Muon Tomography with compact Gas Electron Multiplier Detectors

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Marcus Hohlmann, P.I.

Florida Institute of Technology, Melbourne, FL

Outline

- **Concepts**
  - Gas Electron Multipliers
  - GEM detector basics
- **GEANT4 Simulation**
  - Comparison: Drift Tube Detector vs. GEM Detector
- **Hardware Development**
  - Minimal GEM Muon Tomography Station
    - GEM performance
    - First muon tomography result
  - Development of next prototype
    - Design
    - Electronics and DAQ

Concepts

Homeland Security

Concept: MT with MPGDs

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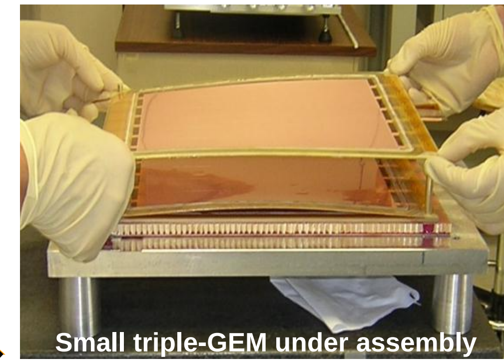
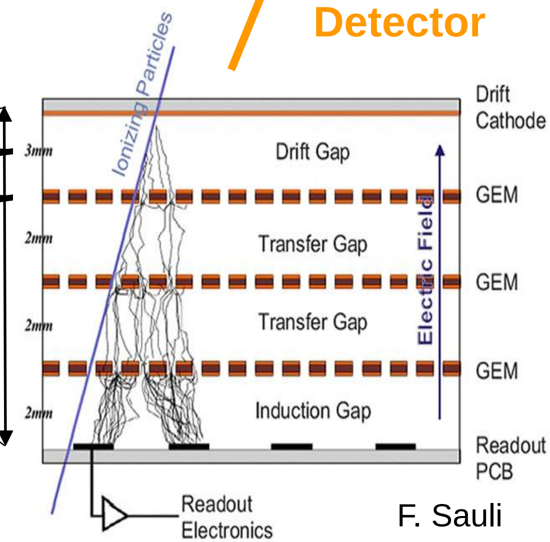
Use Micro Pattern Gaseous Detectors for tracking muons:

ADVANTAGES:

- ❑ small detector structure allows compact, low-mass MT station:
  - thin detector layers
  - small gaps between layers
  - low mult. scattering in detector itself
- ❑ high MPGD spatial resolution (~50µm)
  - provides good scattering angle measurement with short tracks
- ❑ high tracking efficiency



GEM Detector



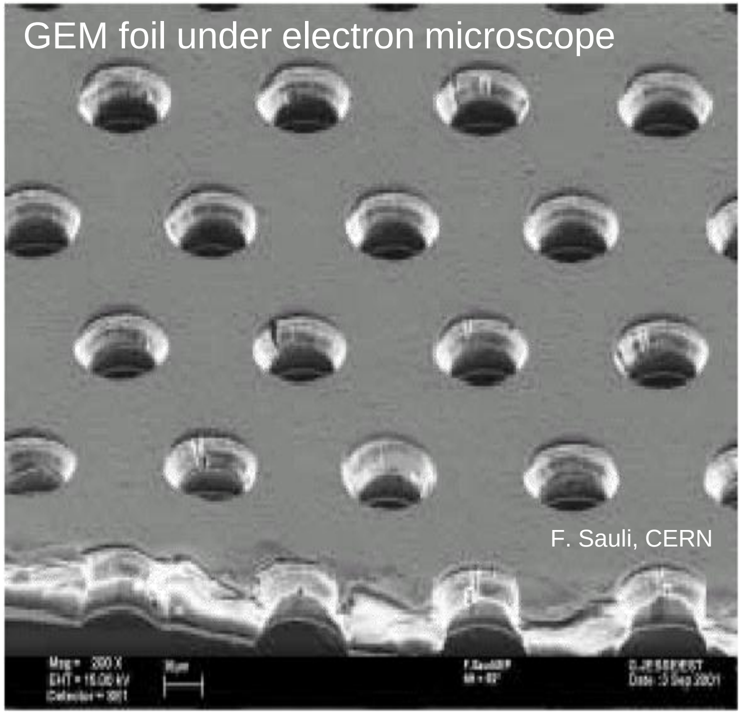
F. Sauli

CHALLENGES:

- ❑ need to develop large-area MPGDs
- ❑ large number of electronic readout channels

Gas Electron Multiplier Detectors

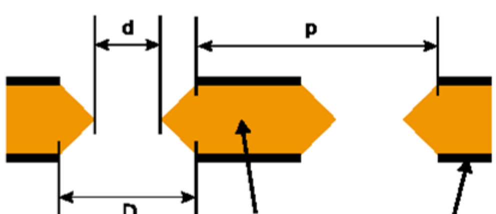
GEM - Electric Field Map

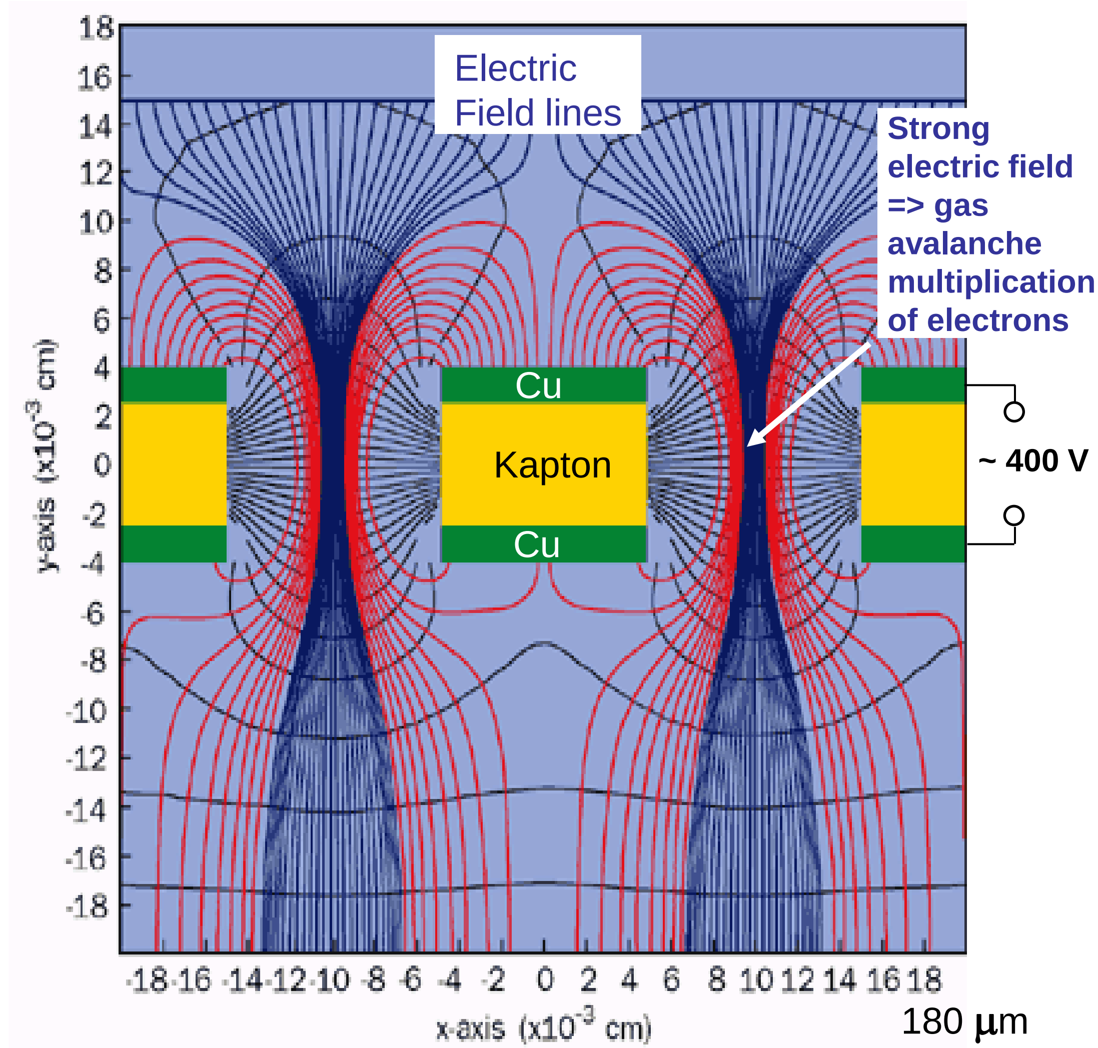


Typical Dimensions:

$$D = 70\ \mu m$$
$$d = 60\ \mu m$$
$$p = 140\ \mu m$$

Cross section:





GEM Detector

Advantages:

- **<u>high spatial resolution</u>:**

  ~ 50 μm for perpendicular tracks

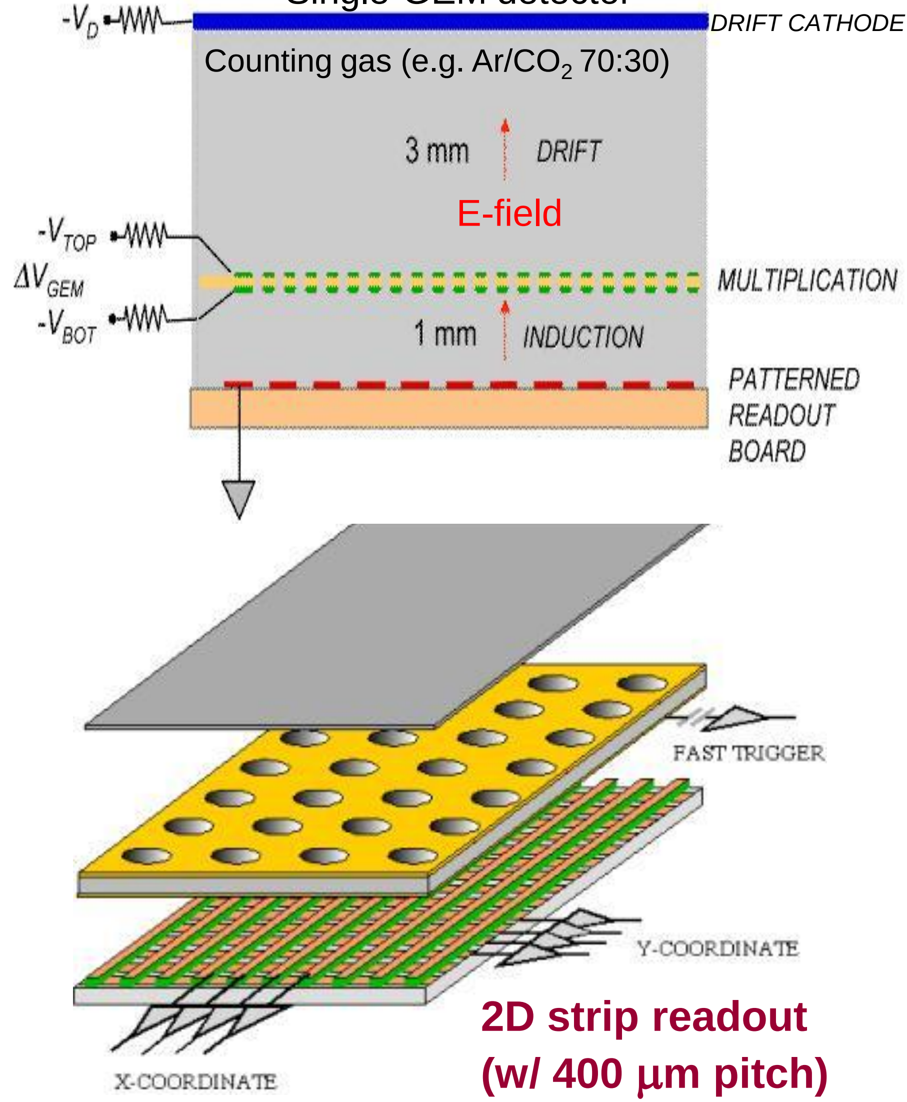
  100-300 μm for inclined tracks
- **compact detector**
- **larger area than Si-strip det.:**

  now: 30cm × 30cm

  soon: 100cm × 100cm
- **fast signal (few ns rise time)**
- **high-rate capable (MHz rates)**
- **low gas aging**

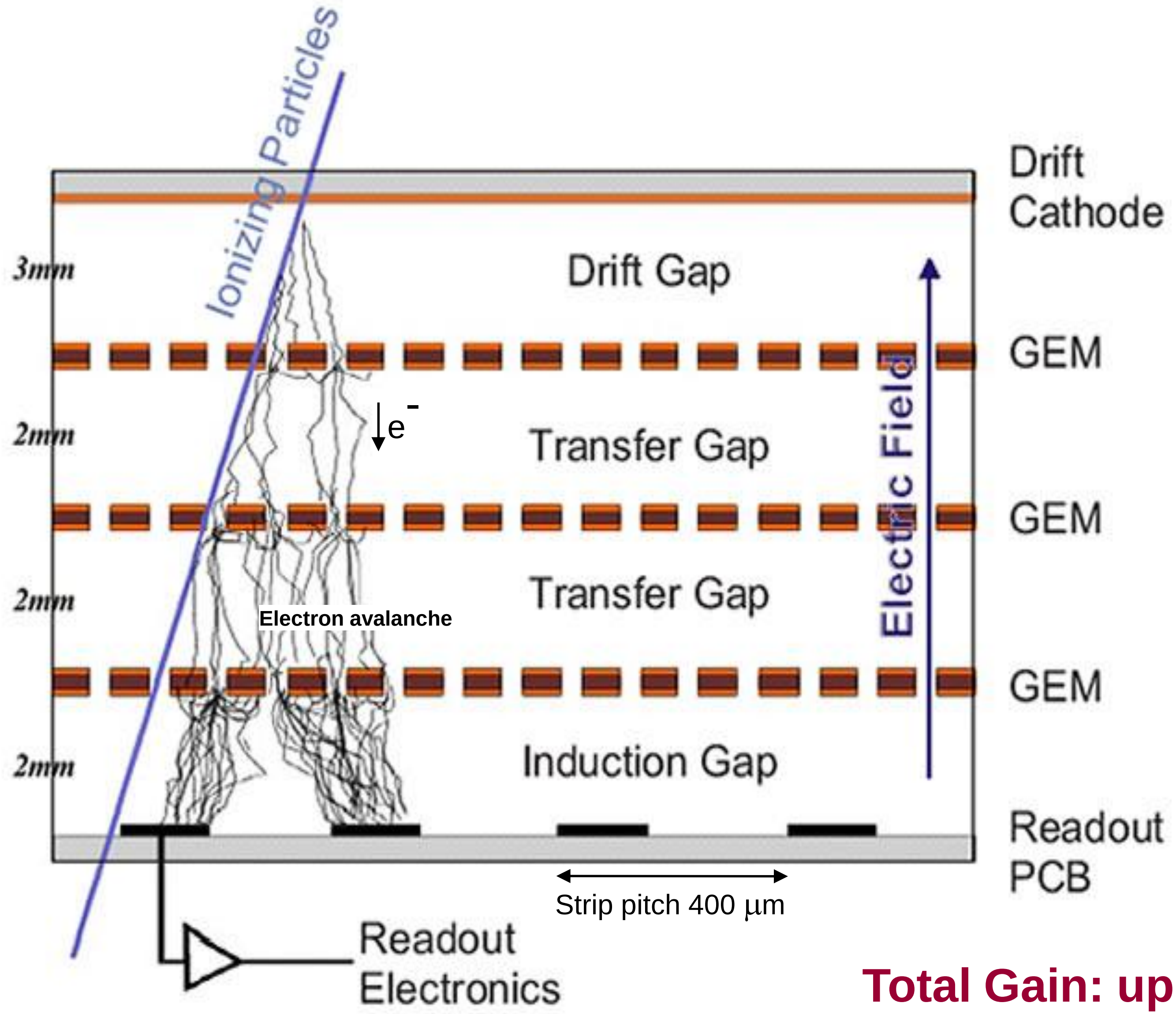
Developed for High Energy Physics

Single-GEM detector



2D strip readout (w/ 400 μm pitch)

Triple-GEM Detector



Total Gain: up to 10^5

Simulation results

Monte Carlo Simulation

- Generate cosmic ray muons with **CRY package** (Lawrence Livermore National Lab)

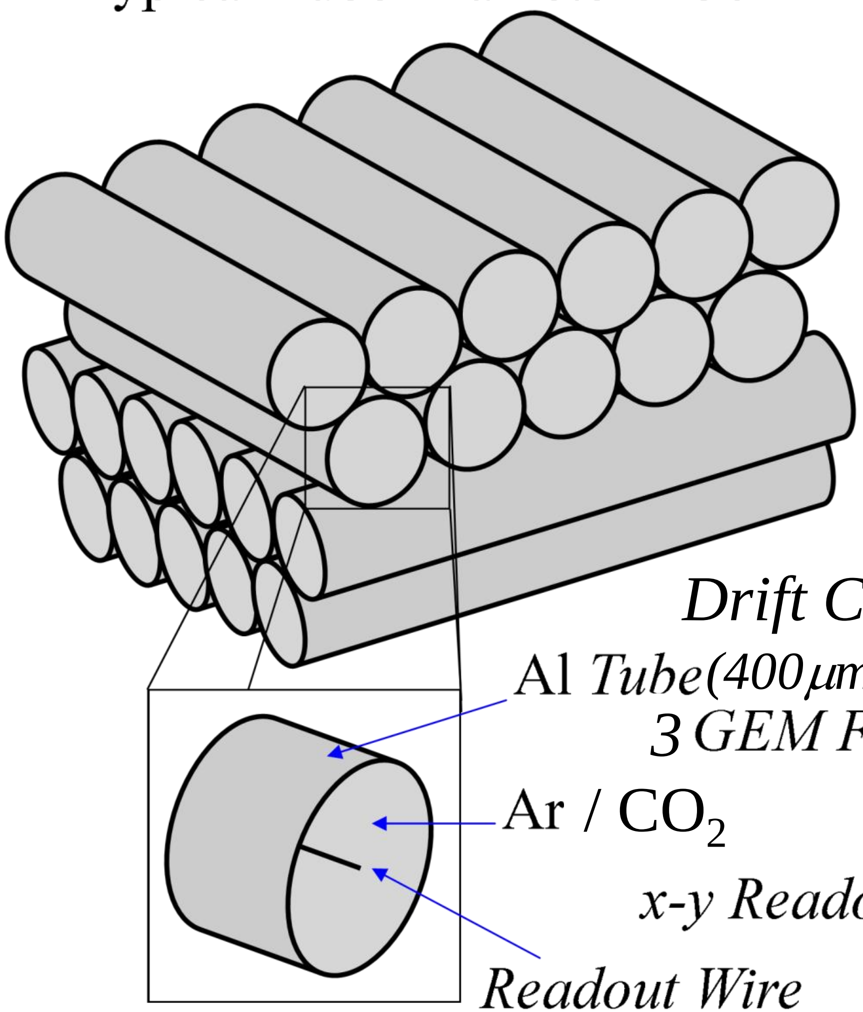
- Use **GEANT4** to simulate station geometries, detectors, targets, interaction of muons with all materials, and tracks
  - →Take advantage of detailed description of **multiple scattering** effects within GEANT4 (follows Lewis theory of multiple scattering)

