Simulation of an MPGD application for Homeland Security

Muon Tomography for detection of Nuclear contraband

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Outline

- MPGD for Muon Tomography
- Simulation of Muon Tomography Station performances
- Results and limitations
- Plans for the future

Muon Tomography to prevent nuclear material contraband

- Highly Enriched Uranium (HEU) or highly radioactive material could be smuggled across border for terrorist attack
- Various detection techniques in place or understudy to prevent smuggling and contraband of such dangerous materials across borders
- Muon Tomography based on cosmic ray muons is one promising detection technique

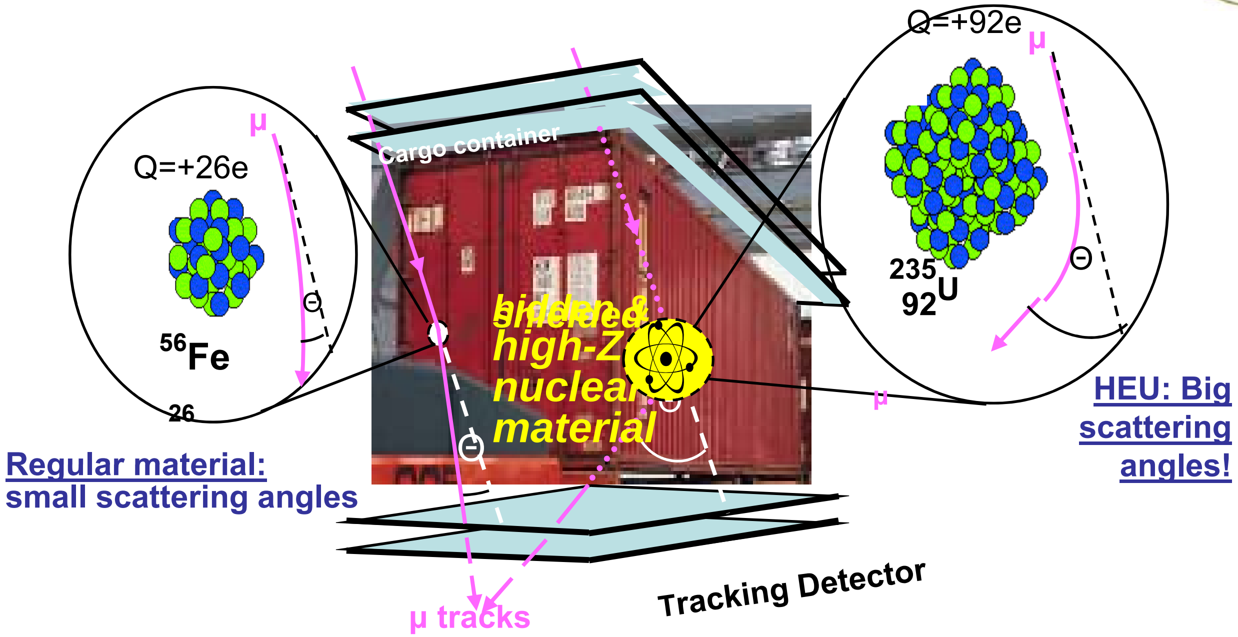
Muon Tomography Station (MTS) based on cosmic ray muons

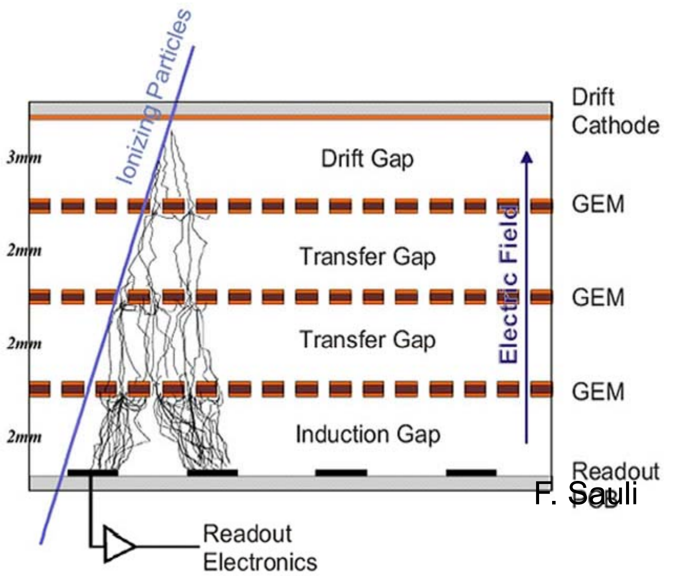
- Multiple Coulomb scattering is ~ prop. to Z and could discriminate materials by Z

$$\Theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta cp}\sqrt{\frac{x}{X_0}}\left[1+0.038\ln(x/X_0)\right] \text{ with } \frac{1}{X_0} \propto Z(Z+1)$$

