A Muon Tomography Station with GEM Detectors for Nuclear Threat Detection

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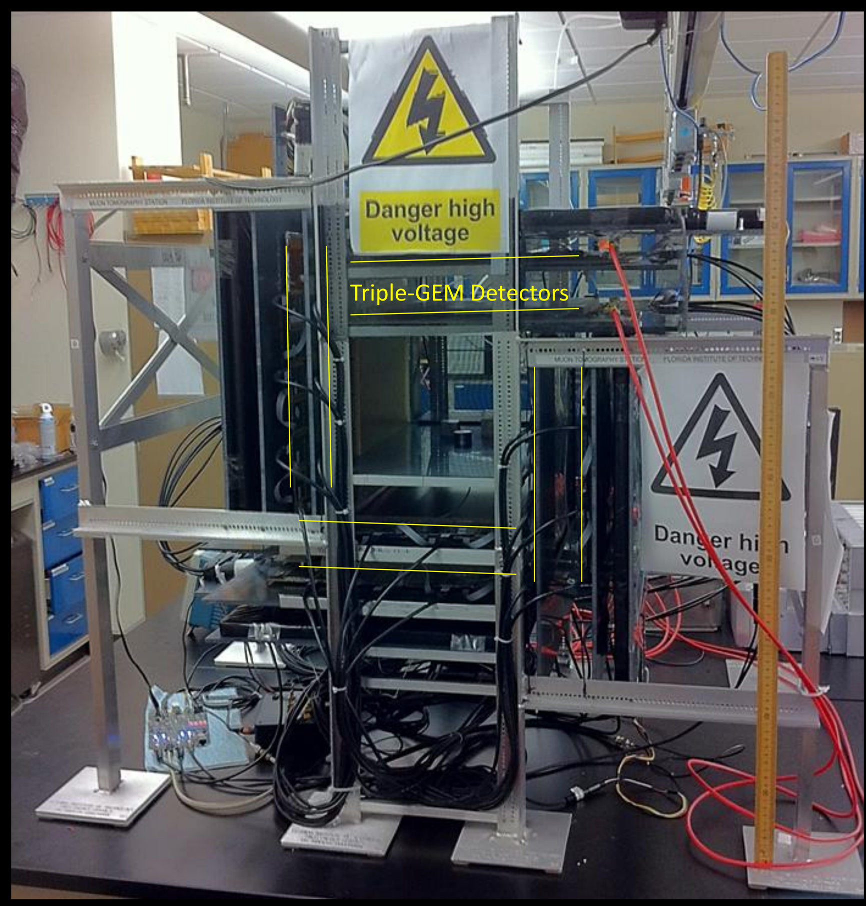
Abstract

