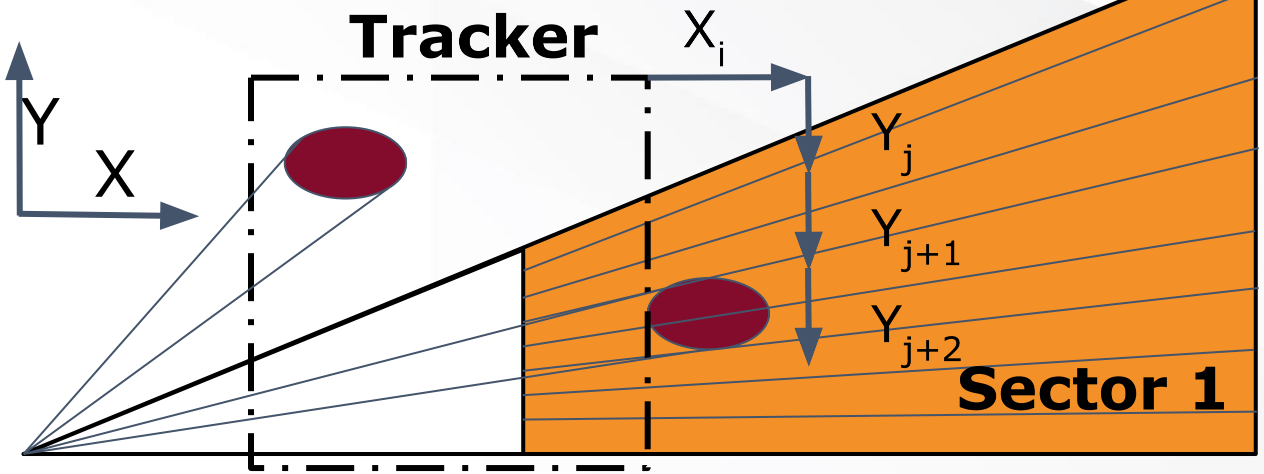
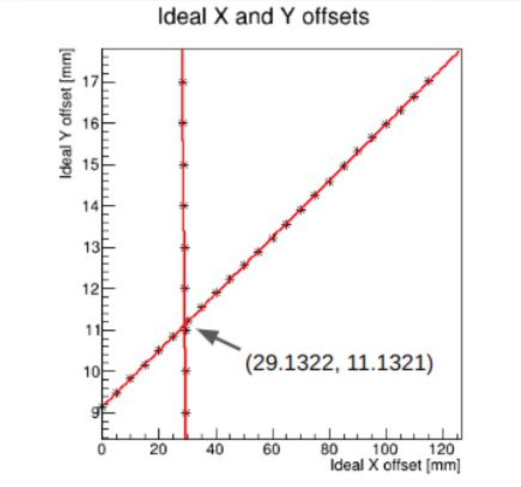
# Aligning the Trackers with the LAGD

- Need to determine X,Y offsets to align trackers with the active sector on the LAGD
- LAGD only measures azimuthal angle
- Convert tracker XY coordinates to polar coordinates
- The tracker beam spot is shifted throughout the active sector and tracks are reconstructed
  - Ideal Y offset minimizes LAGD residual mean
  - Ideal X offset minimizes LAGD residual standard deviation