- Cosmic ray muons: natural radiation source or no beam needed

- Muons highly penetrating; potential for sensing high-Z material shielded by Fe or Pb





Gas Electron Multipliers (GEMs) as tracking detectors for the MTS

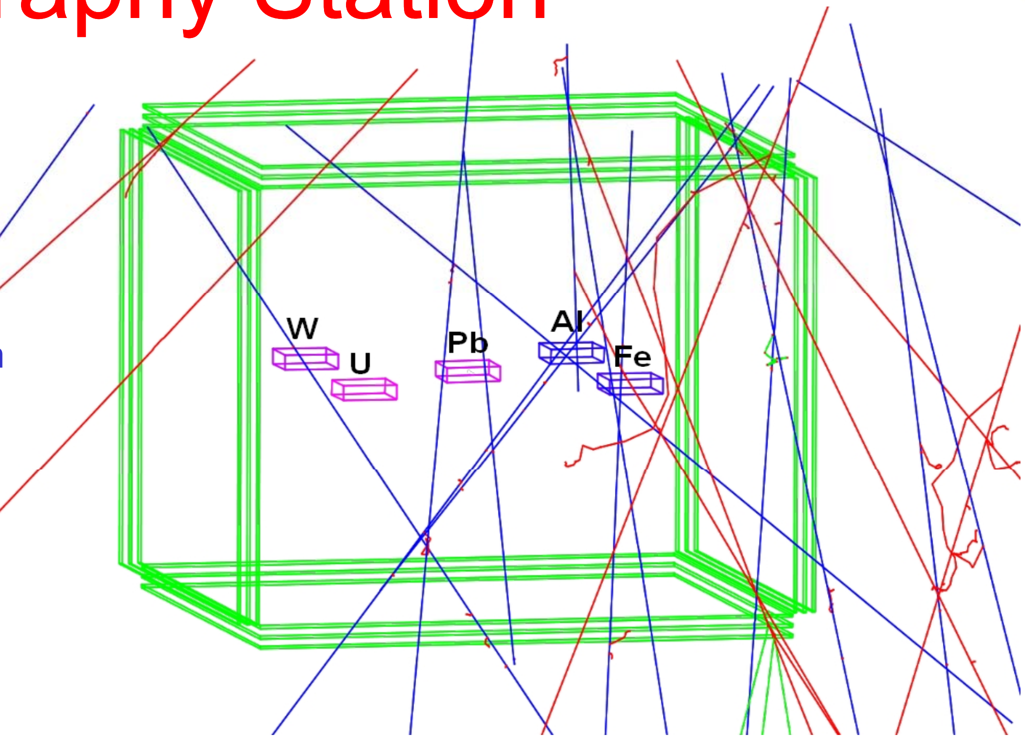
- Advantages:
  - Excellent 2D spatial resolution =>precise scattering angle measurement
  - Thin detectors layer => low material => low scattering with the detectors
  - Compact

- Challenges:
  - Building large size detectors
  - Maintaining the excellent resolution for large size detectors
  - Cost of the readout and electronics

Simulation of the performances of Muon Tomography Station

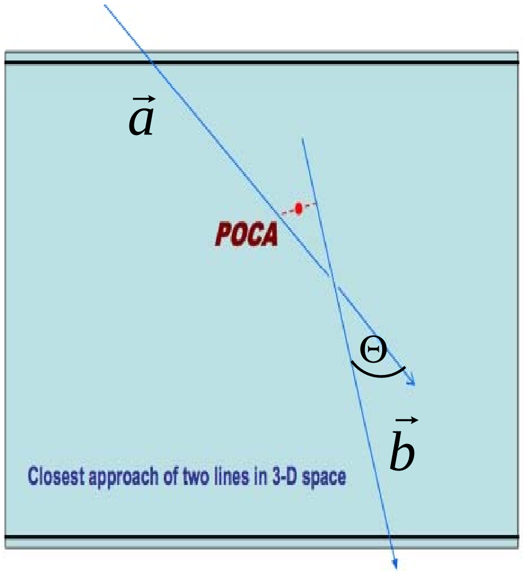
- We use CRY to generate the cosmic ray muons
  - cosmic ray package developped at Laurence Livermore NL
  - Package interfaced with GEANT4
- We use GEANT4 for the simulation
  - Physics of muons interaction with matter
  - Tracking of the muons with their recorded position measurement by the GEM detectors
- ROOT and AIDA/JAS for analysis and plotting of the results