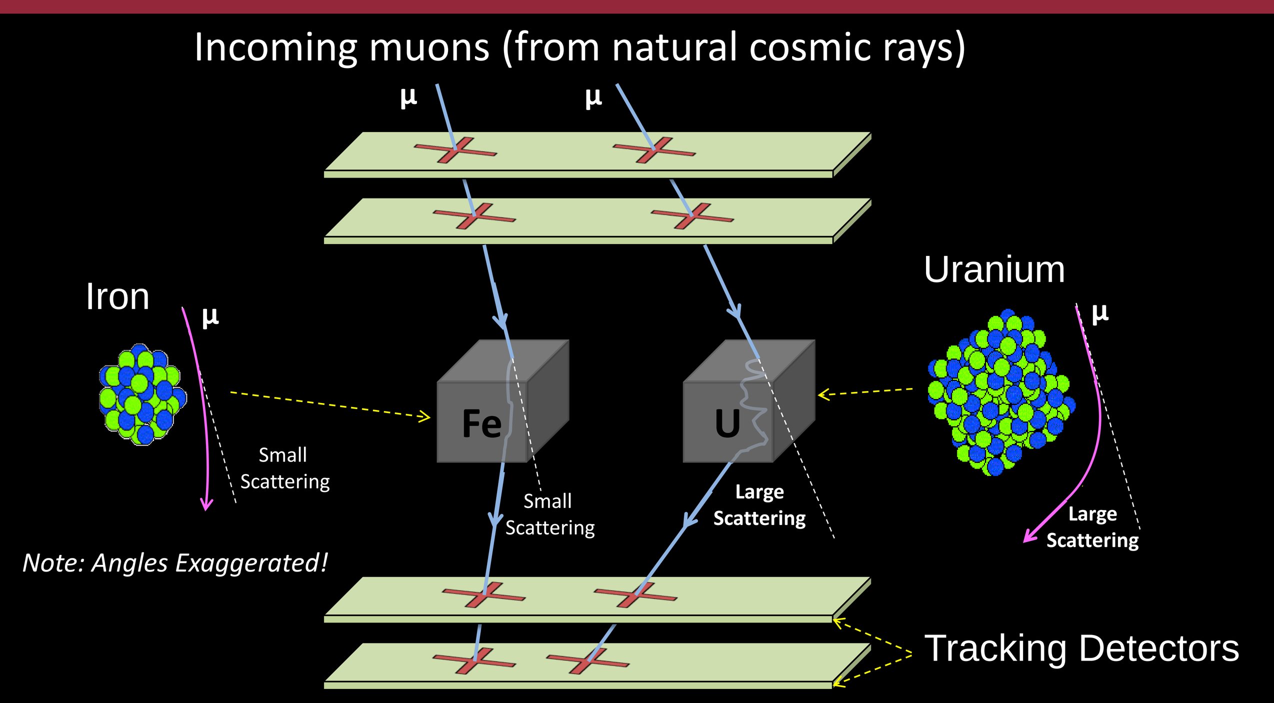
Muon tomography for homeland security aims at detecting well-shielded nuclear contraband in cargo and imaging it in 3D. The technique exploits multiple scattering of atmospheric cosmic ray muons, which is stronger in dense, high-Z nuclear materials, e.g. enriched uranium, than in low-Z and medium-Z shielding materials. We have constructed and operated a compact Muon Tomography Station (MTS) that tracks muons with eight to ten 30 cm x 30 cm Triple Gas Electron Multiplier (GEM) detectors placed on the sides of a 27-liter cubic imaging volume. The 2D strip readouts of the GEMs achieve a spatial resolution of ~120 μm in both dimensions and the station is operated at a muon trigger rate of ~35 Hz. The 1,536 strips per GEM detector are read out with the first medium-size implementation of the Scalable Readout System (SRS) developed specifically for Micro-Pattern Gas Detectors by the RD51 collaboration at CERN. We discuss the performance of this MTS prototype and present experimental results on tomographic imaging of high-Z objects with and without shielding.

Cubic-Foot Muon Tomography Station with 8 GEMs



Prototype muon tomography station designed and built at Florida Tech. The design allows for adjustable station configurations including side detectors. The current configuration includes 8 triple-GEM detectors (yellow) surrounding four sides of a ft^3 (27 l) active volume.