- Simulate Drift tube MT station (using ~DS/LANL design) and GEM MT station, reconstruct muon scattering, and **compare performances**

Detector Geometries

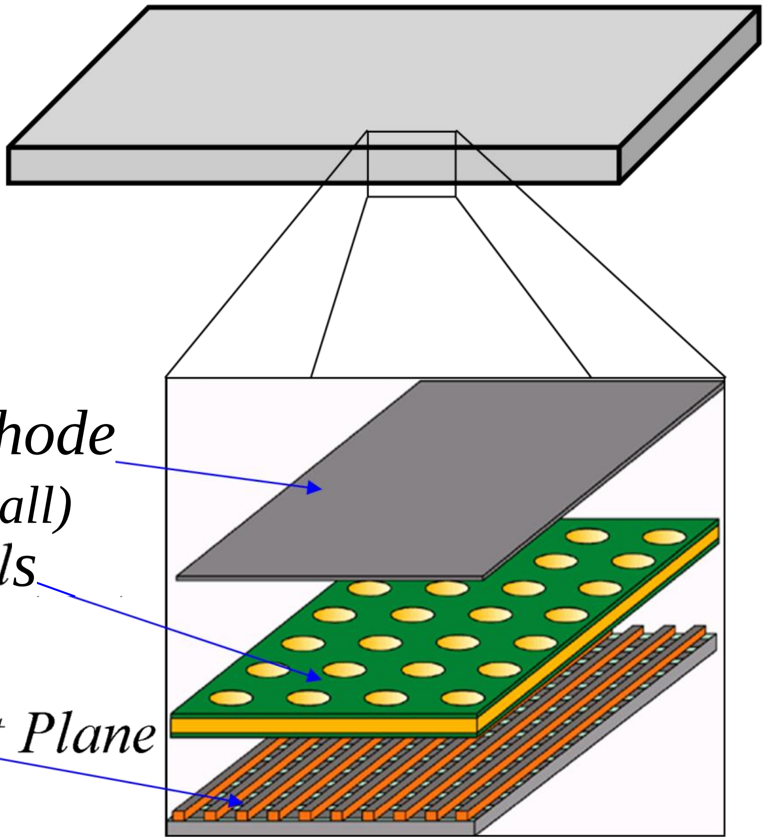
Drift Tube Detector

Typical Tube Diameter = 5cm



GEM Detector

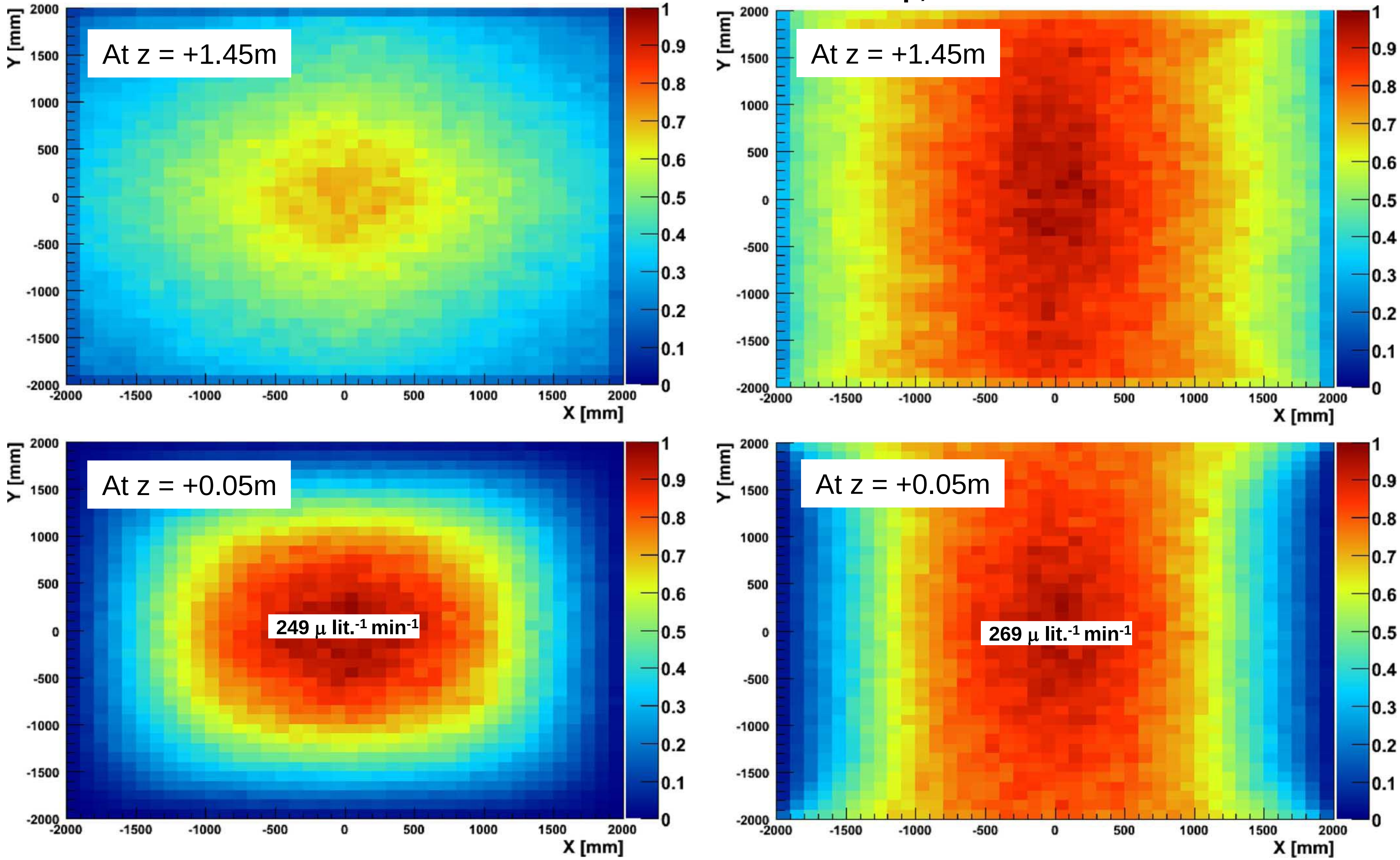
Typical Thickness = 1cm



Volume Coverage

Top & Bottom Detectors only – no side detectors

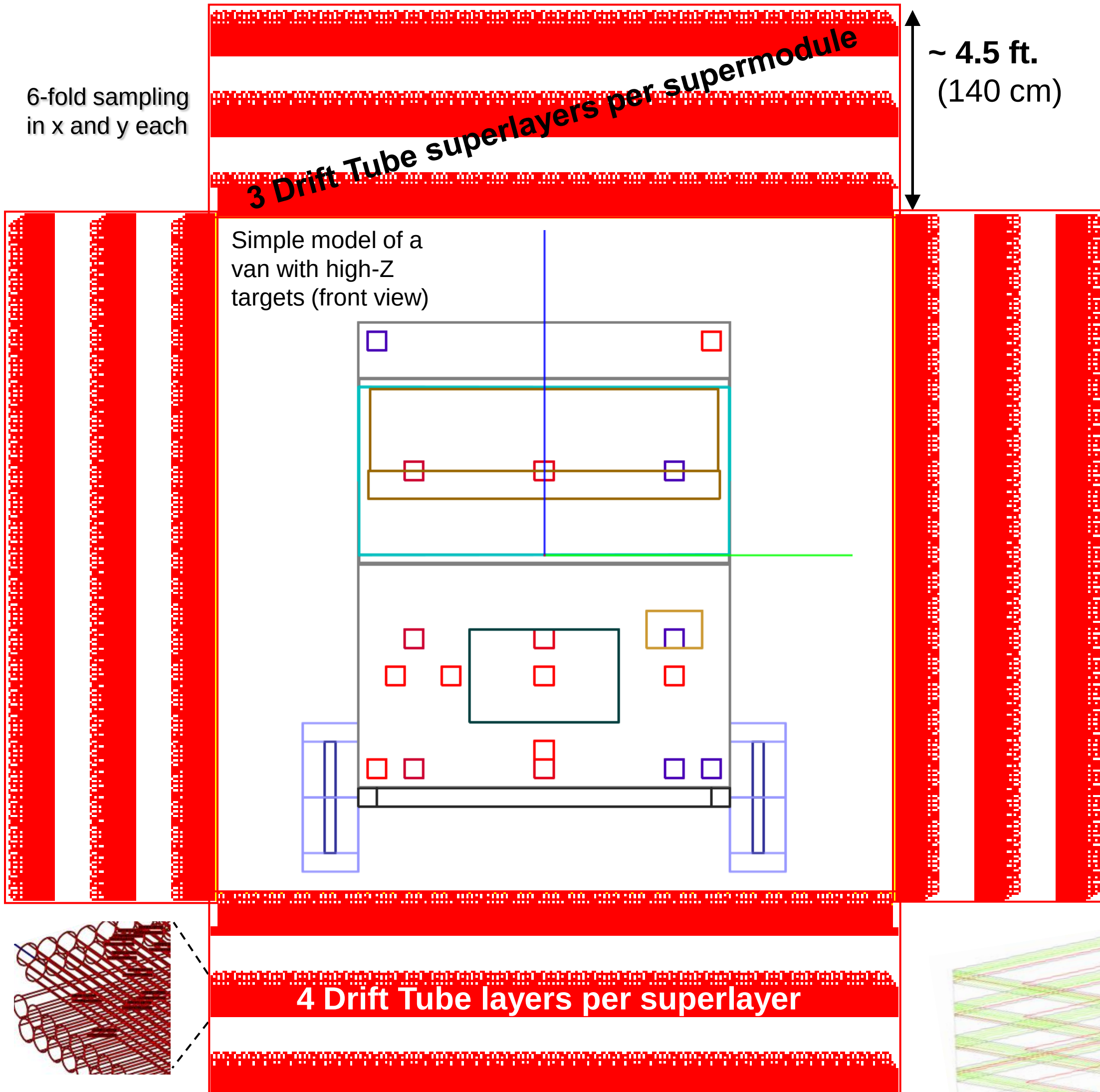
Top, Bottom & Side Detectors



MT Station Geometries

DS/LANL: Drift Tube Station

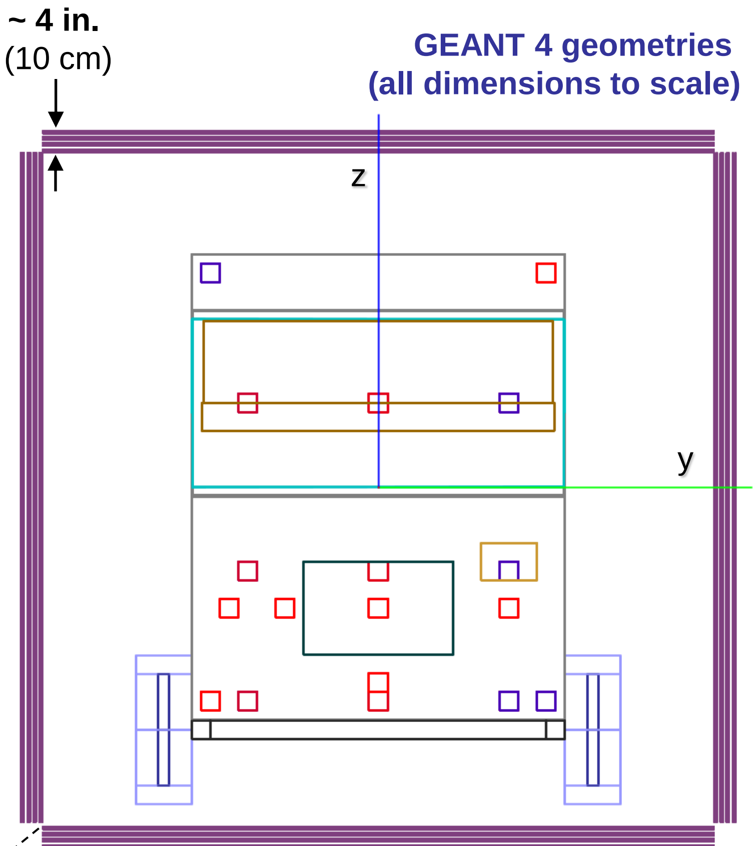
6-fold sampling in x and y each



FIT: Compact GEM station

(same detector area as DTs)

GEANT 4 geometries (all dimensions to scale)

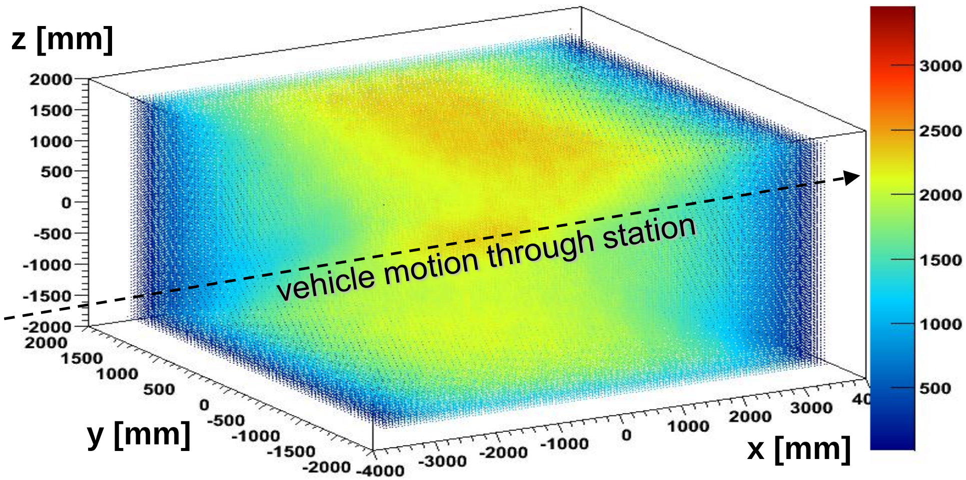


4 GEM layers with triple-GEM & x-y r/o board (4-fold track sampling in x and y each)

Acceptance Comparison

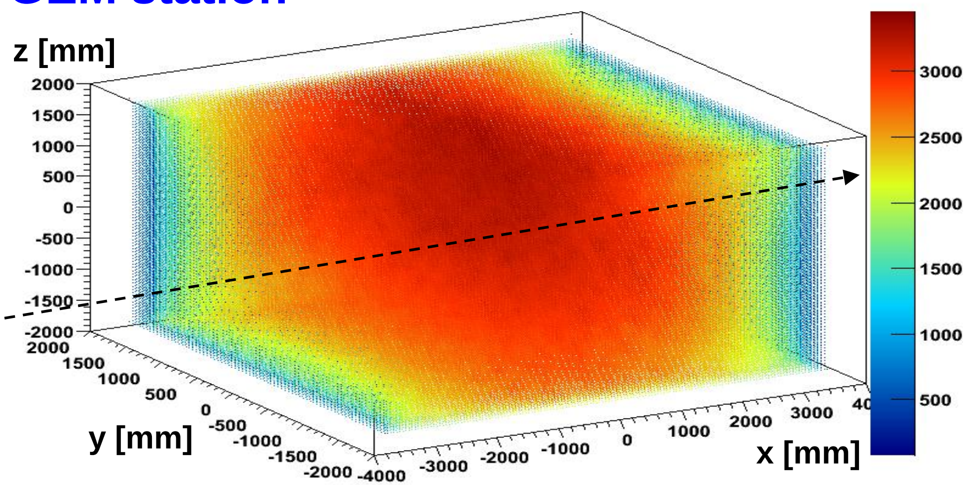
DT station

No. of muons in 10cm×10cm×10cm voxel in 10min



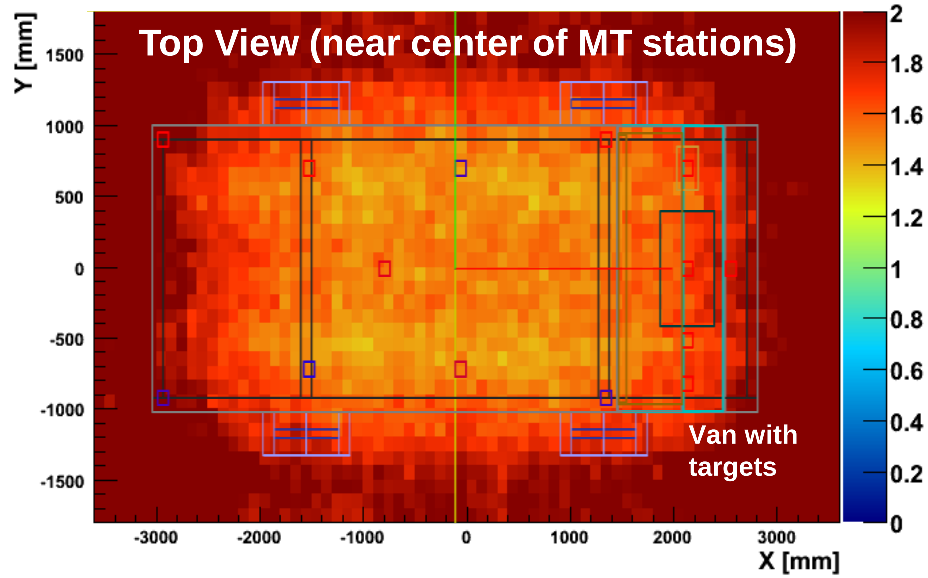
GEM station

No. of muons in 10cm×10cm×10cm voxel in 10min



- Require $\geq$ 3 hits in DT or GEM station to accept muon
- Reduced DT acceptance is mainly due to "holes" in solid angle coverage in the corners of the DT station