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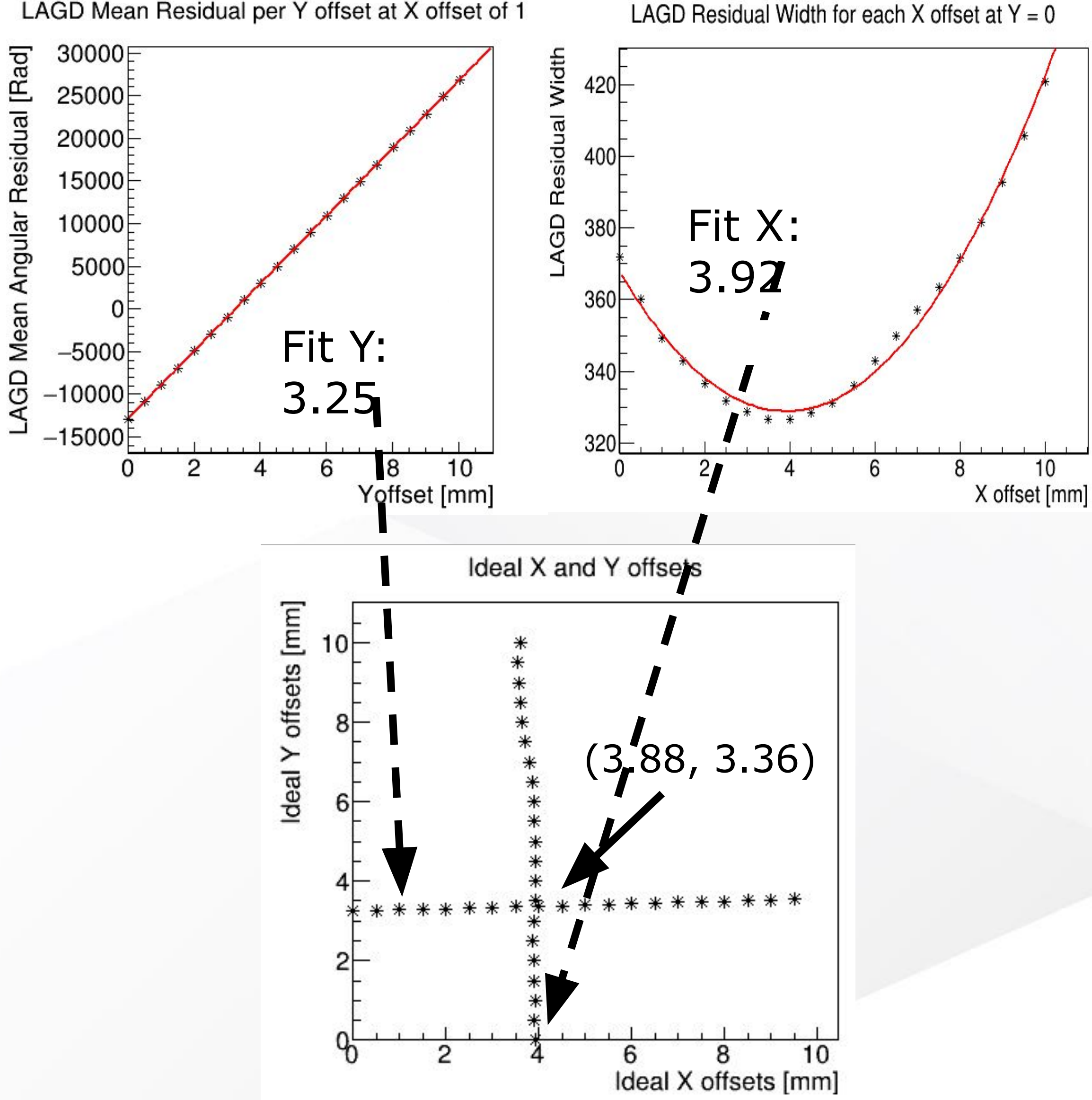
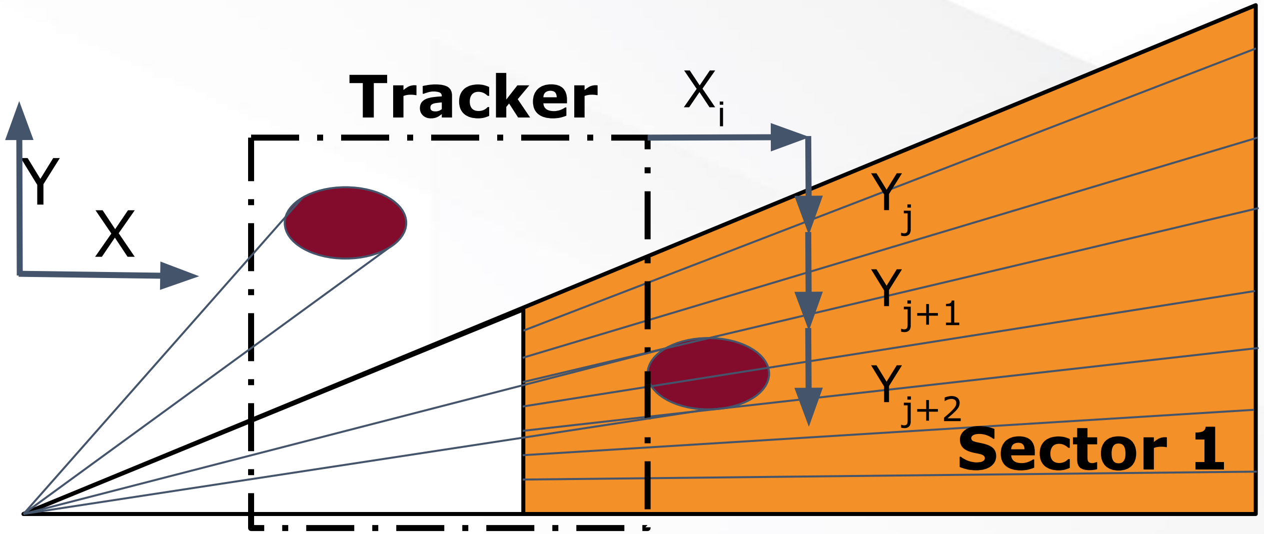
# Aligning the Trackers with the LAGD