Muon Tomography Concept



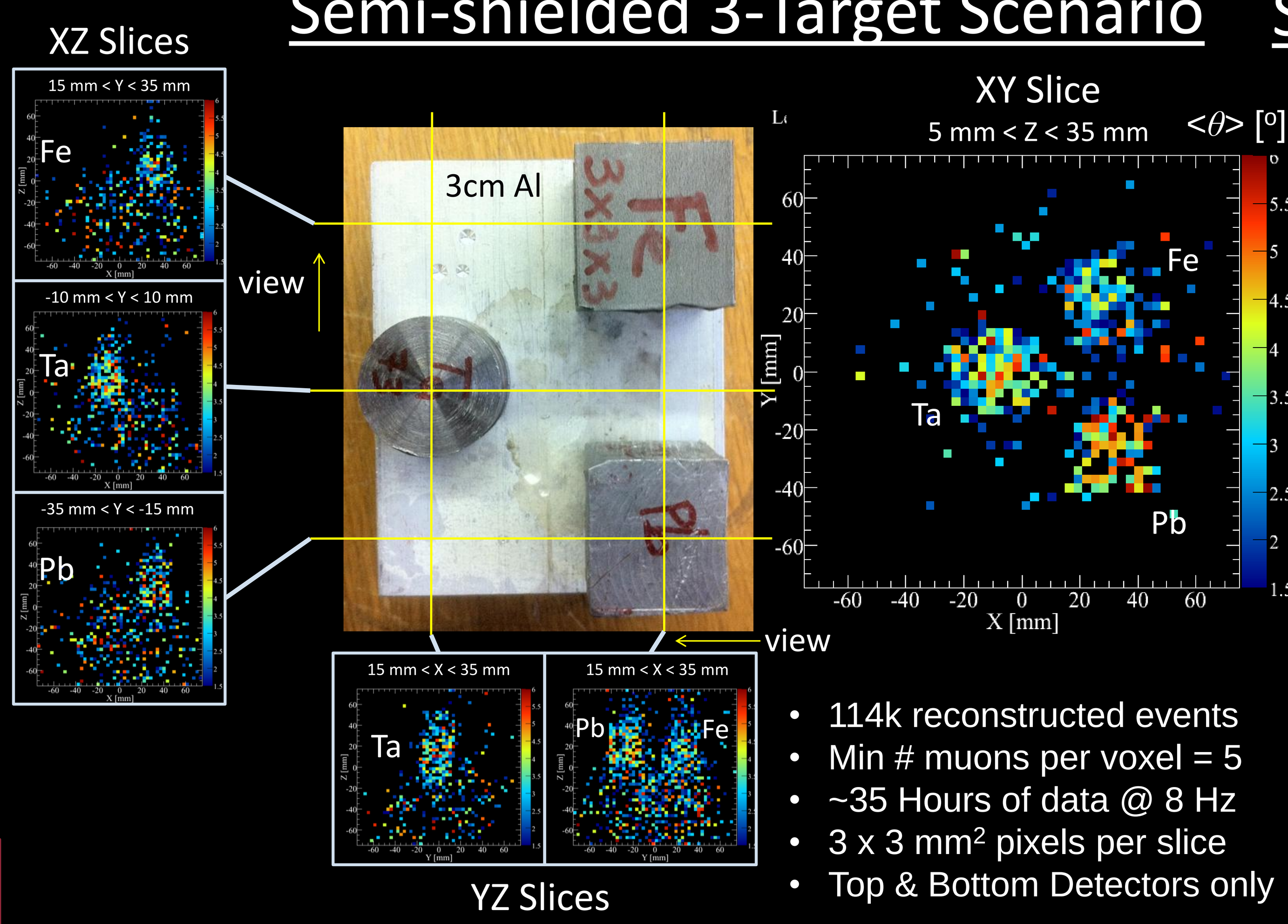
Main Idea: Multiple Coulomb scattering is proportional to Z, allowing for the discrimination of materials by Z.

$$\theta_0 = \frac{13.6\mathrm{MeV}}{\beta c p} \cdot z \sqrt{\left(\frac{x}{X_0}\right)} \cdot \left[1 + 0.038 \ln\left(\frac{x}{X_0}\right)\right]$$

$\beta c \rightarrow$ Velocity
$p \rightarrow$ Momentum
$z \rightarrow$ Charge Number
$x \rightarrow$ Width of Medium
$X_0 \rightarrow$ Radiation Length