Acceptance Ratio $\frac{\text{GEM accept.}}{\text{DT accept.}}$

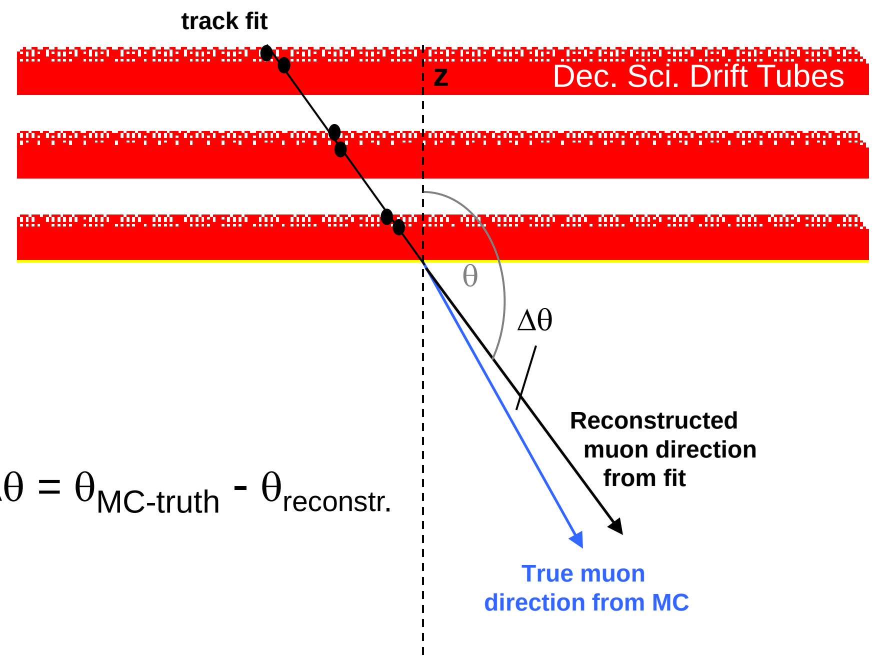


=> GEM MT station provides 50-100% better muon acceptance over the interrogated vehicle

Angular resolution

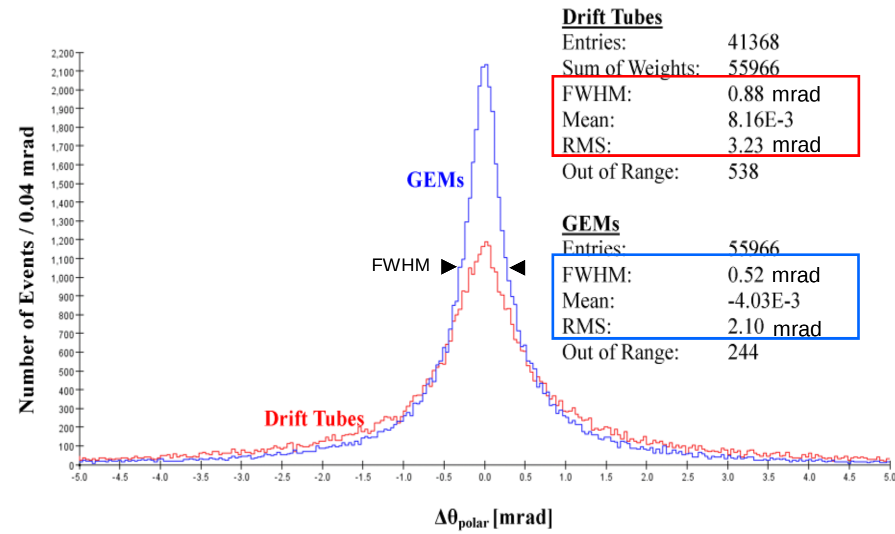
Expected angular resolutions:

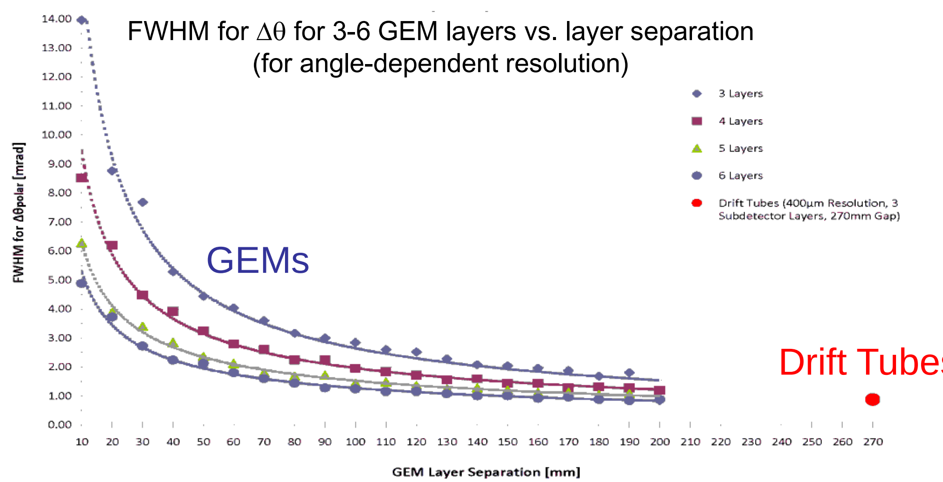
- Compare polar angle θ of reconstructed muon tracks with “true” muon track angle from Monte Carlo at exit of tracking station:



$$\Delta\theta = \theta_{MC\text{-}truth} - \theta_{reconstr.}$$

$\Delta\theta_{polar}$ for
Drift Tubes with 3 Detector Layers, 400µm Resolution, 270mm Gap
GEMs with 4 Detector Layers, 50µmResolution, 150mm Gap



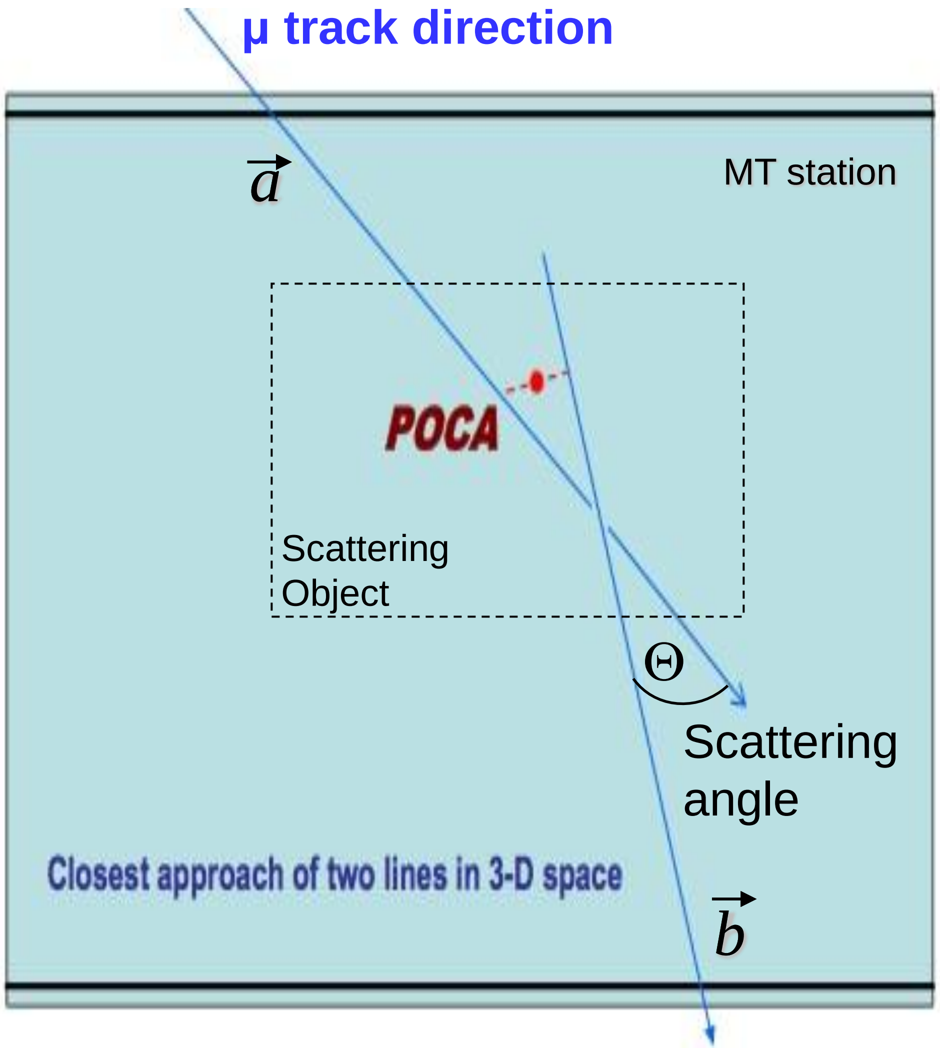


Simple Scattering Reconstruction

- Simple reconstruction algorithm using **Point of Closest Approach** ("POCA") of incoming and exiting 3-D tracks
- Treat as **single scatter**
- Scattering angle:

$$\theta = \cos^{-1}\left(\frac{\vec{a}\cdot\vec{b}}{|a||b|}\right)$$

(with θ >0 by definition)



Homeland Security

Simple Statistic for Z-discrimination: Mean Scattering Angles

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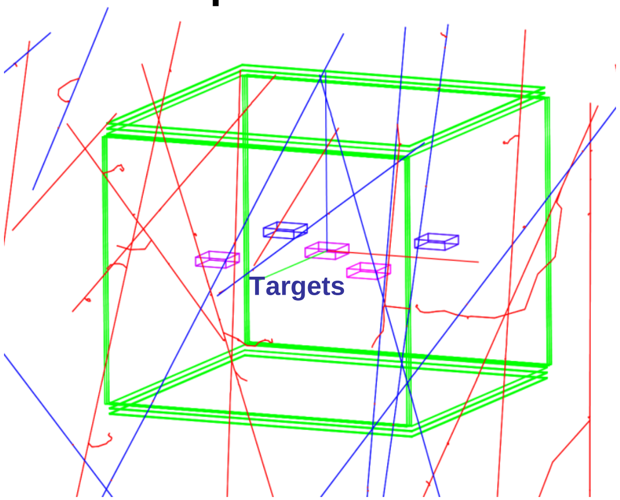
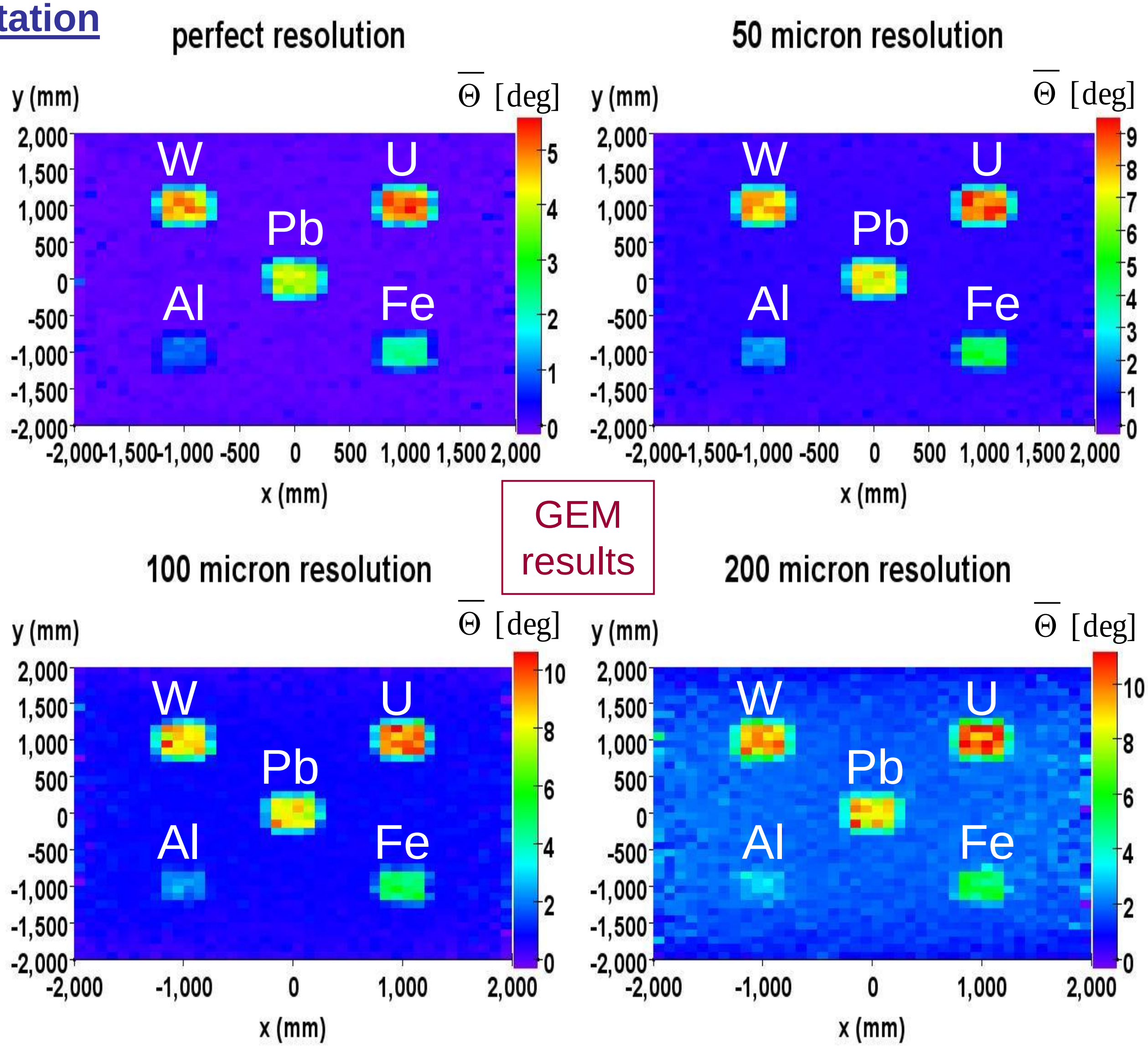
Simple MC Scenario for GEM station

- Top, bottom & side detectors
- 40cm × 40cm × 10cm targets
- 5 materials (low-Z to high-Z)
- Divide volume into 1-liter voxels
- **10 min exposure**





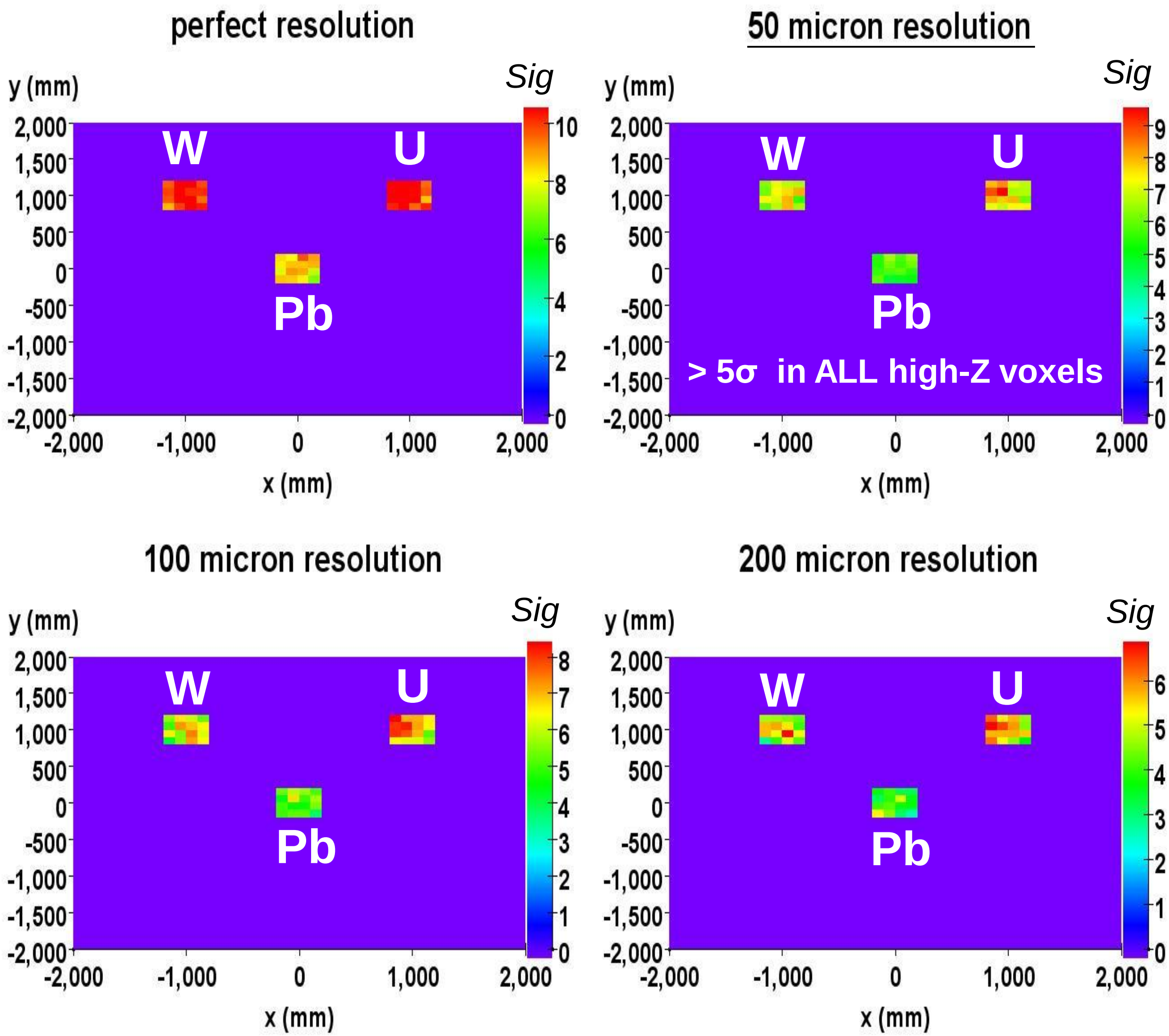
Results:

- Scattering angles 20-100 mrad; >> angular resolution (few mrad)
- Good Z discrimination
- Targets well imaged
- Detector resolution matters