- Need to determine X,Y offsets to align trackers with the active sector on the LAGD
- Convert tracker XY coordinates to polar coordinates
- The tracker beam spot is shifted throughout the active sector and tracks are reconstructed
  - Ideal Y offset minimizes LAGD residual mean
  - Ideal X offset minimizes LAGD residual standard deviation



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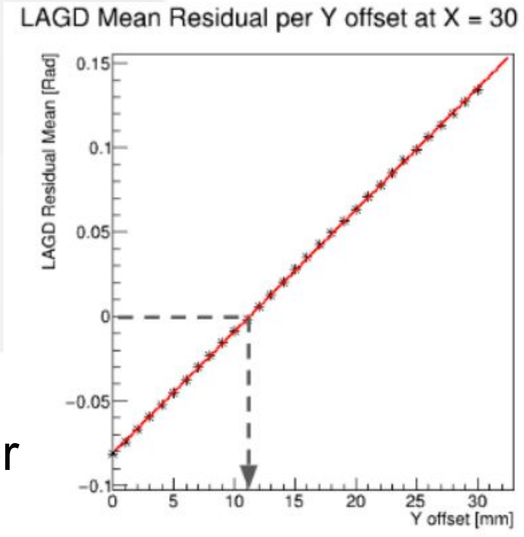
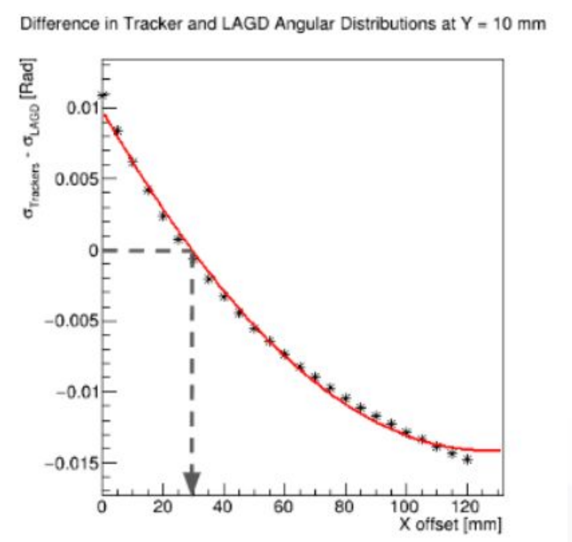