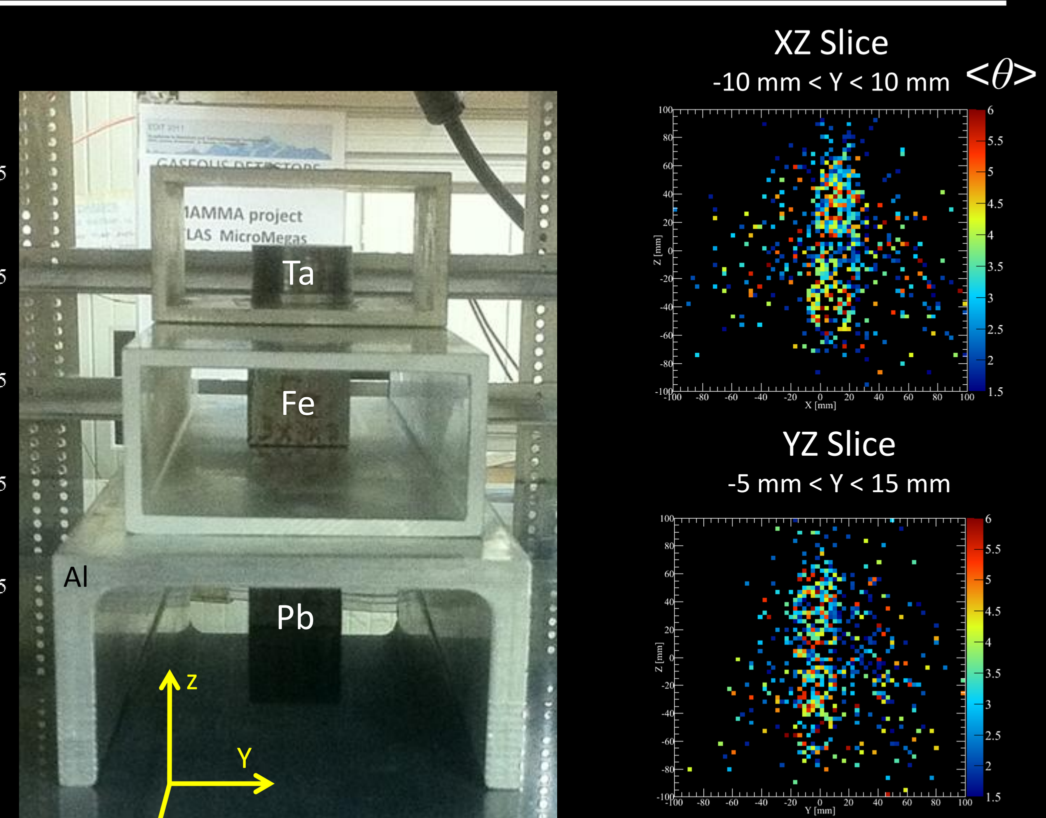
Point-Of-Closest-Approach (POCA) Reconstruction of Target Scenarios

Semi-shielded 3-Target Scenario



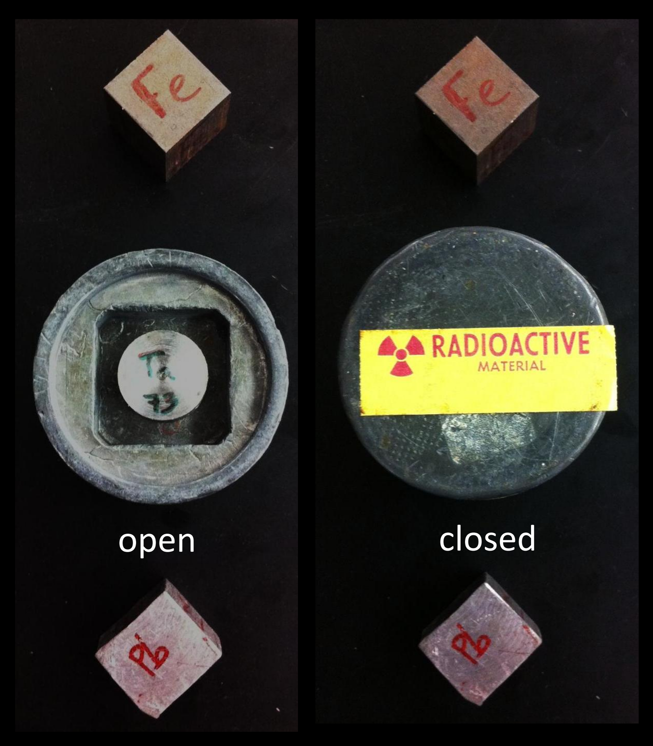
- 114k reconstructed events
- Min # muons per voxel = 5
- ~35 Hours of data @ 8 Hz
- 3 x 3 mm^2 pixels per slice
- Top & Bottom Detectors only