Significance of Excess

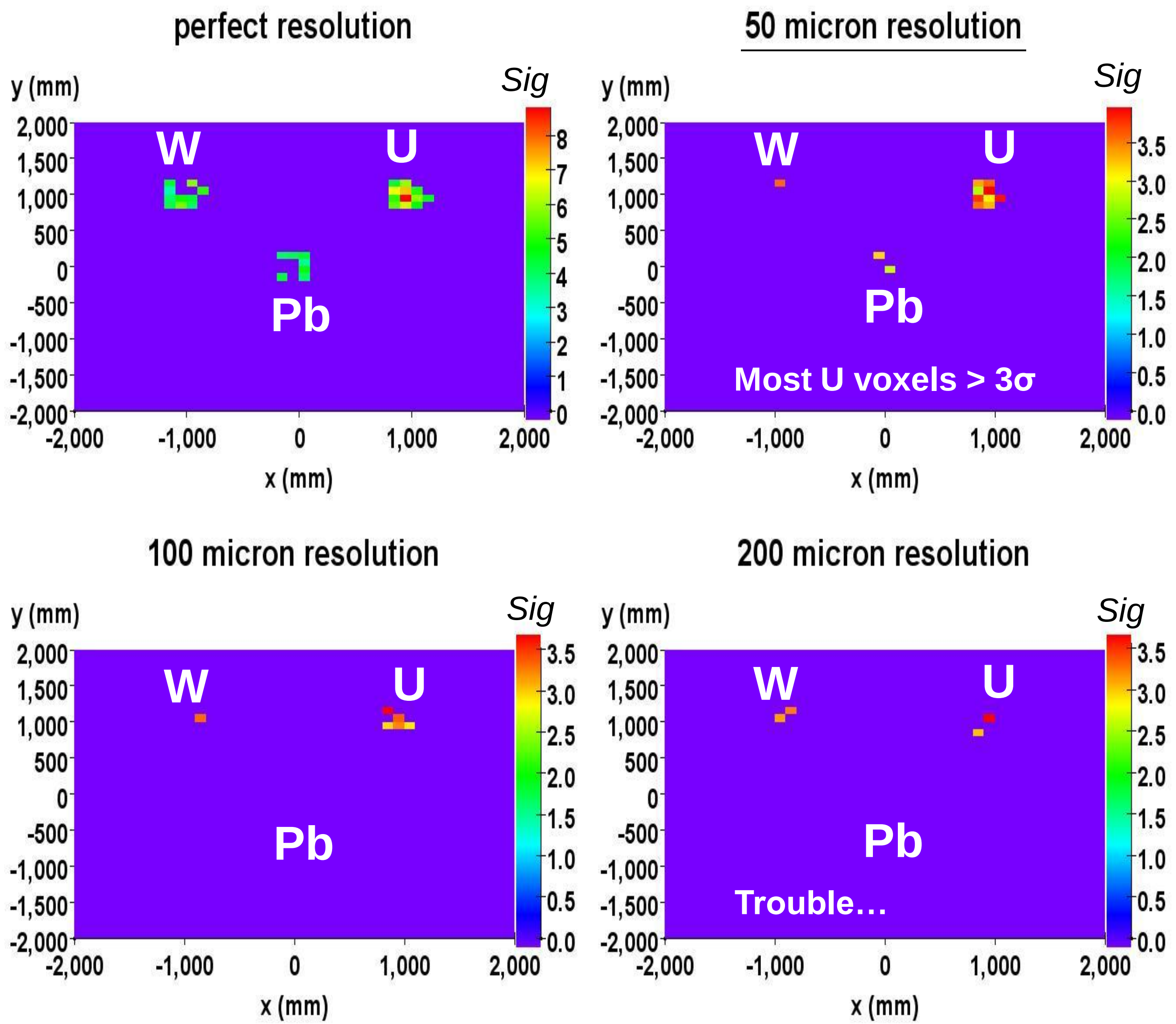
- [10 min exposure]
- **Compare targets against Fe back-ground** using Fe ref. samples w/ high statistics
- Significance for all voxels with an excess at ≥ 99% confidence level over Fe standard:

$$Sig = \frac{\overline{\Theta}_{\text{voxel}} - \overline{\Theta}_{\text{Fe}}}{\sigma_{\overline{\Theta}_{\text{voxel}}}}$$



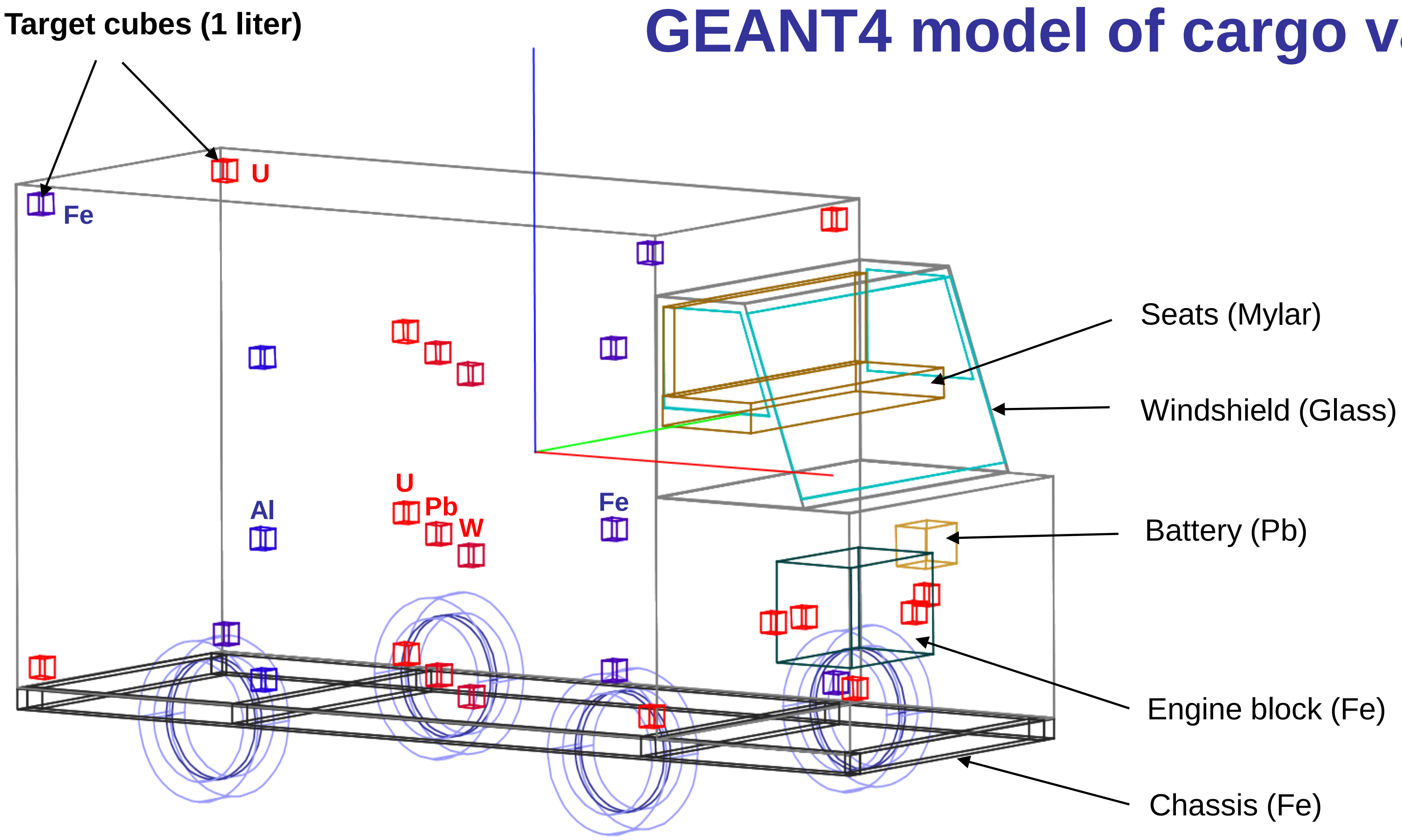
Significance of Excess

- **1 min exposure**
- Significance for all voxels with an excess at ≥ 99% confidence level over Fe standard
- **Doing ok with 50µm resolution**
- With 200 micron resolution we are losing some sensitivity

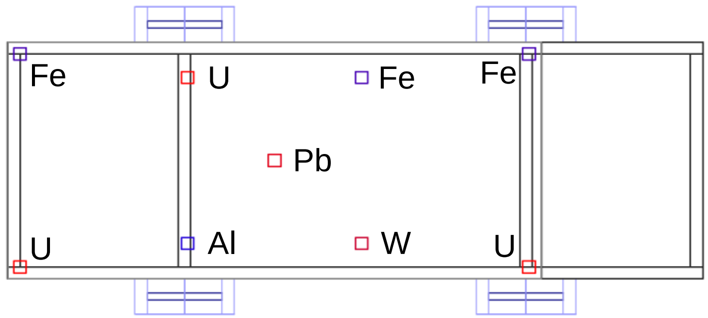


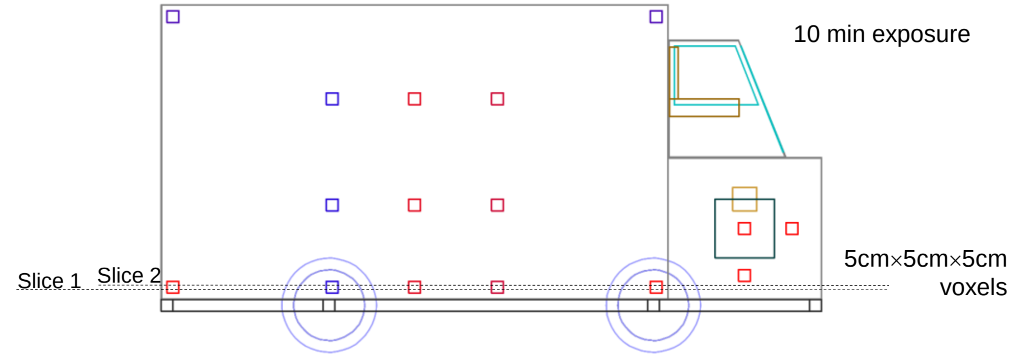
Simple van scenario

GEANT4 model of cargo van

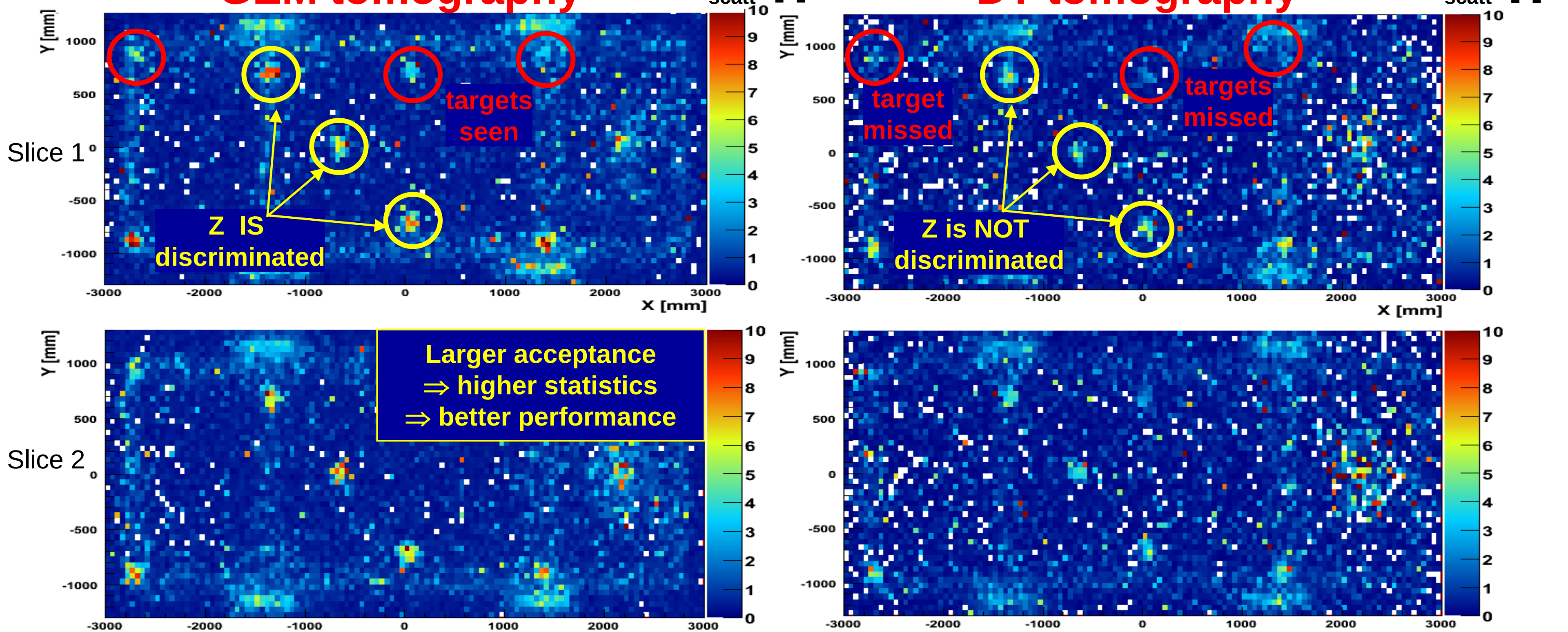


Target Detection

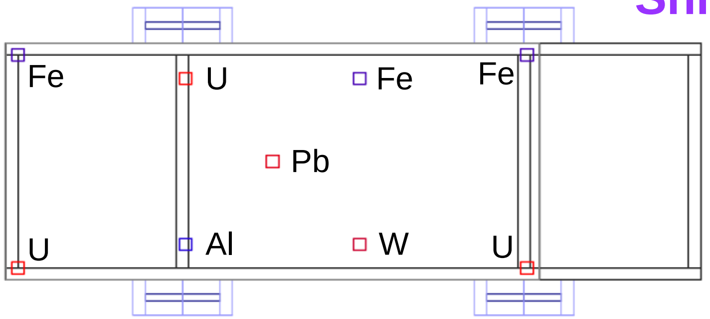


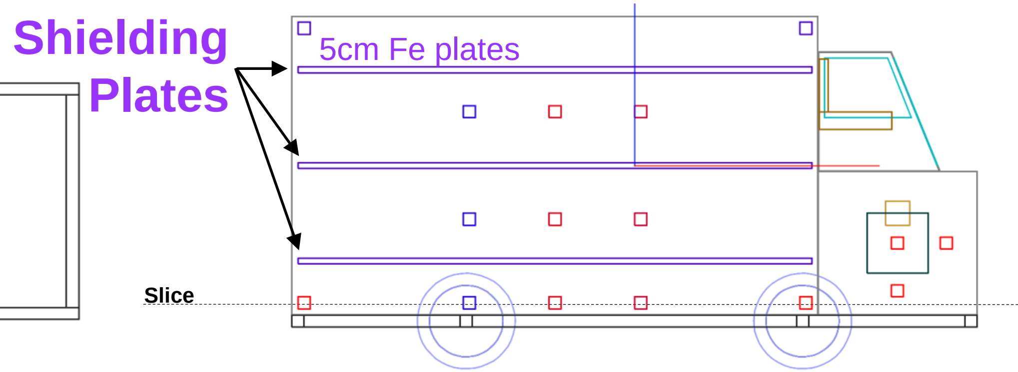


GEM tomography | DT tomography

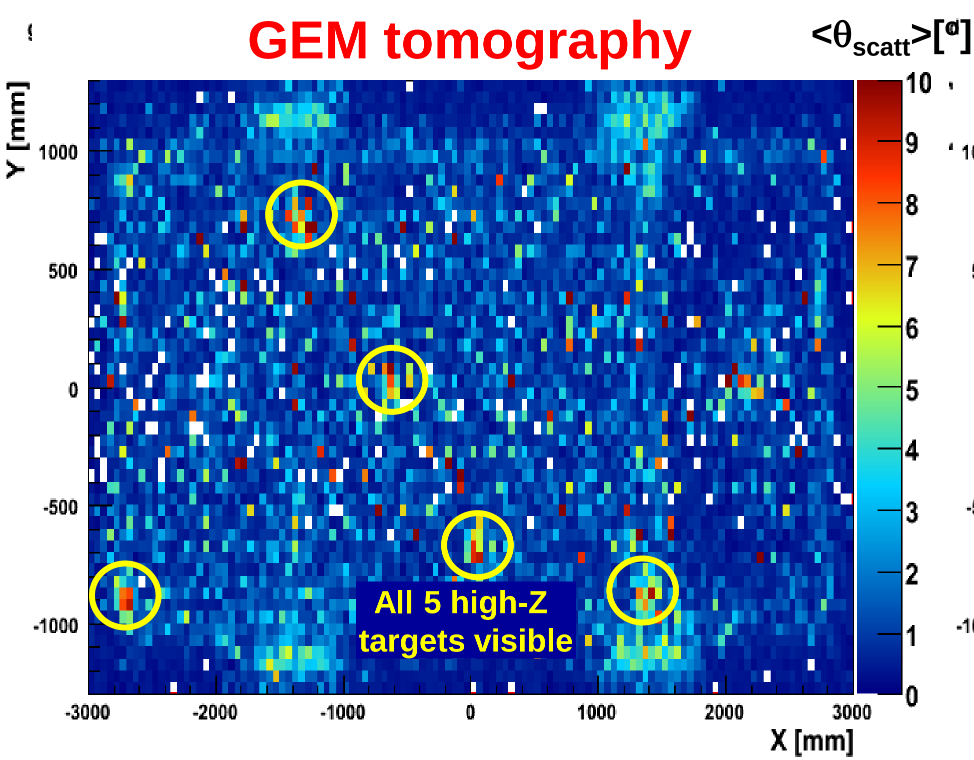


MT performance with shielding

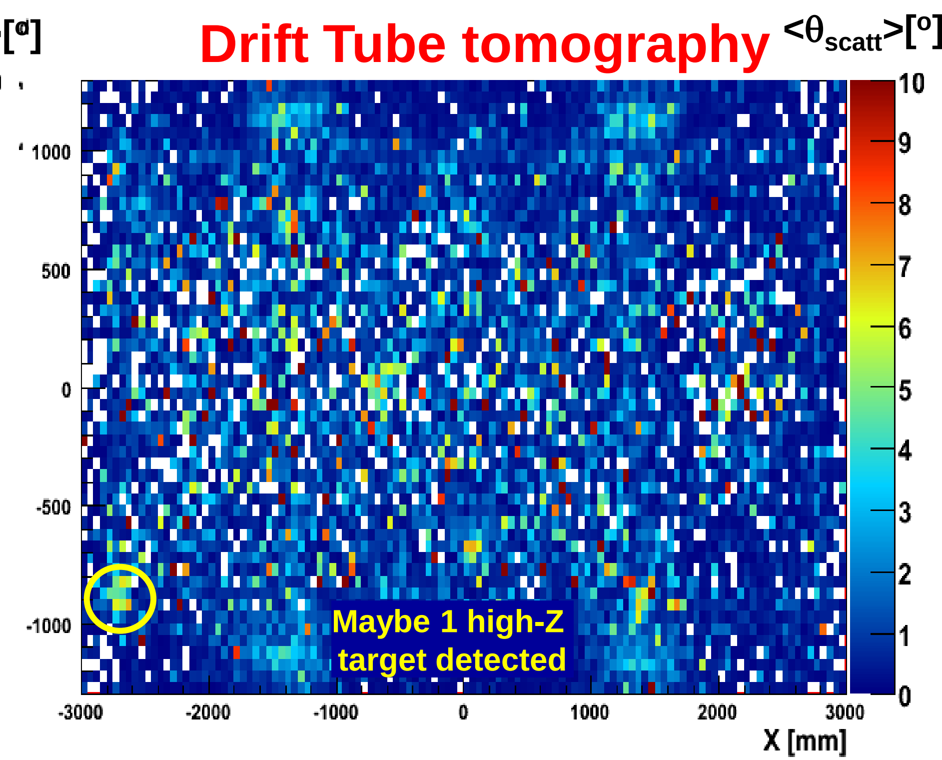




GEM tomography



Drift Tube tomography



Conclusion from simulation

Muon Tomography with GEM detectors could very well improve performance while making the MT station compact…

=> Develop some GEM hardware for Muon Tomography!