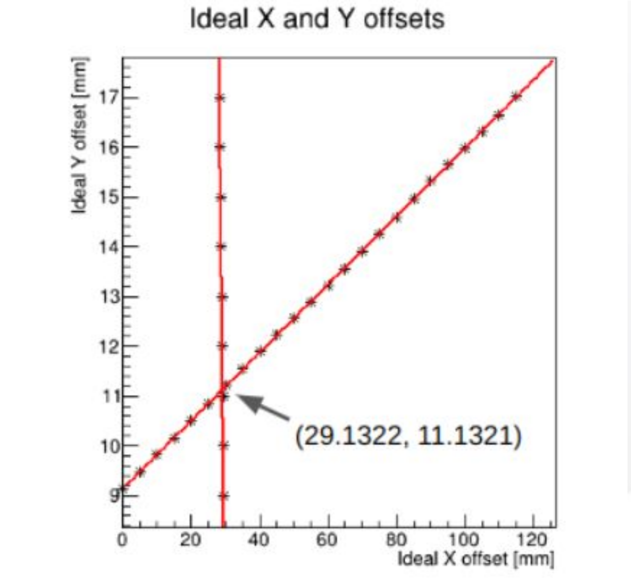
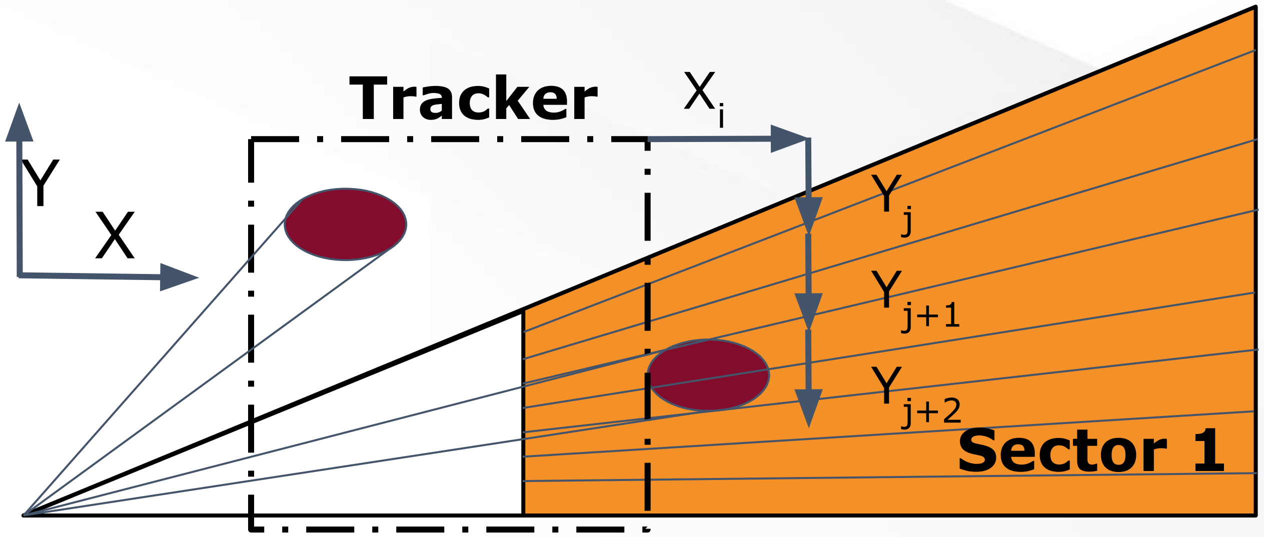
# Aligning the Trackers with the LAGD

- Need to determine X,Y offsets to align trackers with the active sector on the LAGD
- LAGD only measures azimuthal angle
- Covert tracker XY coordinates to polar coordinates
- The tracker beam spot is shifted throughout the active sector and tracks are reconstructed
  - Ideal Y offset minimizes LAGD residual mean
  - Ideal X offset minimizes LAGD residual standard deviation