Shielded Vertical Clutter Scenario

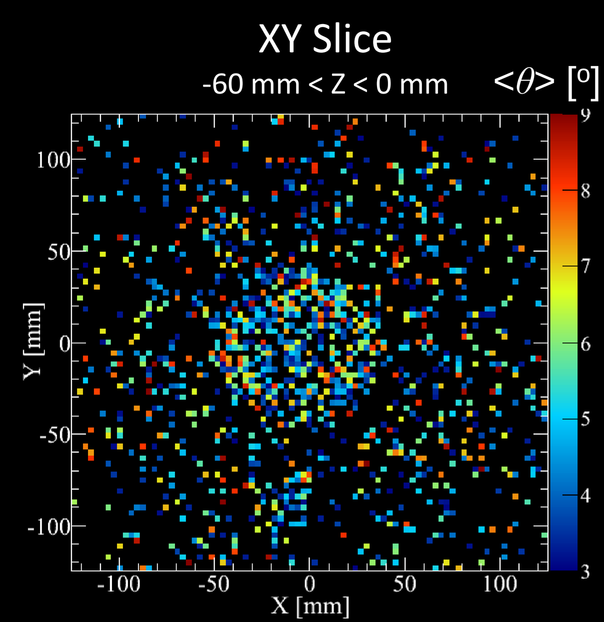


- 168k reconstructed events
- Min. # muons per voxel = 4
- ~50 Hours of data @ 8 Hz
- Top & Bottom Detectors only