Simulation of the performances of Muon Tomography Station



G4 simulation Geometry for the MTS:

- 3 Detectors per planes (top, bottom laterals)
- From 1 to up to 10 targets of different materials from low Z Al to high Z U
- CRY for cosmic muons as primary particles
- We collect the incoming and outgoing muon position recorded at the detectors level



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

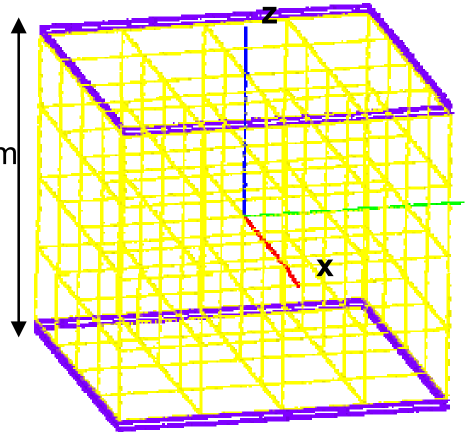
Reconstruction of the muons track

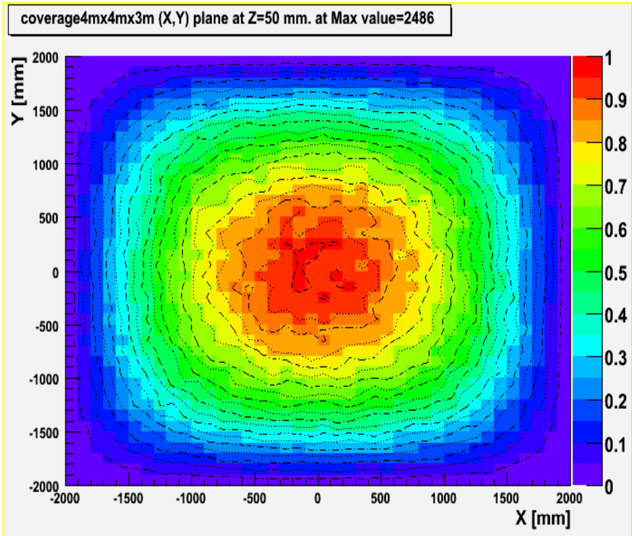
- Point Of Closest Approach (POCA) algorithm is used to get the interaction point of each muon
- The scattering angle of the muon calculated
- The MTS volume is divided in voxels (10 cm); each voxel displays the mean scattering angle of all the POCA points it contains. The value of the angle is then a good approximation of the z value of the material