Hardware Development

Overall Hardware Strategy

- Build **first prototype** of GEM-based Muon Tomography station & evaluate performance (using ten 30cm × 30cm GEM det.)
  - Detectors
  - Mechanics
  - Readout Electronics
  - HV & Gas supply
  - Data Acquisition & Analysis

- Develop **large-area Triple-GEMs** together with RD51

- Build **1m×1m×1m GEM** Muon Tomography prototype station

- Measure **performance** on shielded targets with both prototypes

2009/10 Strategy

Two-pronged approach:

1. **Build minimal** first GEM-based Muon Tomography station:
   - four Triple-GEM detectors (two at top and two at bottom)
   - temporary electronics (~ 800 ch.)
   - minimal coverage (read out 5cm × 5cm area per detector)
   - preliminary data acquisition system
   - **Objectives:**
     - **take real data as soon as possible and analyze it**
     - demonstrate that GEM detectors work as anticipated for cosmic ray muons
     - → produce **very first experimental proof-of-concept**

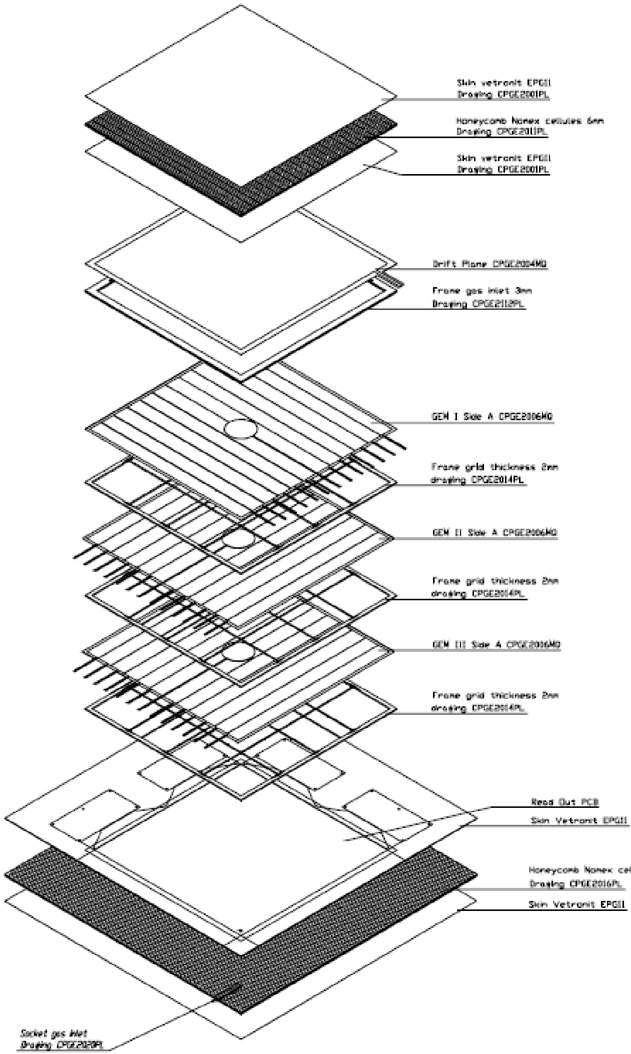
2. **Simultaneously prepare** the 30cm × 30cm × 30cm MT prototype:
   - Top, bottom, and side detectors (10 detectors)
   - Mechanical stand with flexible geometry, e.g. variable gaps b/w detectors
   - Fully instrumented front-end electronics (15,000 ch.) with RD51 coll.
   - Final data acquisition with RD51 & analysis

Hardware Progress

- **Detector Assembly:**
  - **Seven** 30cm × 30cm Triple-GEM detectors assembled in CERN clean rooms
  - **One** 30cm × 30cm Double-GEM detector assembled in CERN clean rooms

- Tested triple-GEM detectors with X-rays and cosmic ray muons with respect to **basic performance parameters:**
  - HV stability (sparks?)
  - Gas gain
  - HV plateau
  - Rate capability
- **=> Six Triple-GEM detectors at CERN show good and stable performance**
- One Triple-GEM detector has bad HV section; to be fixed later
- **Built minimal prototype station** for Muon Tomography; **currently operating at CERN**
  - Used GASSIPLEX frontend r/o cards electronics with ~800 readout channels for two tests
  - Designed and produced circuit board for interfacing detector r/o board (x-y strips) with preliminary "GASSIPLEX" frontend electronics
  - Developed DAQ system for first prototype tests – lots of debugging work
- Developed GEANT4 simulation for minimal and 30cm×30cm×30cm MT prototype stations
- Operating also 10cm × 10cm Triple-GEM detectors at Fl. Tech

Triple-GEM design



Top honeycomb plate

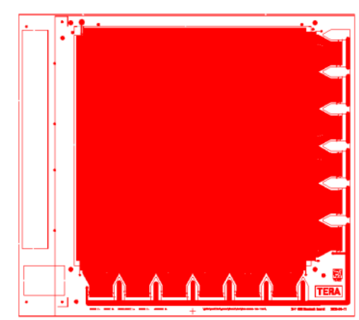
Drift cathode and spacer

3 GEM foils stretched & glued onto frames/spacers

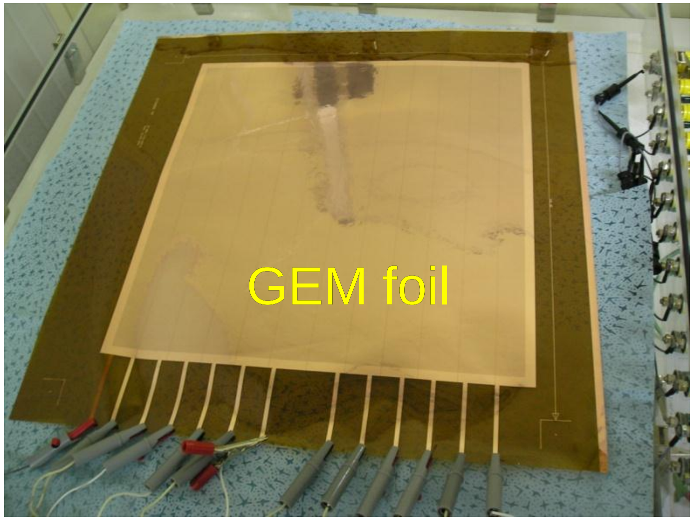
2D Readout Foil with ~1,500 strips

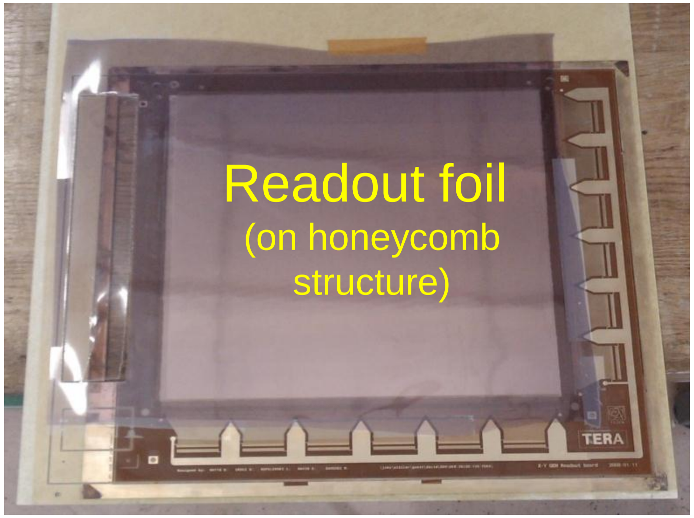
Bottom honeycomb base plate

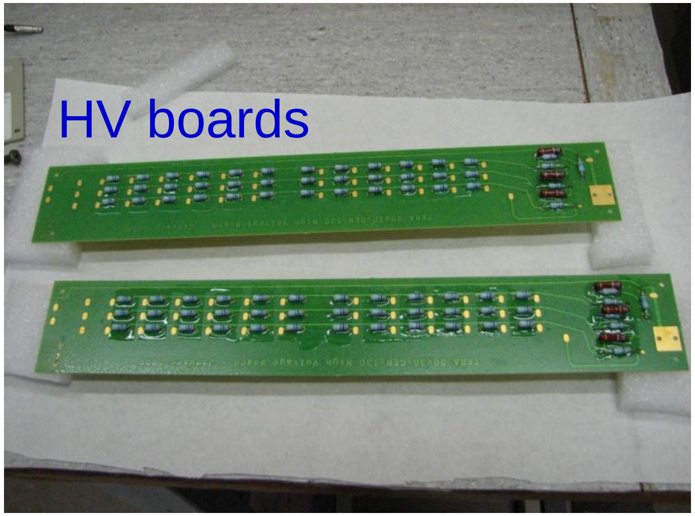
Follows original development for COMPASS exp. at CERN & further development for a proton therapy application (TERA)



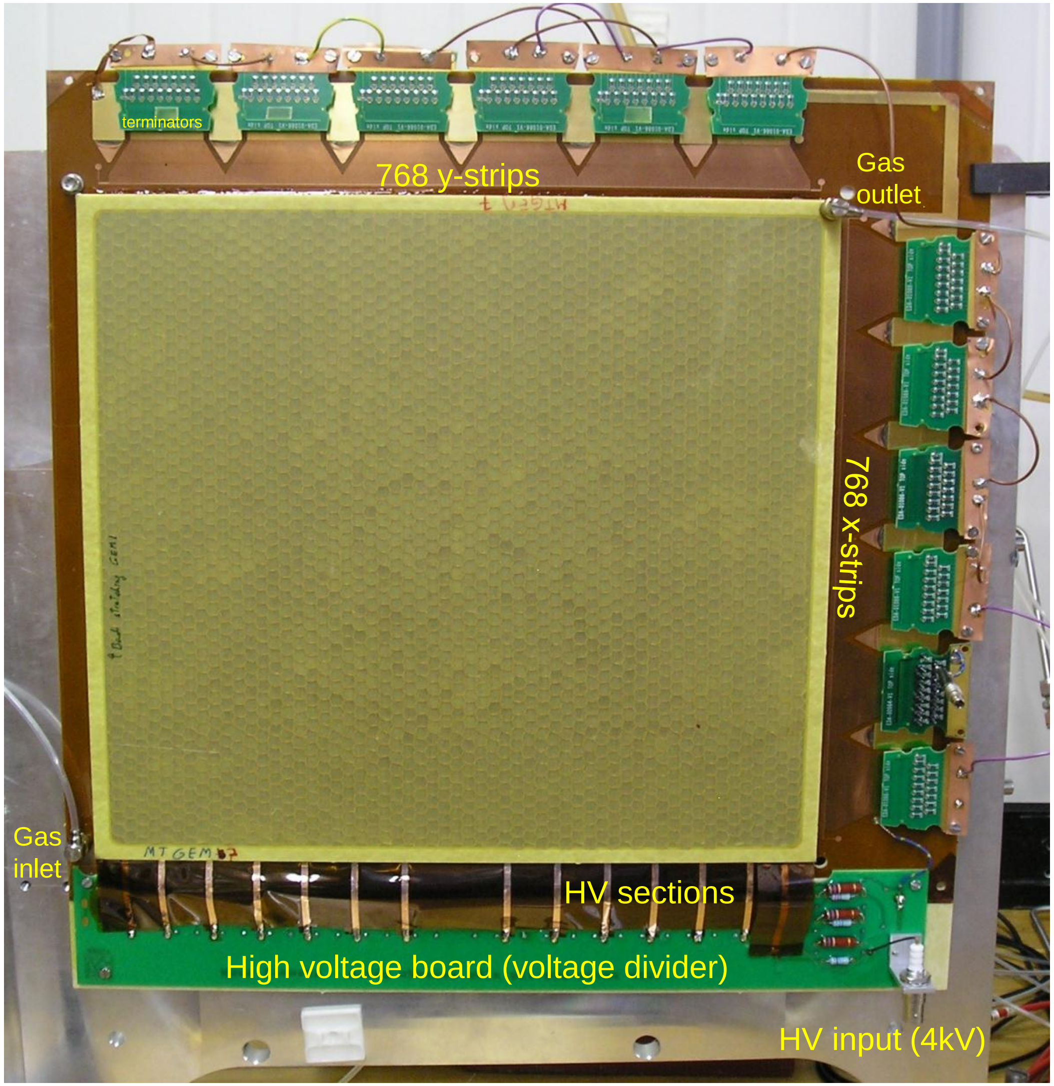
Detector Production

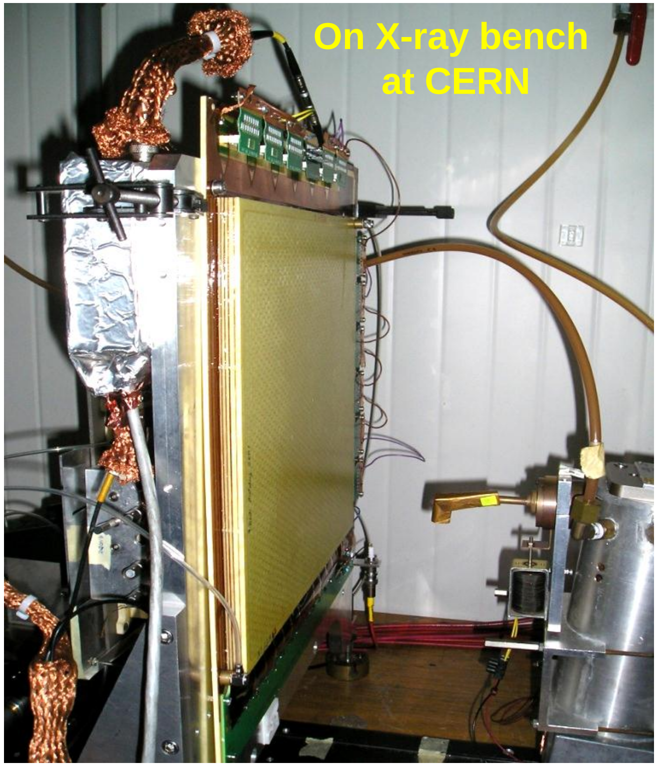


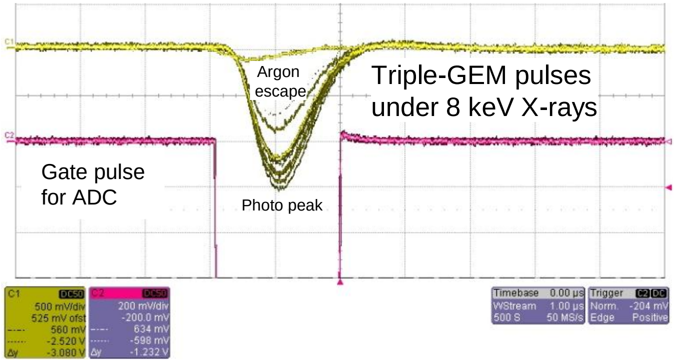




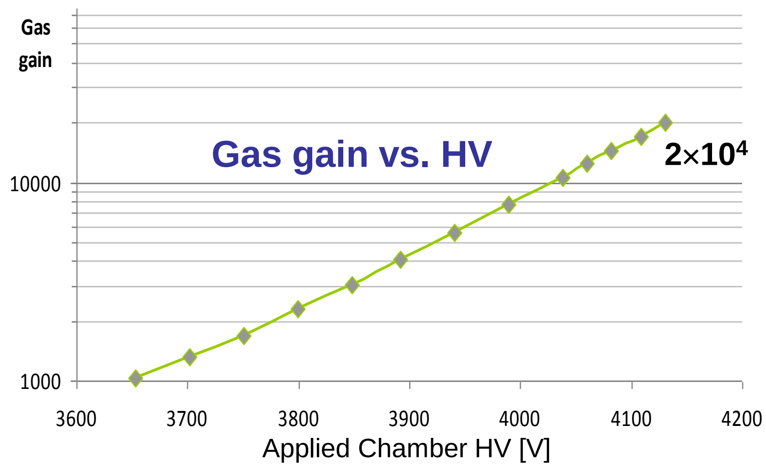
Triple-GEM Detector

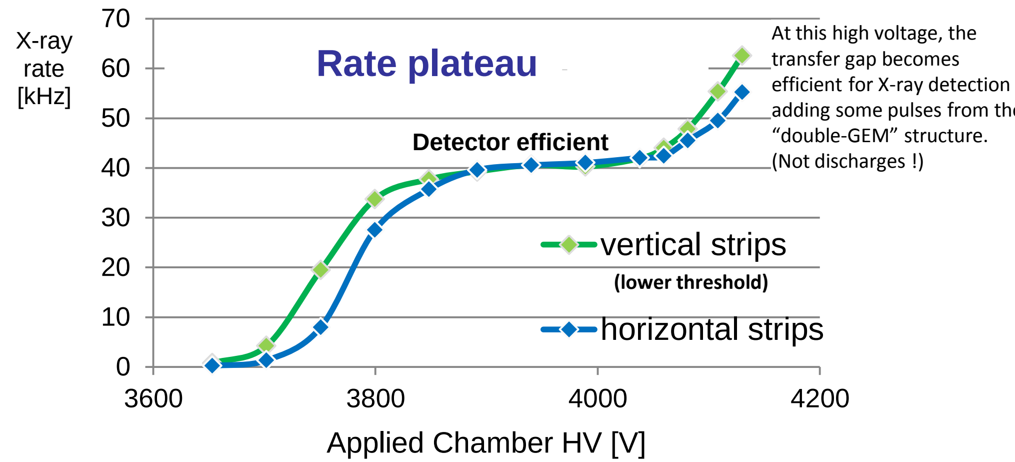


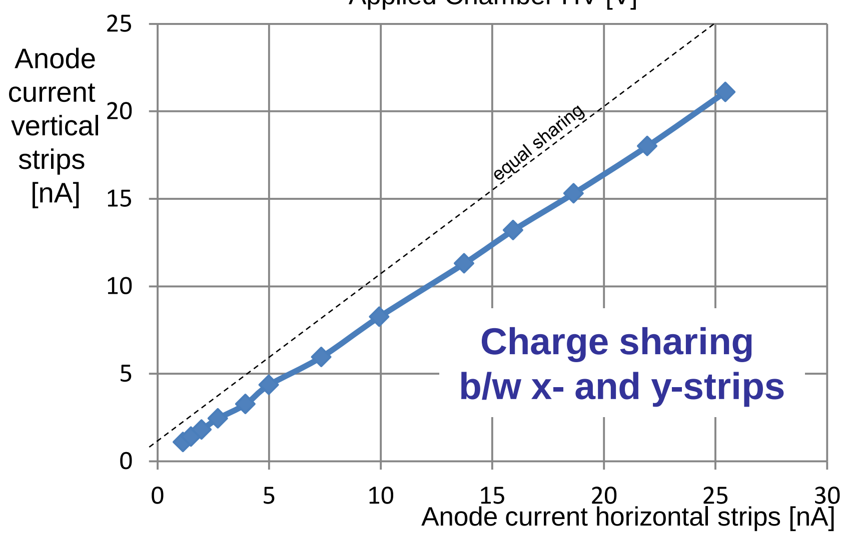


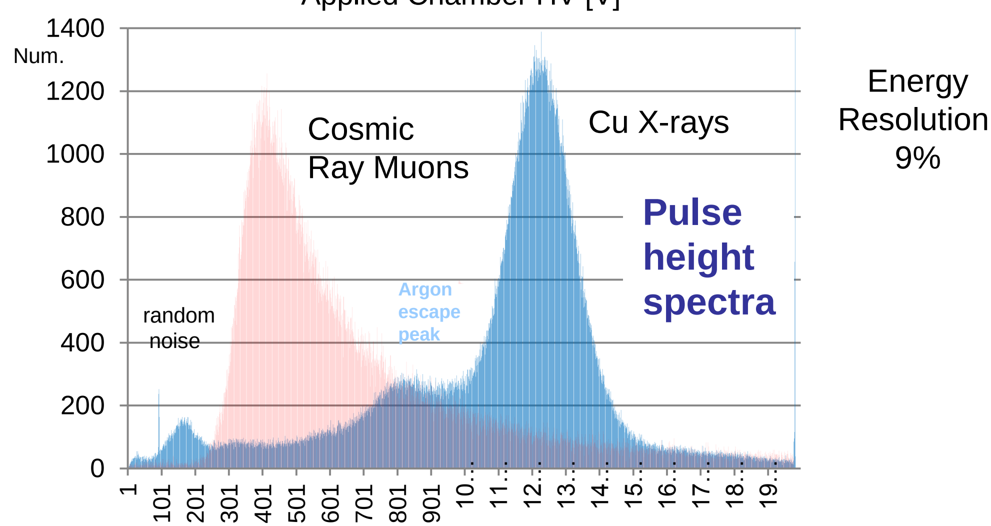


Results from detailed commissioning test of Triple-GEM detector using 8 kV Cu X-ray source at CERN