Lead Shield Scenario

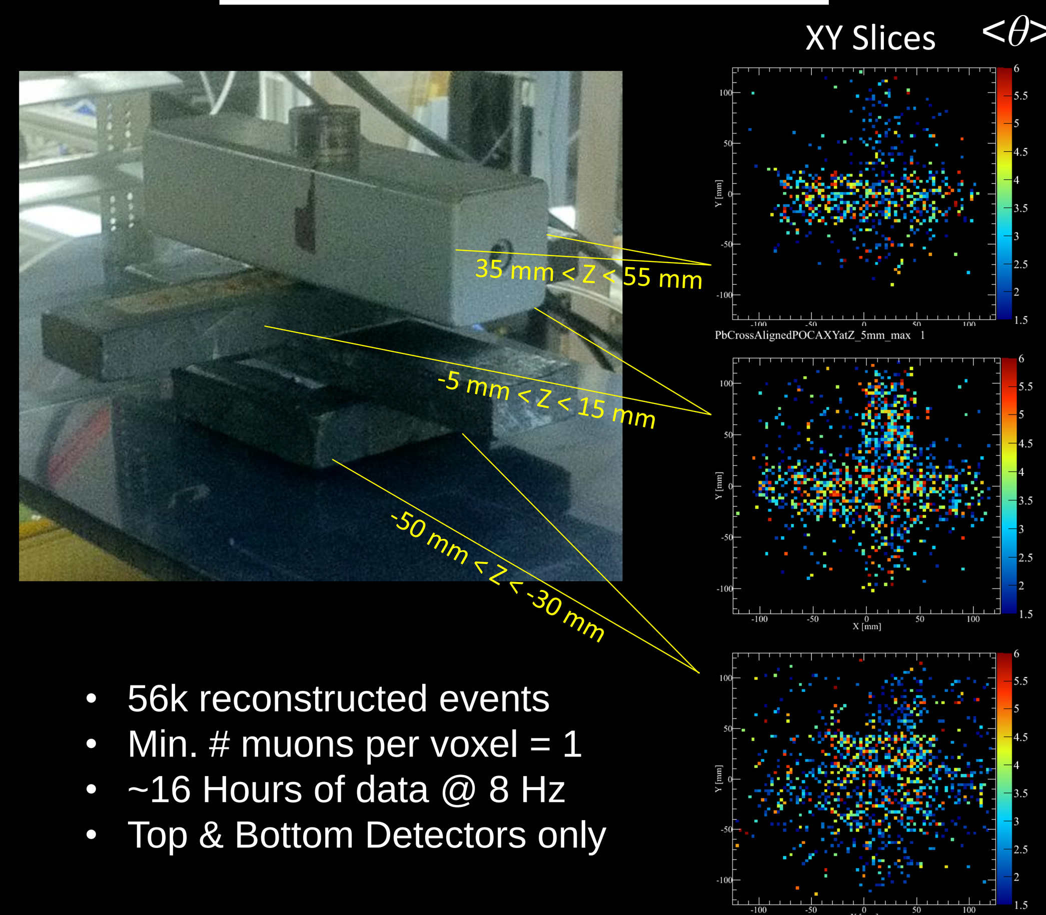


Tantalum cylinder fully shielded within a lead container



- 102k reconstructed events
- Min. # muons per voxel = 2
- ~7 Hours of data @ 35 Hz
- Top, Bottom & Side Detectors
- Only preliminary detector alignment

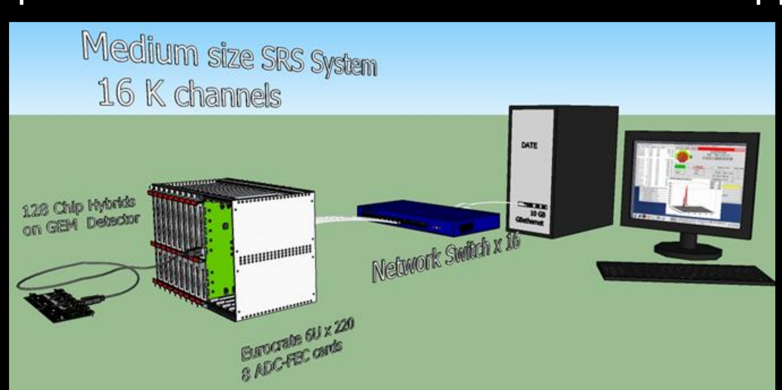
Lead Cross Scenario



- 56k reconstructed events
- Min. # muons per voxel = 1
- ~16 Hours of data @ 8 Hz
- Top & Bottom Detectors only