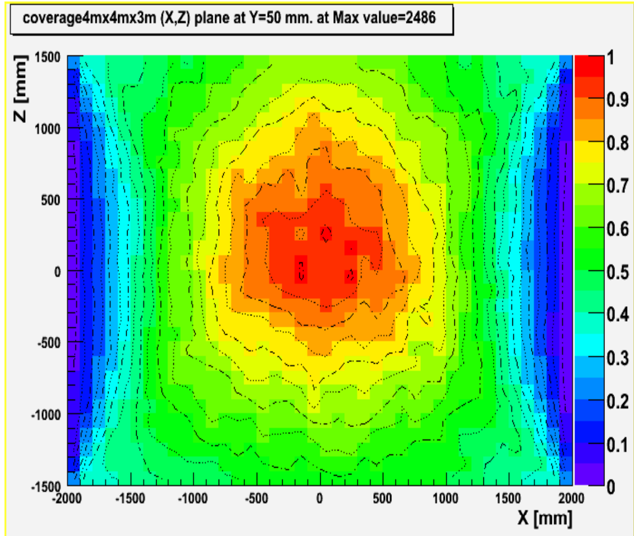
Acceptance and coverage of the MTS

MT station type | **Top View (x-y plane)** | **Side View (x-z plane)**

Top & bottom detectors only



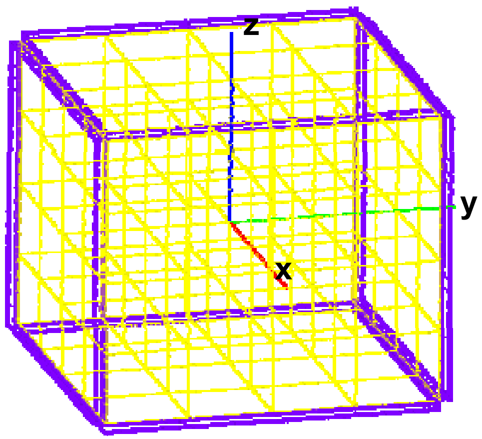


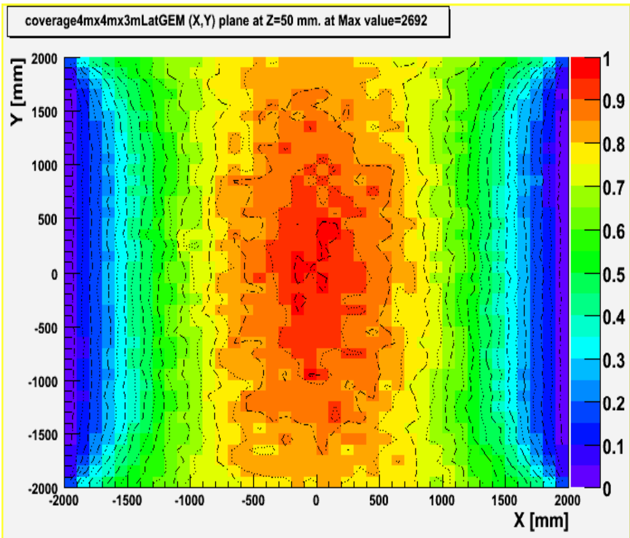


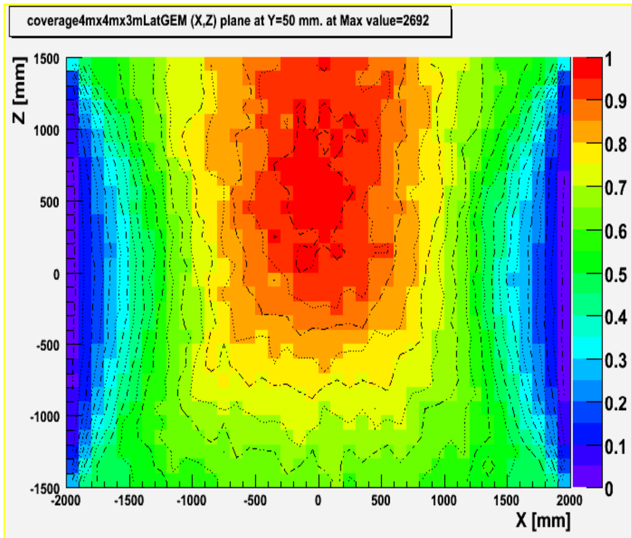
~ 10 min exposure => ~ 2500 muons in maximum coverage voxel.