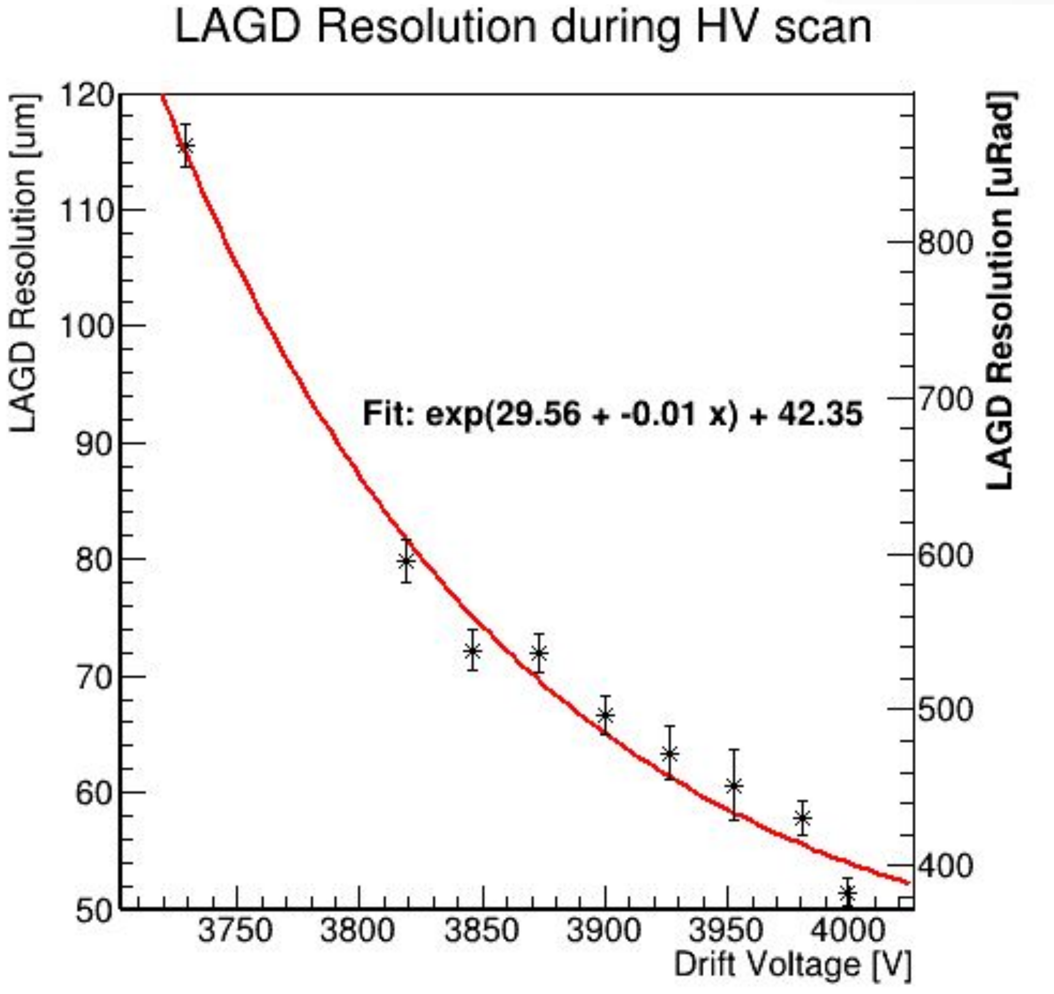


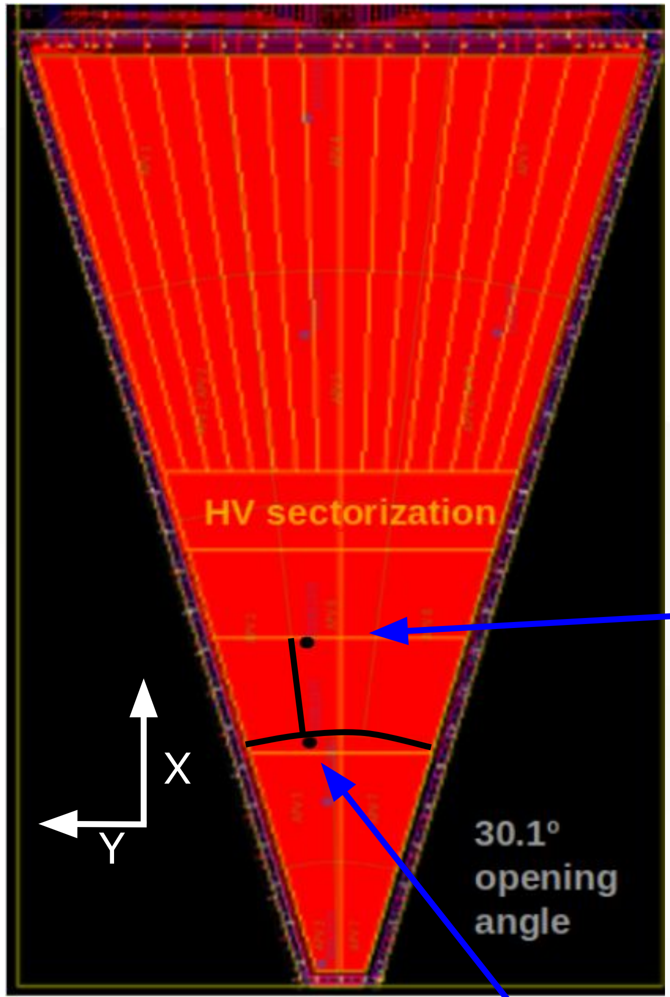



# HV effect on Resolution in Straight Strips

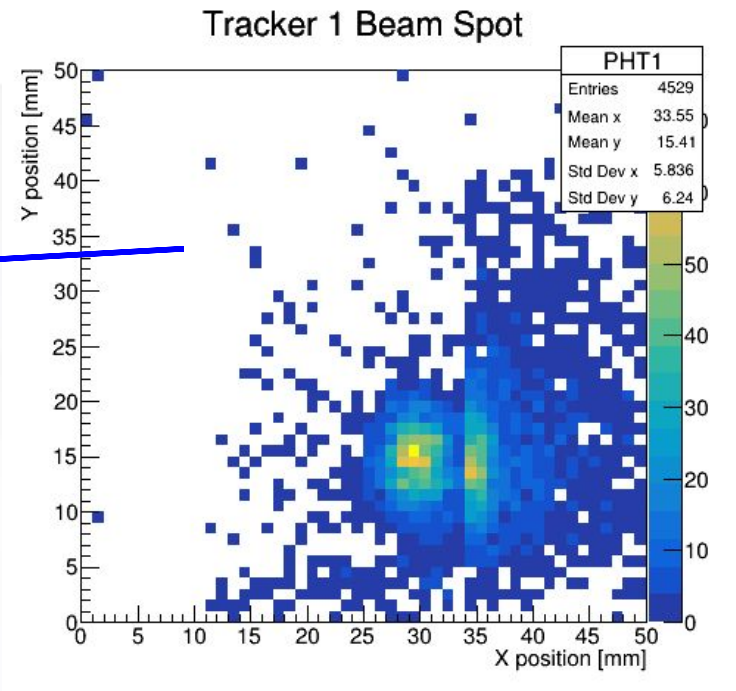


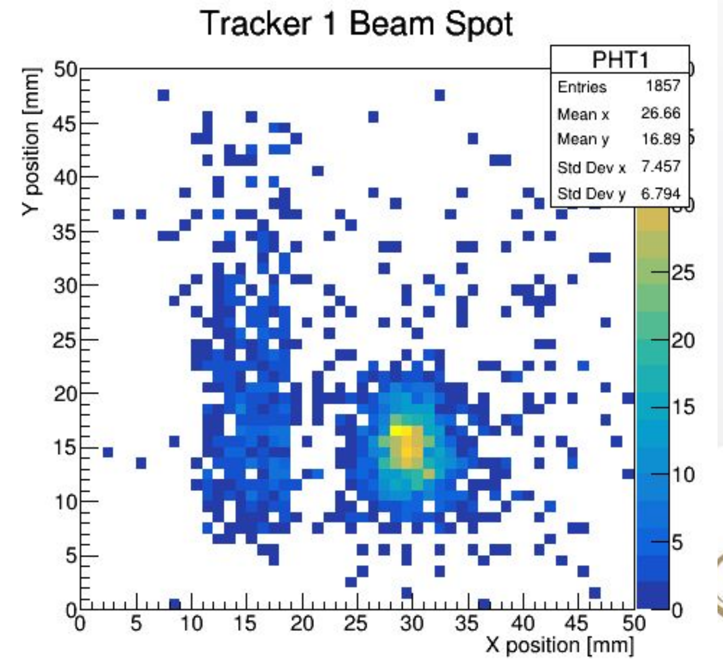

- Resolution decreases as voltage to GEMs increase
- Electron showers are accelerated, which generates more electrons and improves resolution of hit
- Fit function shows convergence towards 42 um