DAQ Hardware & Software

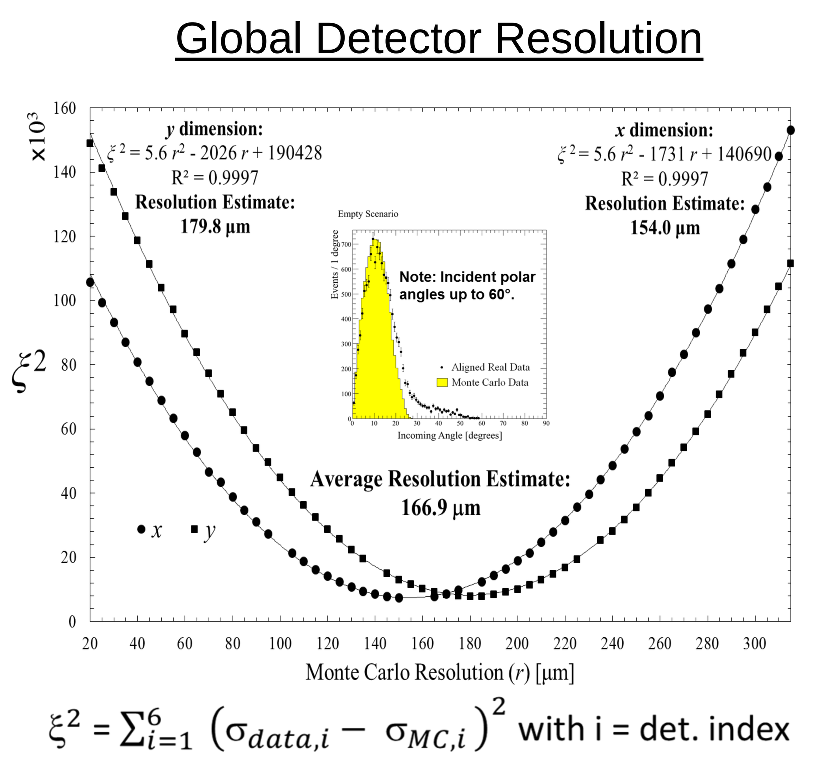
The >12k analog channels are read out at ≈35 Hz using the largest implementation of the RD51 Scalable Readout System (SRS) to-date. The SRS was developed at CERN as a low–cost scalable DAQ system for specific use with micropattern gaseous detectors. Data are collected using a hybrid card based on the 128-channel APV25 chip and sent via HDMI cables to ADC cards which support 16 APV hybrids each. ADC data are formatted by a front end concentrator (FEC) based on the Virtex LX50T FPGA. Data from 6 FECs are sent via gigabit ethernet through two switches to a DAQ computer at 15 MB/s and processed for online and offline analysis using DATE and AMORE software developed for the ALICE experiment. Raw event size without zero suppression is ≈500 kB.



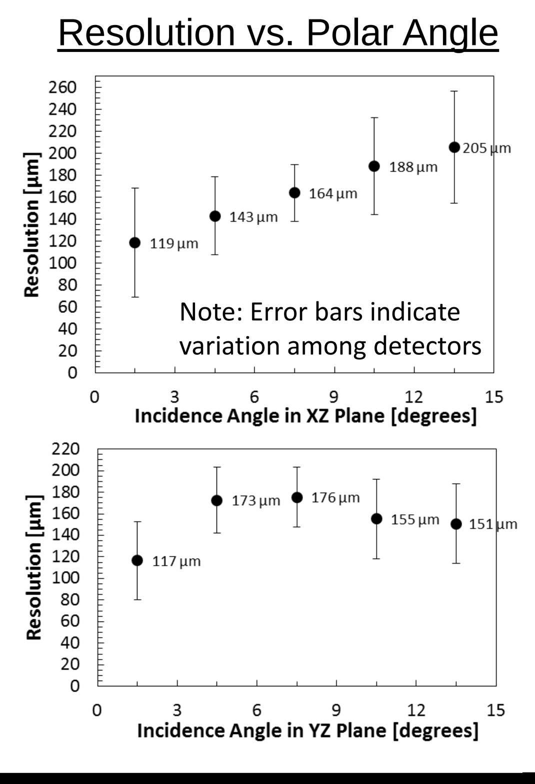
APV Hybrid Card
(RD 51 series production)