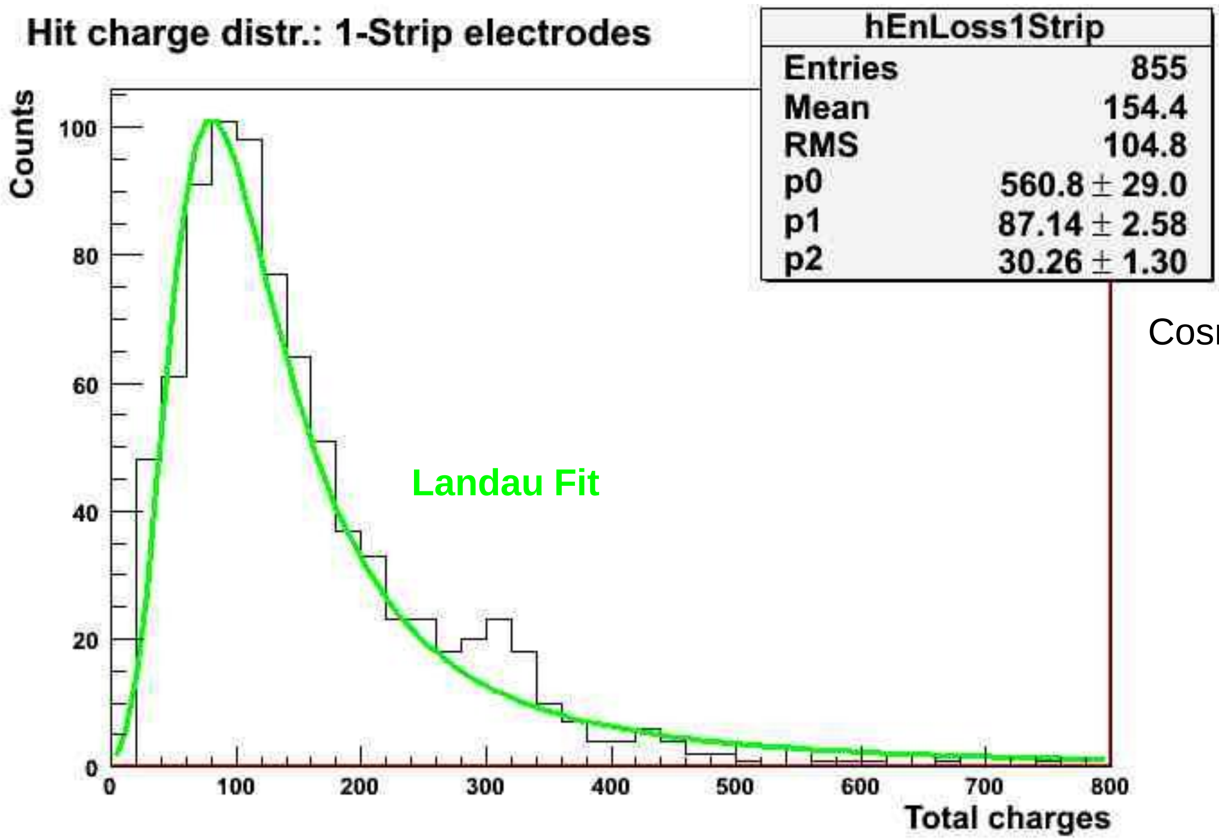








Ionization charge



Cosmic Ray Muons

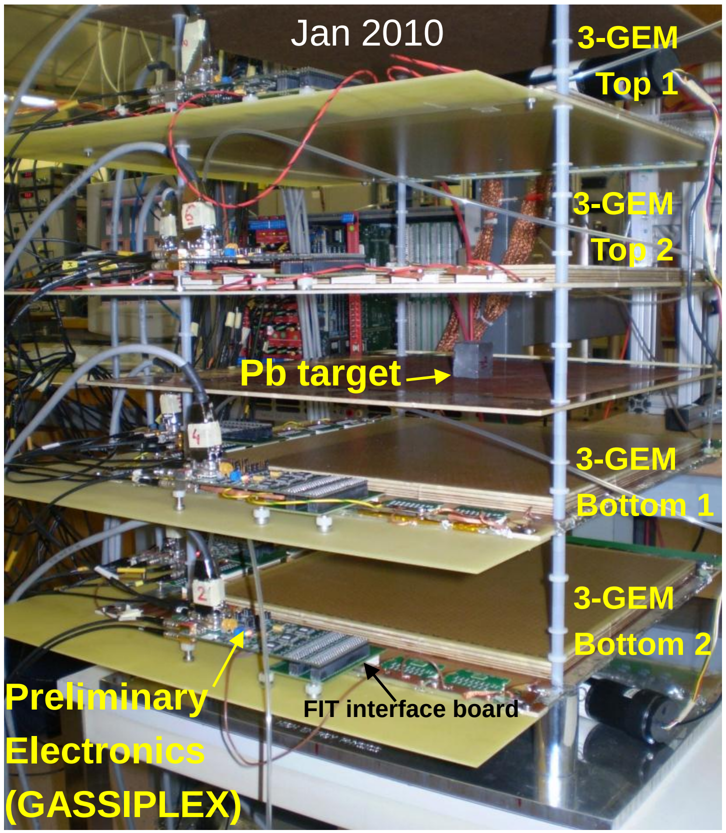
Distribution of total strip cluster charge follows Landau distribution as expected

Homeland Security

Minimal MT Station

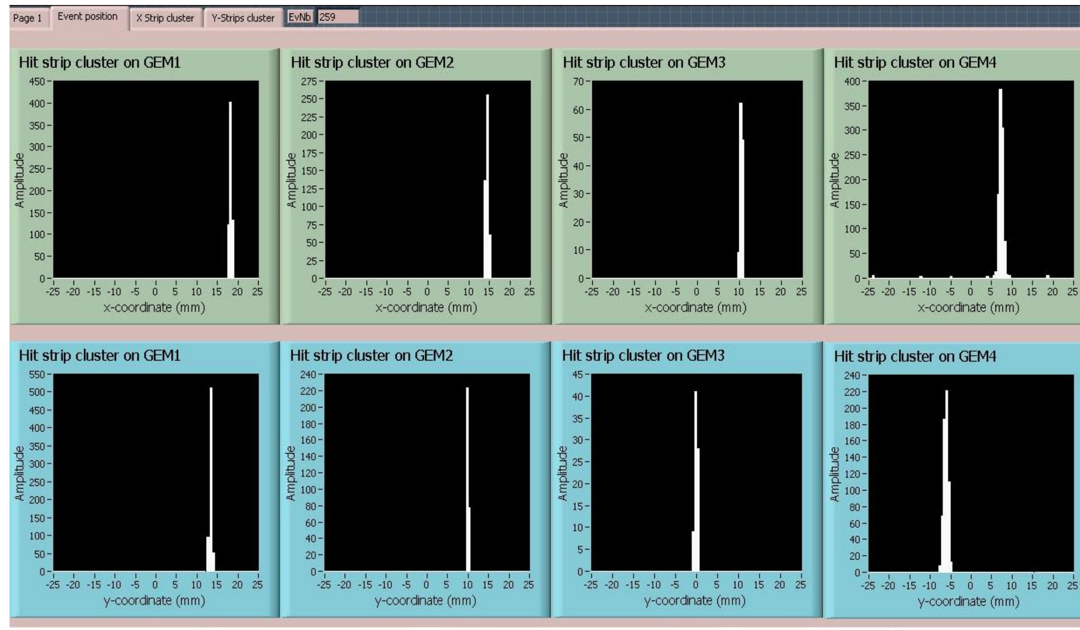
Florida Tech

Setup of first cosmic ray muon run at CERN with four Triple-GEM detectors



Event Display: Tracking of a cosmic ray muon traversing minimal GEM MT station

Top 1 **Top 2** **Bottom 1** **Bottom 2**



x

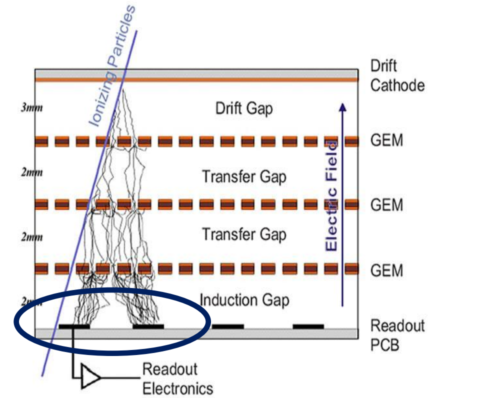
y

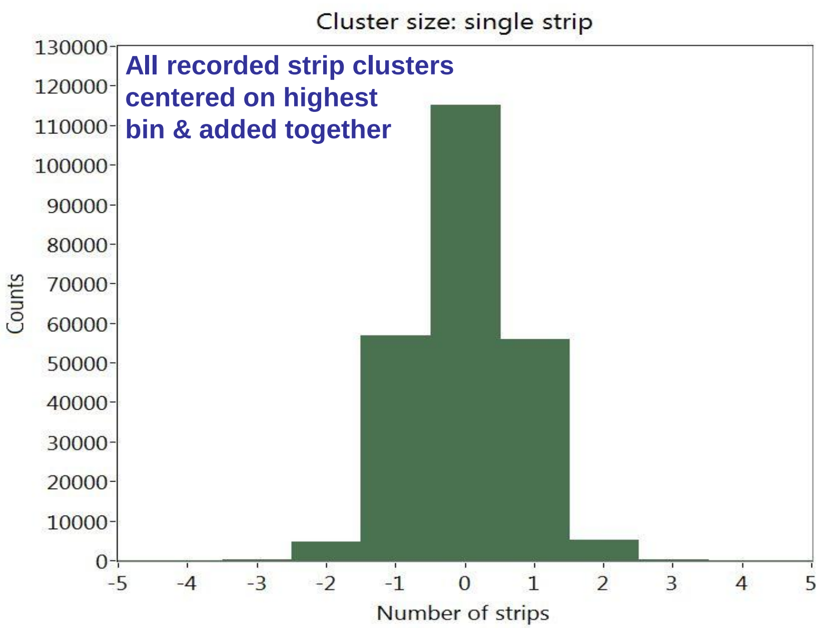
Strip Position [mm]

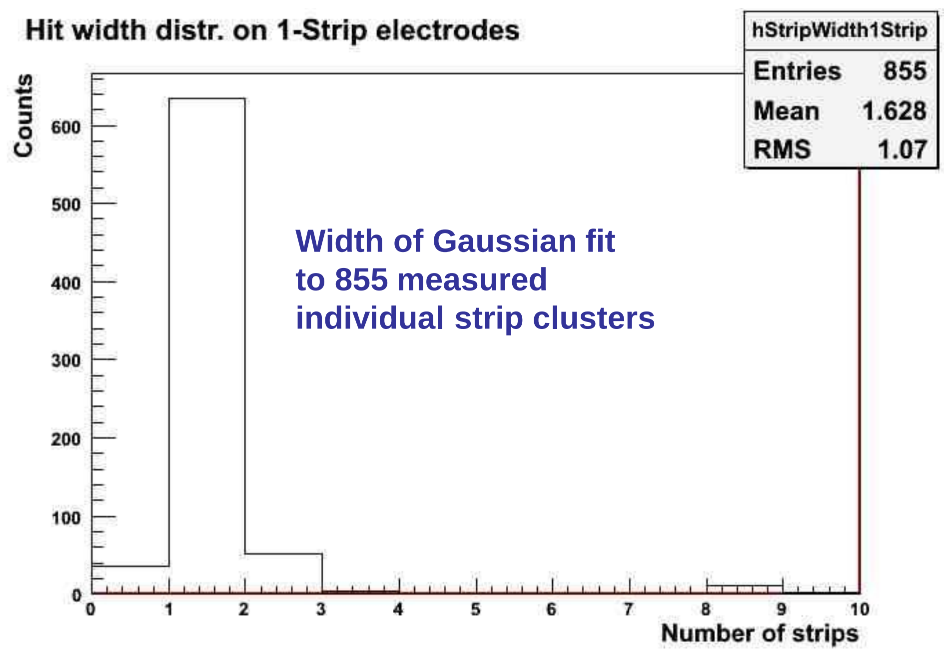
- **Pulse heights on x-strips and y-strips recorded by all 4 GEM detectors using preliminary electronics and DAQ**
- **Pedestals are subtracted**
- **No target present; Data taken 4/13/2010**

First Data: Strip Clusters

Sharing of deposited charge among adjacent strips will enable high spatial resolution by using the “center-of-gravity” of charge deposition when calculating the “hit” position:





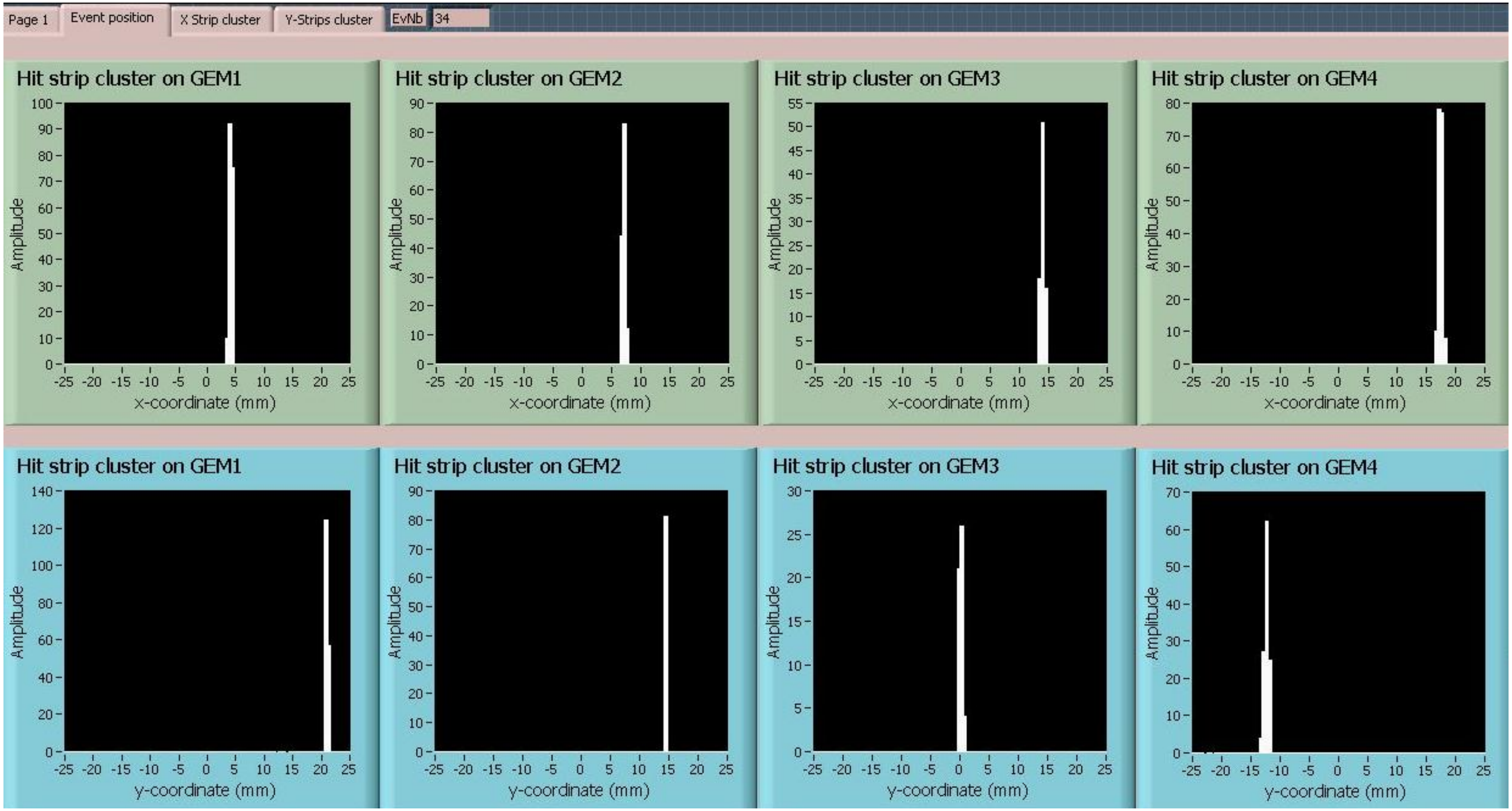


=> Charge is shared between up to 5 strips

=> On the average, strip cluster is 3.2 strips wide ($\pm 1\sigma$)

Minimal MTS with Pb target

Event recorded with Pb target present in center of minimal MTS:



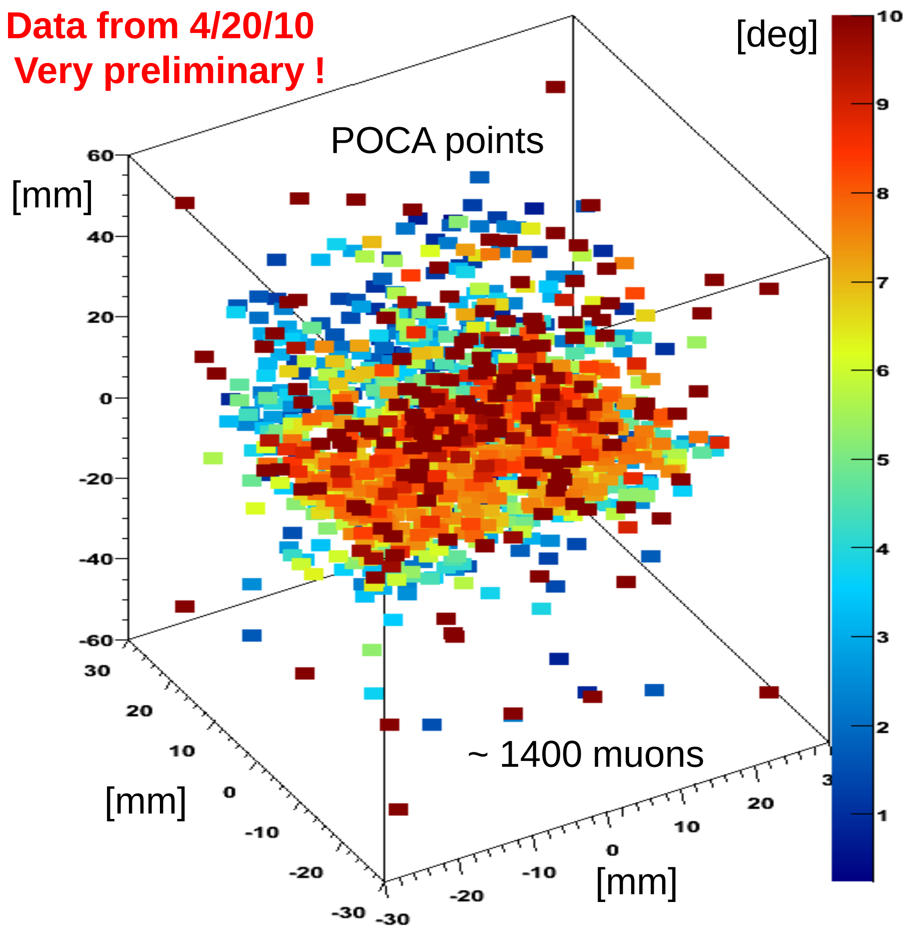
x

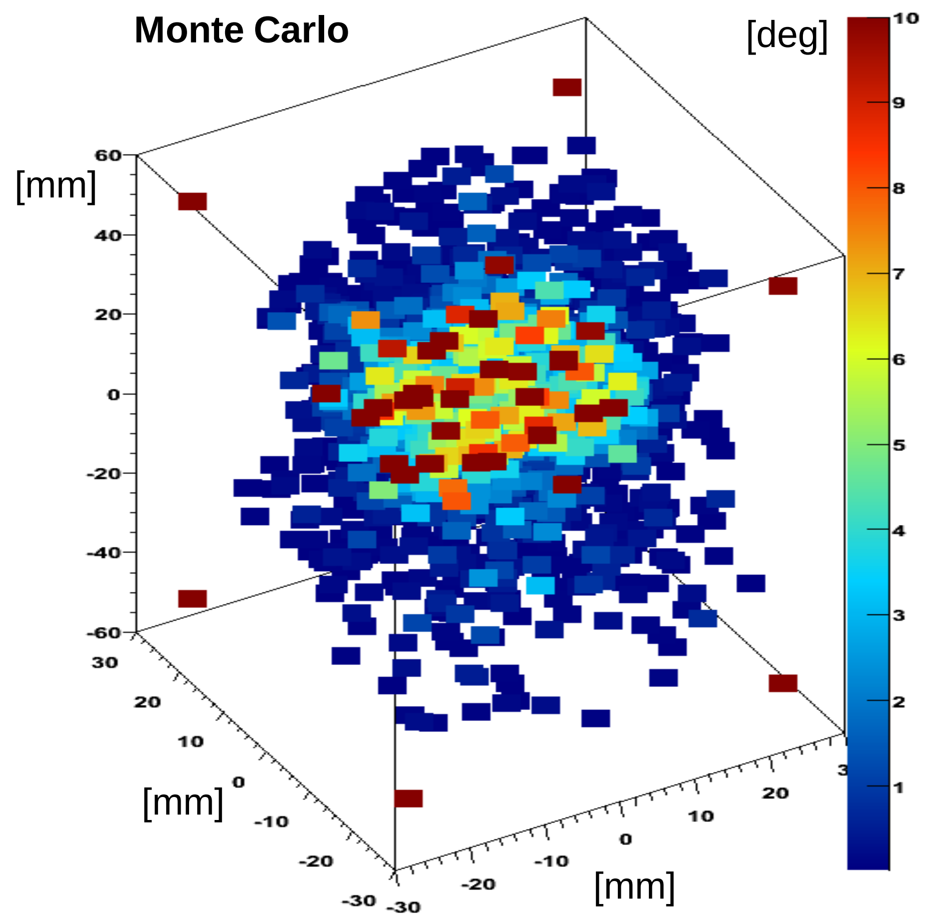
y

First real GEM MT data

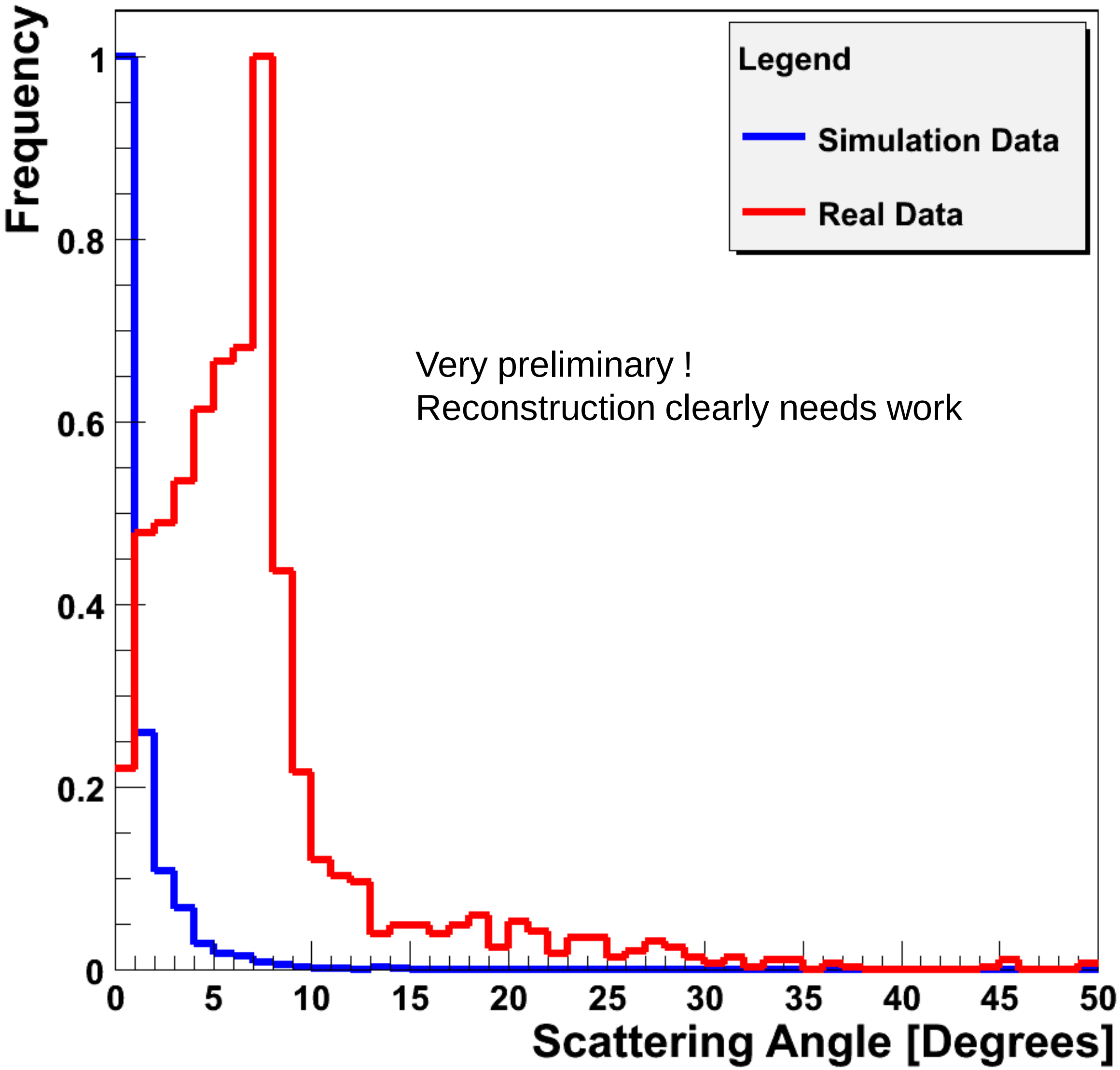
First attempt at reconstruction of muon scattering in high-Z target with Point-of-Closest-Approach (POCA) algorithm:

(3cm × 3cm × 2cm Pb target)



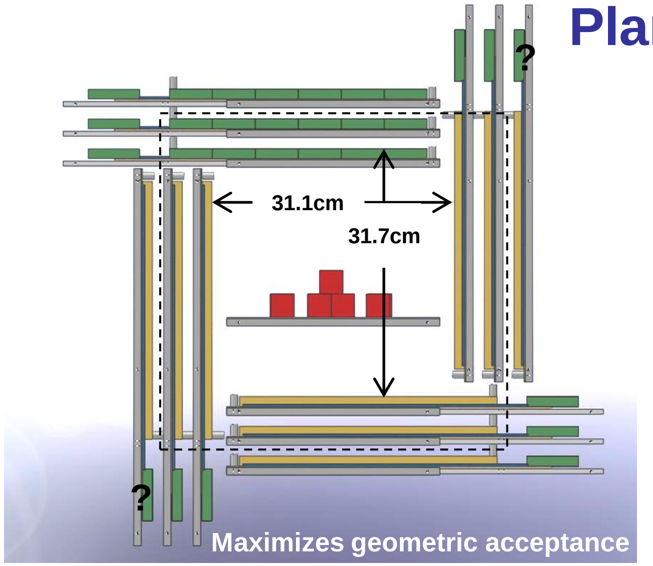


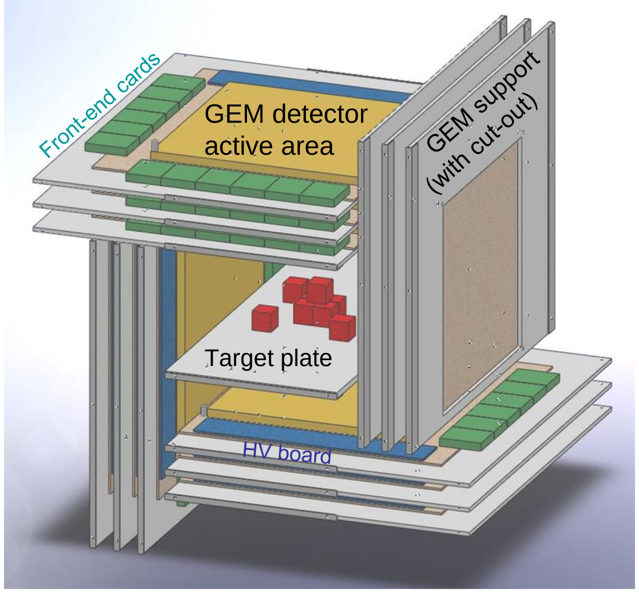
Measured Scattering Angles

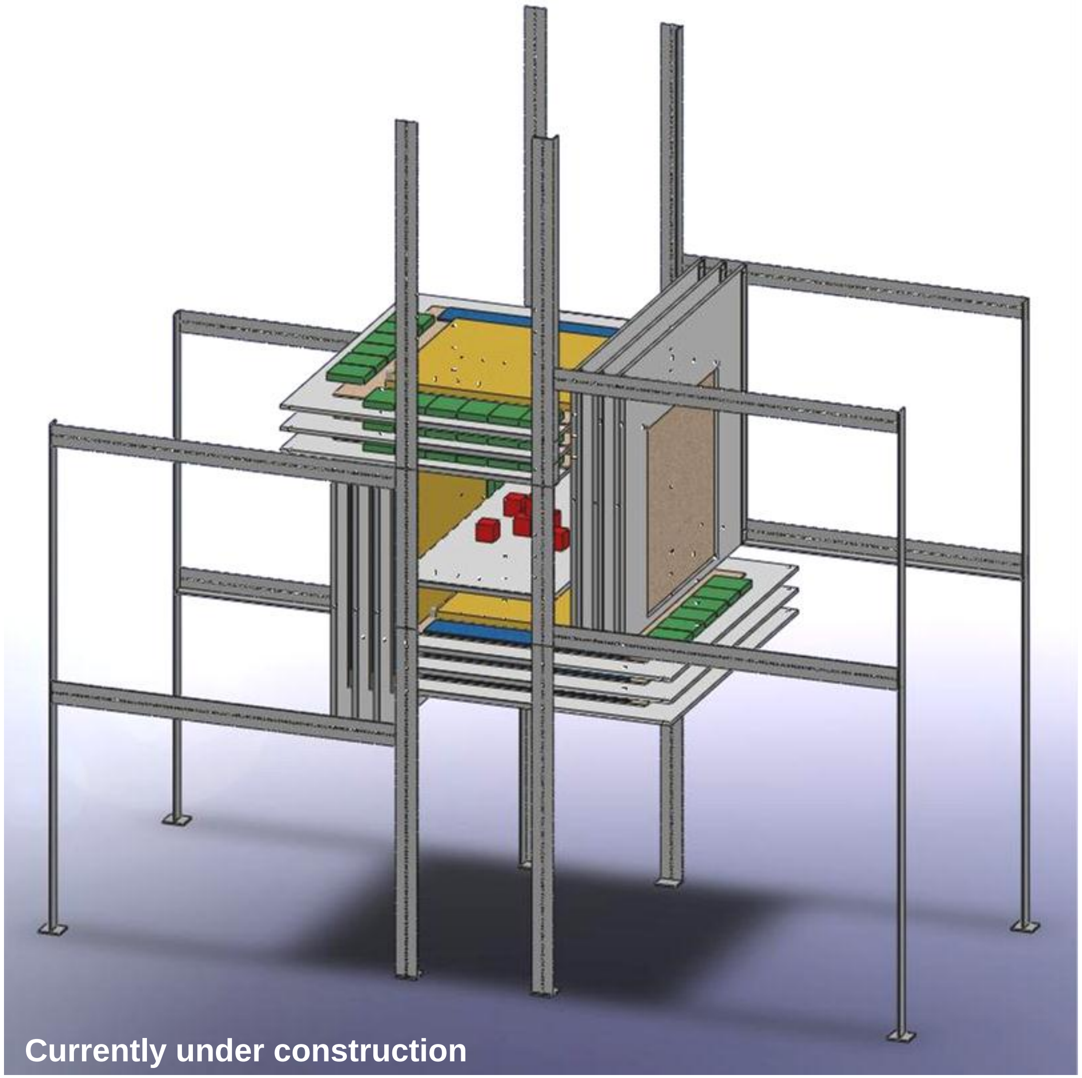


30cm×30cm×30cm Prototype

Planned Geometry & Mechanical Station Design:

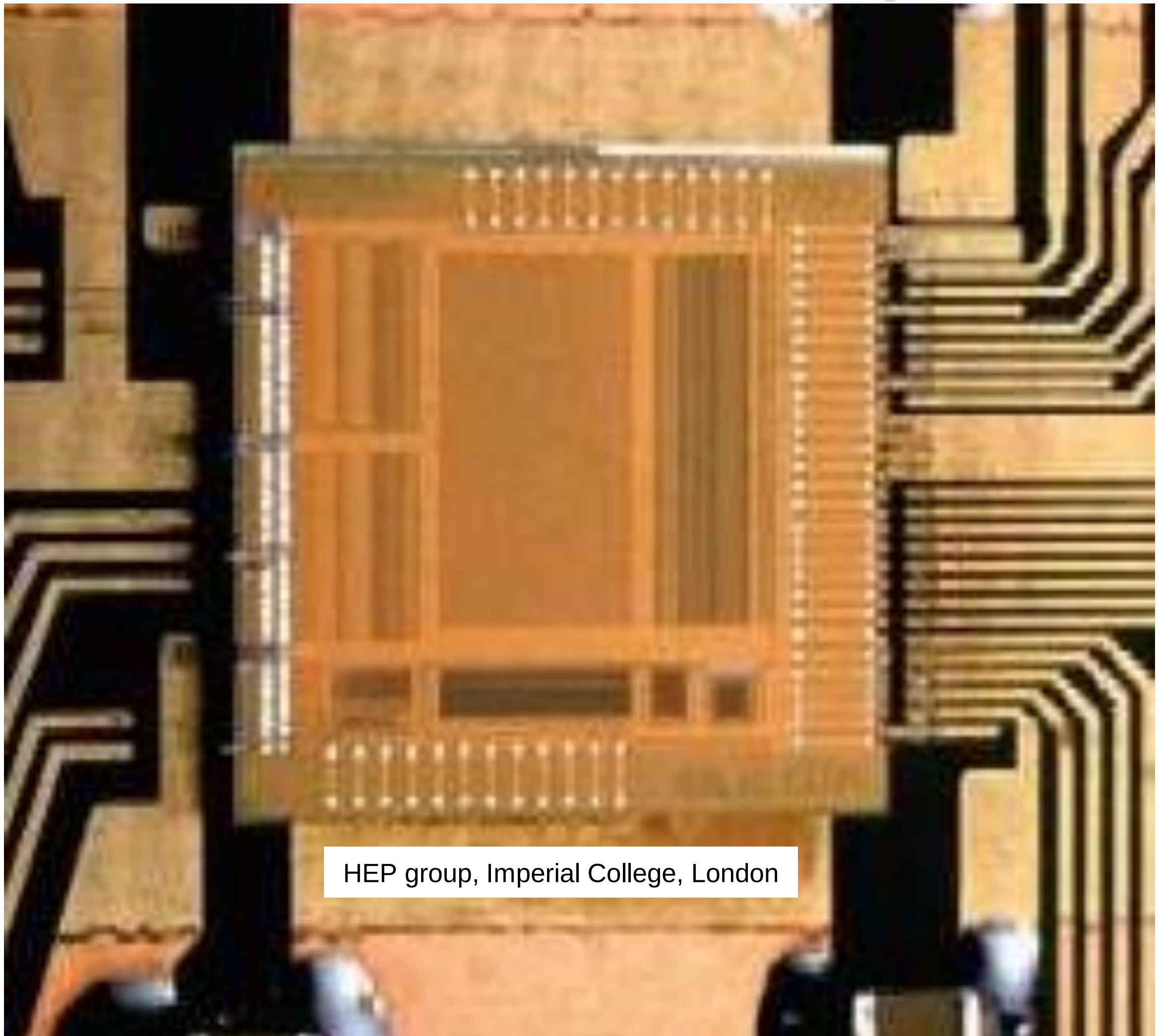






30cm×30cm×30cm Prototype

APV25 readout chip

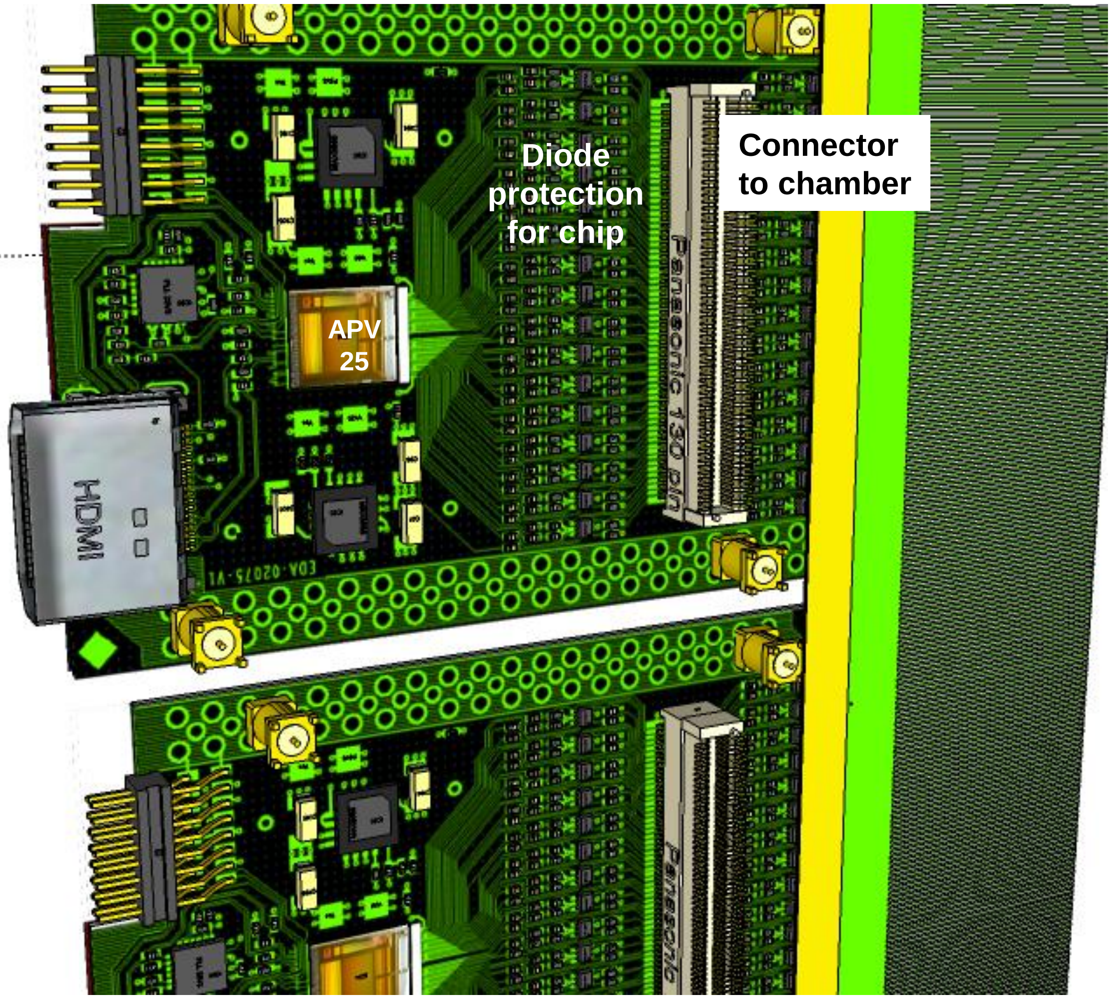


- originally developed for CMS Si-strip detector by ICL
- production in 2003/04
- yield of 120,000 good chip dies
- **128 channels/chip**
- preamplifier/shaper with 50ns peaking time
- 192-slot buffer memory for each channel
- multiplexed analog output
- integrated test pulse system
- runs at 40 MHz
- used e.g. by CMS, COMPASS, ZEUS, STAR, Belle experiments

MOST IMPORTANT:
- Chip is available
- Cheap! (~$20/chip)

- We need 120 chips for our ten 30cm × 30cm detectors.
- **Have procured 160 chips**

Front-end hybrid card



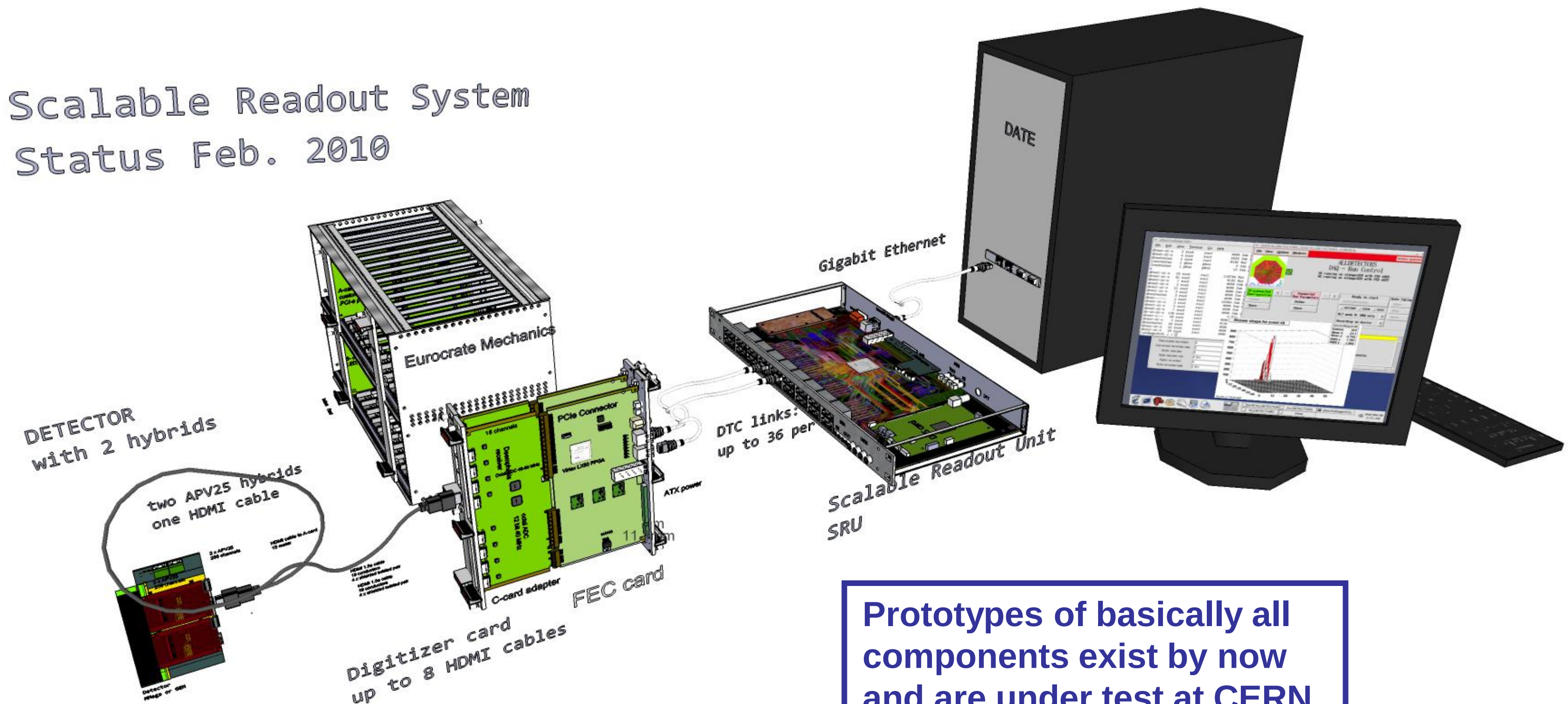
- **128 channels/hybrid**
- Integrated diode protection against sparks in GEM detector
- Estimated cost: $140/card
- Plan to get 160 cards
- 8 Prototype boards made at CERN

30cm×30cm×30cm Prototype

Electronics & DAQ under development

(with engineering support from RD51 collaboration at CERN)

Est. cost per electronics channel: $1-2



Prototypes of basically all components exist by now and are under test at CERN by RD51 electronics group

Plans for 2010

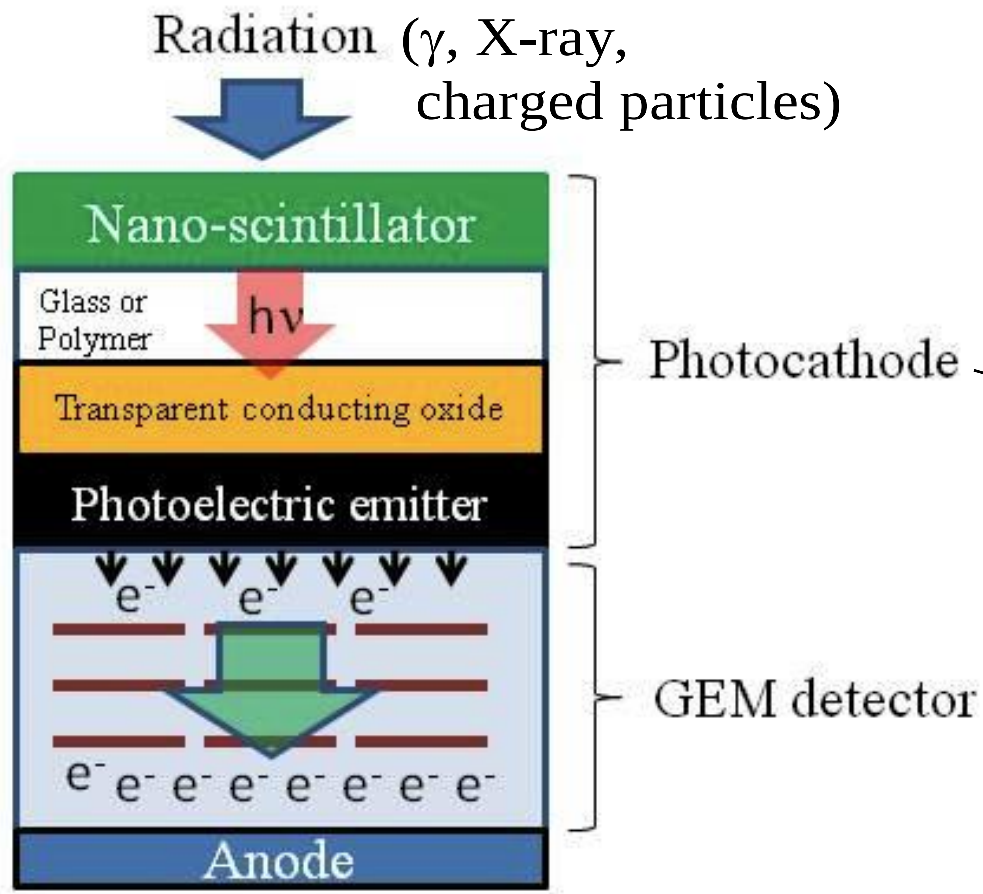
1. **Run minimal station for few weeks**
   - Collect as much data as possible until early May 2010
   - Measure performance: Resolution, efficiency
   - POCA reconstruction for basic muon tomography on real data

2. **Build & operate 30cm × 30cm × 30cm MT prototype**
   - Commission all GEM detectors with final electronics & DAQ
   - Get experimental performance results on muon tracking
   - Take and analyze lots of Muon Tomography data
   - Test performance with shielded targets in various configurations
   - Ship prototype to Florida and install in our lab; continue MT tests there

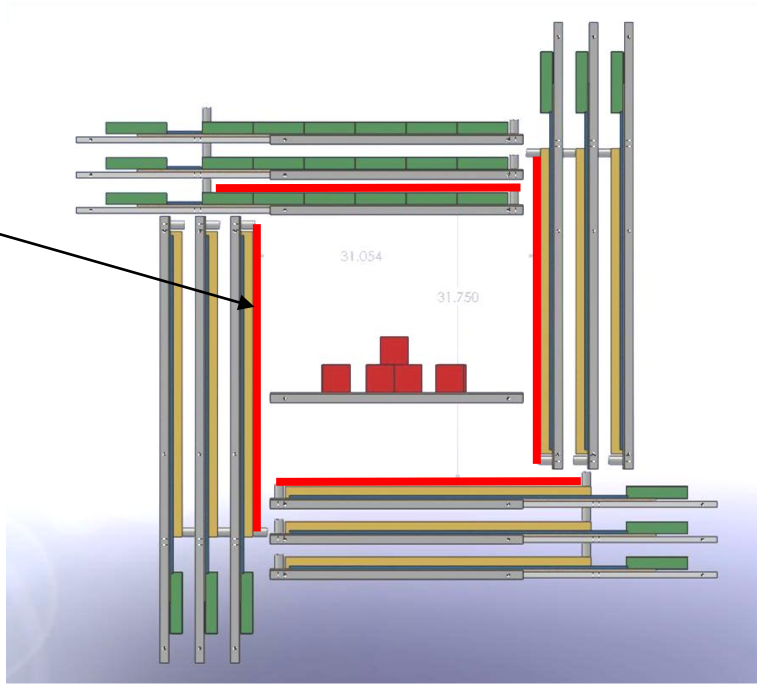
3. **Initial development of final 1m × 1m × 1m MT station**
   - Preparation of large-area GEM foils (~100cm × 50cm):
     Adapt thermal stretching technique to large foils
   - Try to simplify construction technique:
     Build small Triple-GEM detectors without stretching GEM foils
     (using our standard CERN 10cm × 10cm detectors, going on now)

Future Plans

Large photosensitive GEM Detector (100-200 keV γ's) ?



Muon Tomography with integrated γ-detection



Fl. Tech – U. Texas, Arlington planned joint effort (Physics & Material Science Departments)

Thank you !

We thank

Decision Sciences

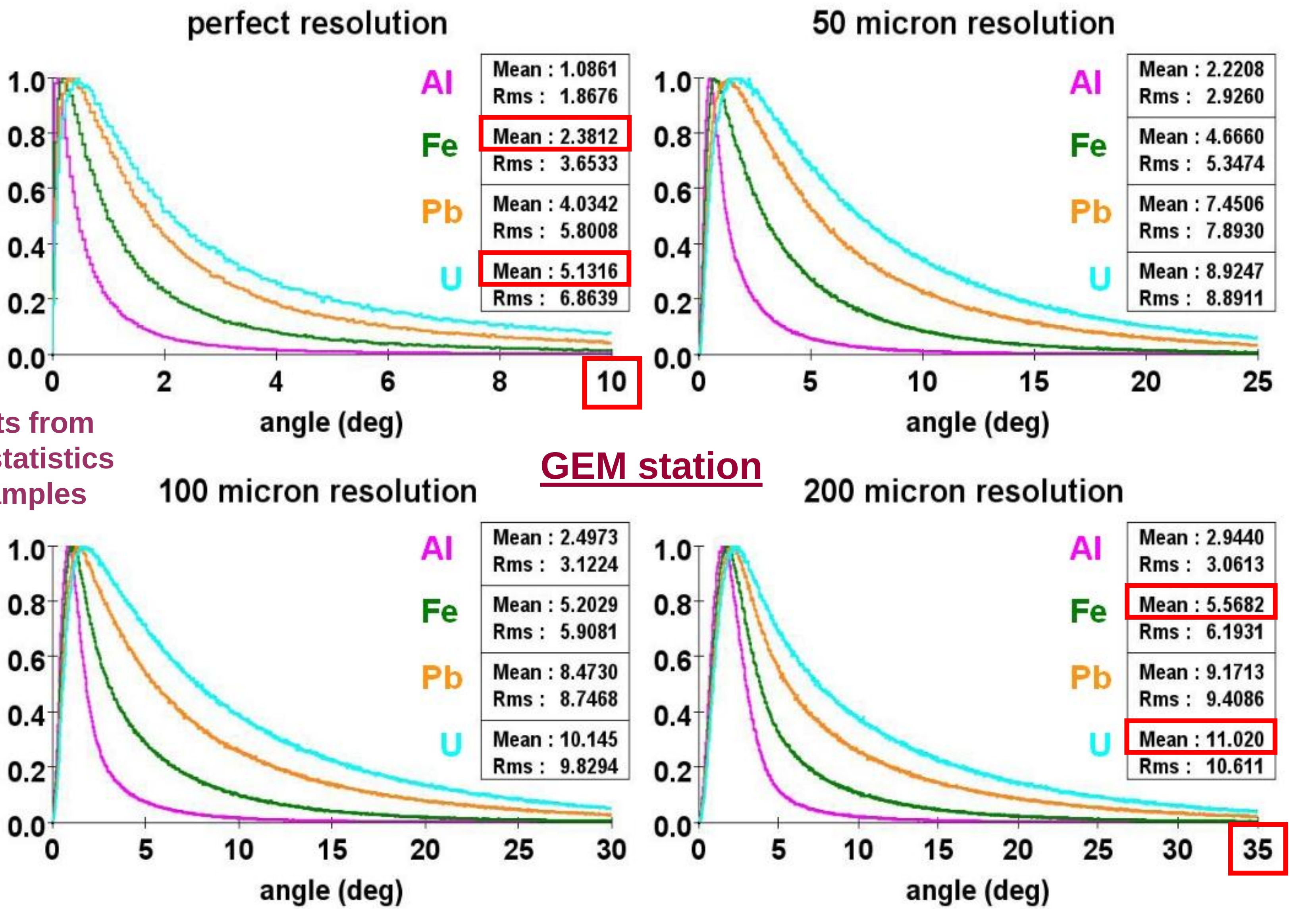
for the opportunity

to participate in the

Muon Summit !

Backup Slides

Scattering Angle Distributions

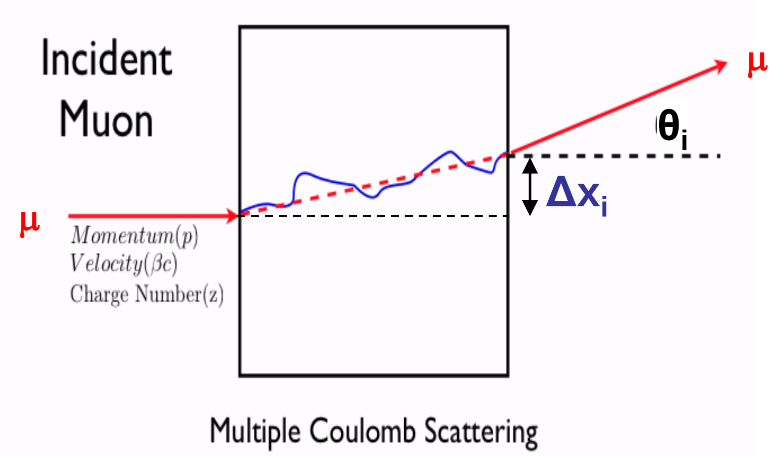


Results from high-statistics MC samples

Maximum Likelihood Method:

Reproducing Los Alamos Expectation Maximization (**EM**) algorithm

- **Input**: Use lateral shift Δx_i in multiple scattering in addition to information from scattering angle θ_i for each muon track



- **Procedure**:
  - Maximize log-likelihood for assignment of scattering densities to all voxels given all observed muon tracks
  - **Analytical derivation leads to iterative formula for incrementally updating λ_k values in each iteration**
- **Output**: Scattering density λ_i for each voxel of the probed volume

EM Result for Van Scenario