# Current Hypothesis of why two sectors have Bad Resolutions




- Superimposed image of GEM foil and Readout foil
- Shows these two bad locations share an HV sector, and one is splitting two sectors
  - If this sector was shorted, it would explain loss in gain here
- … located on the intersection of 3 sectors,



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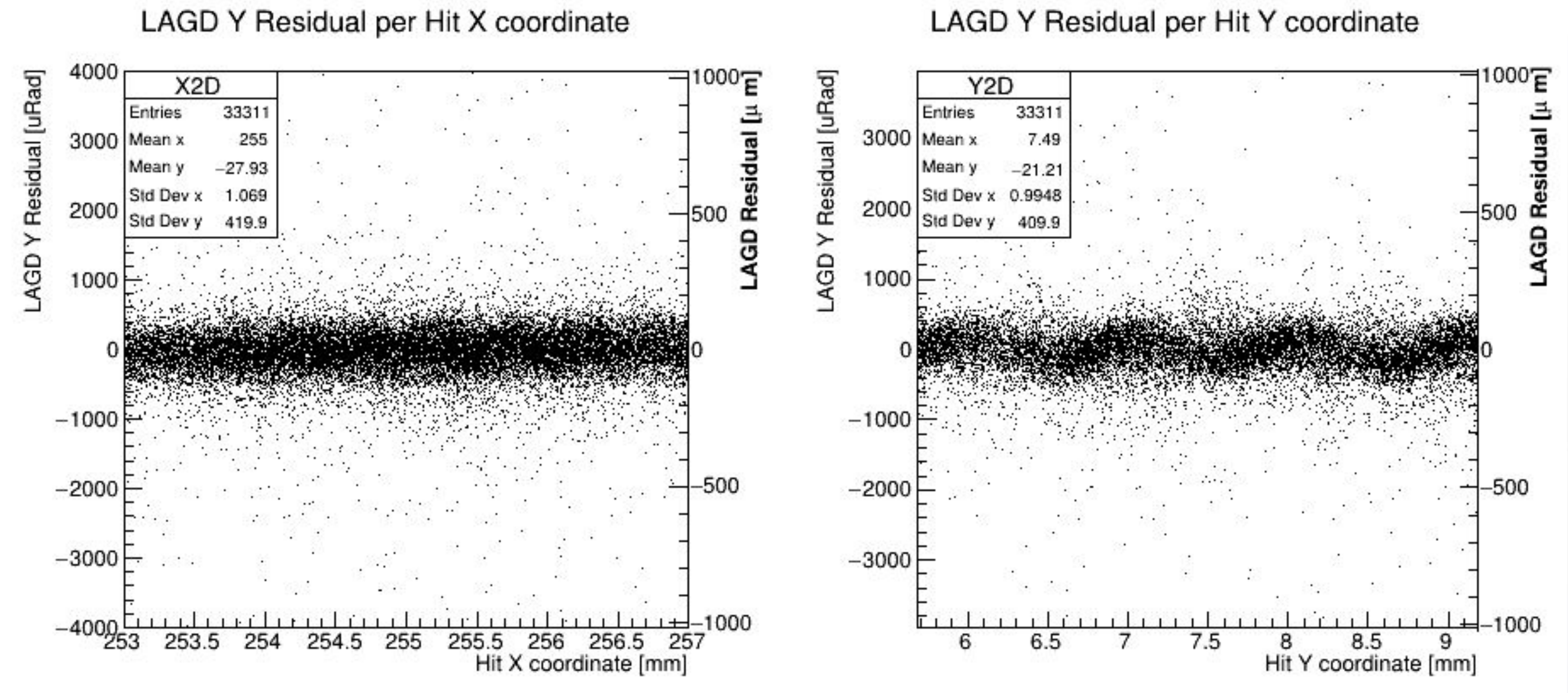
# Non-linear Residual on ZigZag Strips




- Uneven charge sharing across the width of the strip causes biasing