Spatial Resolution

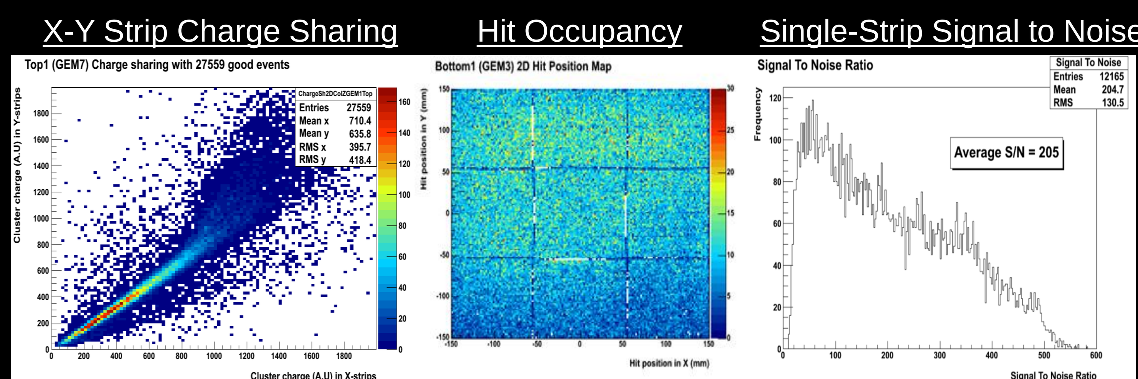
The spatial resolution of the GEM detectors was measured using data from an empty station with 3 GEMs each at top and bottom. Unbiased residuals are found for each detector using straight tracks and compared to GEANT4 Monte Carlo simulation. Utilizing all tracks, including those with higher polar angles, a global spatial resolution of ~170 μm is found. If the selection is limited to incident polar angles < 3°, the spatial resolution estimate is ~120 μm.



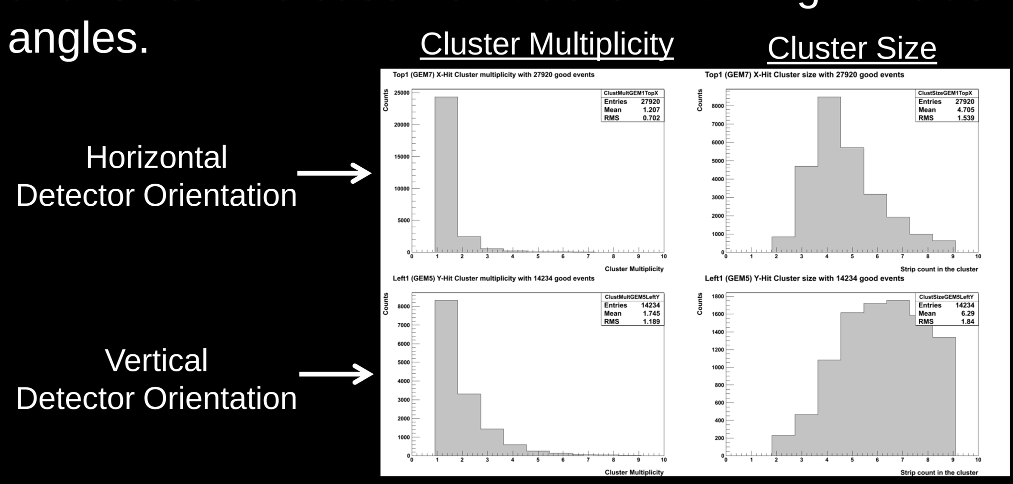
$\xi^2 = \sum_{i=1}^{6} \left(\sigma_{data,i} - \sigma_{MC,i}\right)^2$ with i = det. index



Detector Characterization



Charge is unequally shared between the top and bottom strips of the readout due to their geometry. The fiberglass support structure within the GEM detectors is clearly visible in the hit occupancy plot. It is important to note the effect of high incidence angles on the side detectors. Cluster multiplicities and sizes increase for tracks with high incidence angles.



Future Work

We plan to improve the reconstruction in the future, e.g. include more robust hit and track selection algorithms to account for improperly assigned tracks and to include an automatic alignment procedure to improve the quality of the side detector reconstruction by aligning the detectors to the sub-mm scale. There is also a need to suppress zeroes in the data at the hardware level to reduce the data size. Imaging resolution and discrimination time are also currently under investigation.

Acknowledgments & Disclaimer

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