3% of the volume around the center with 80% of voxel with max muons

Top, bottom & side detectors



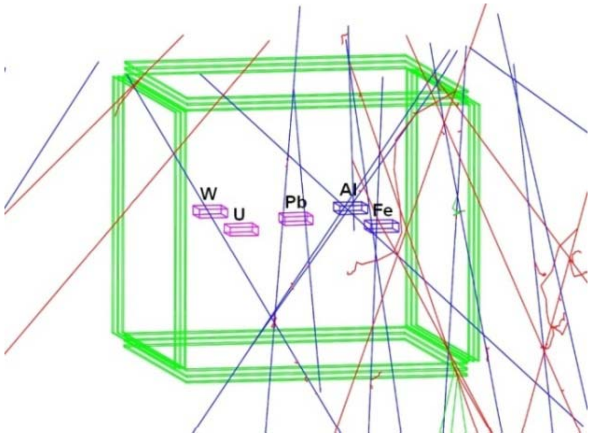




Maximum coverage 10% higher

18% of the volume around the center with 80% of voxel with max muons

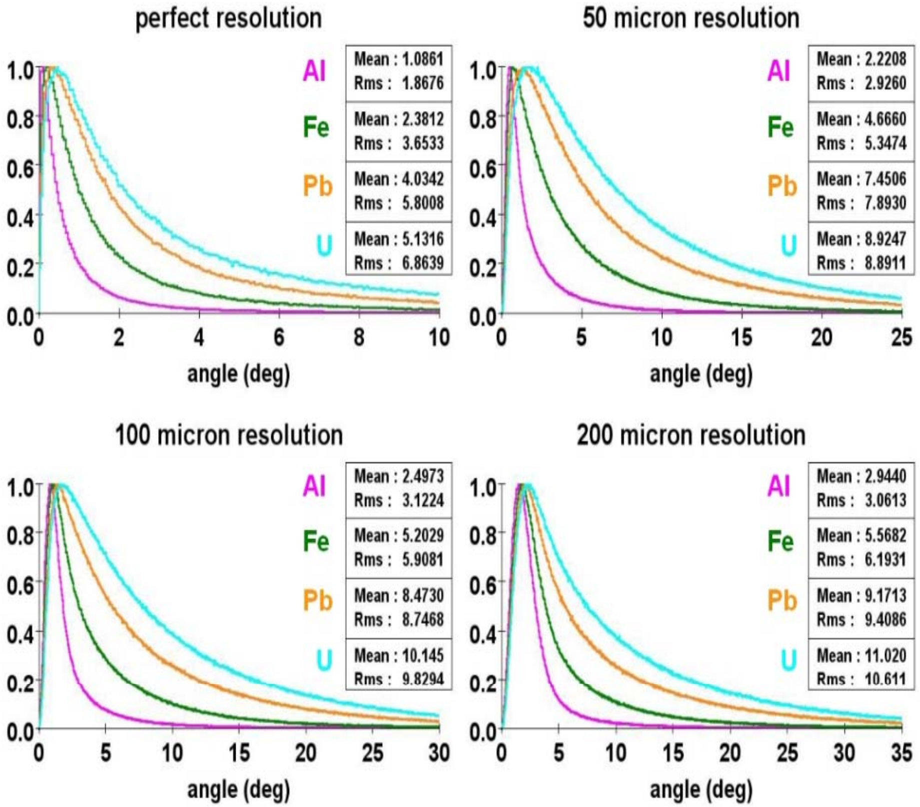
Scattering Angle Distribution

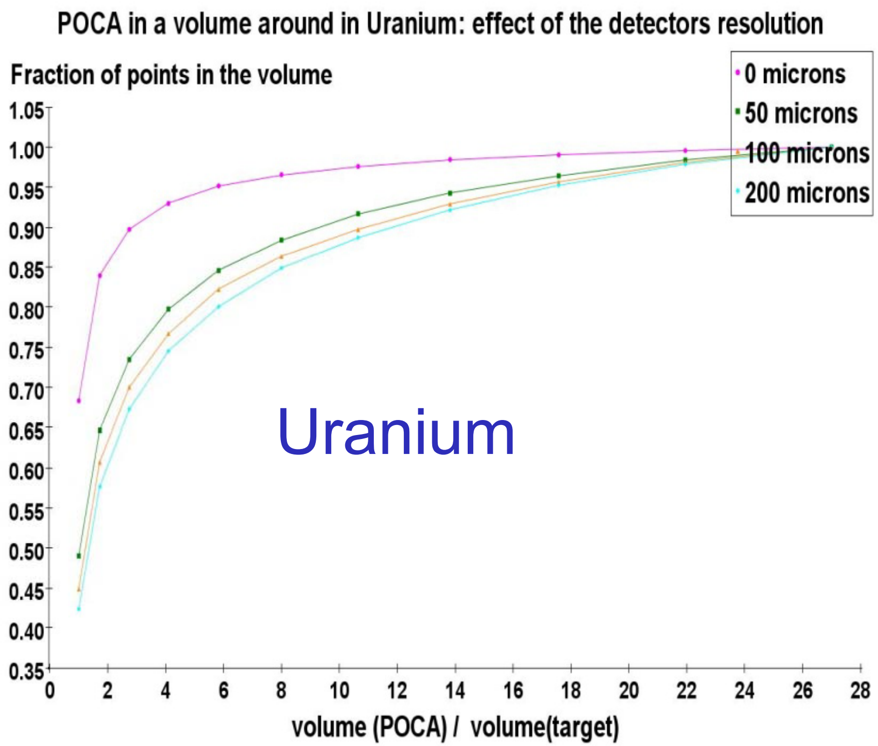


With resolution, the reconstructed POCA point of small deviation angle muons don't fall within the material volume.

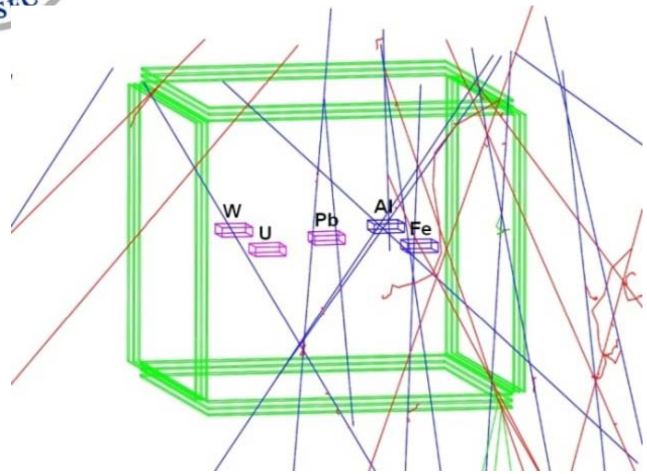
- The reconstructed mean value of the scattering angle is then higher the than the actual mean angle for the given material.

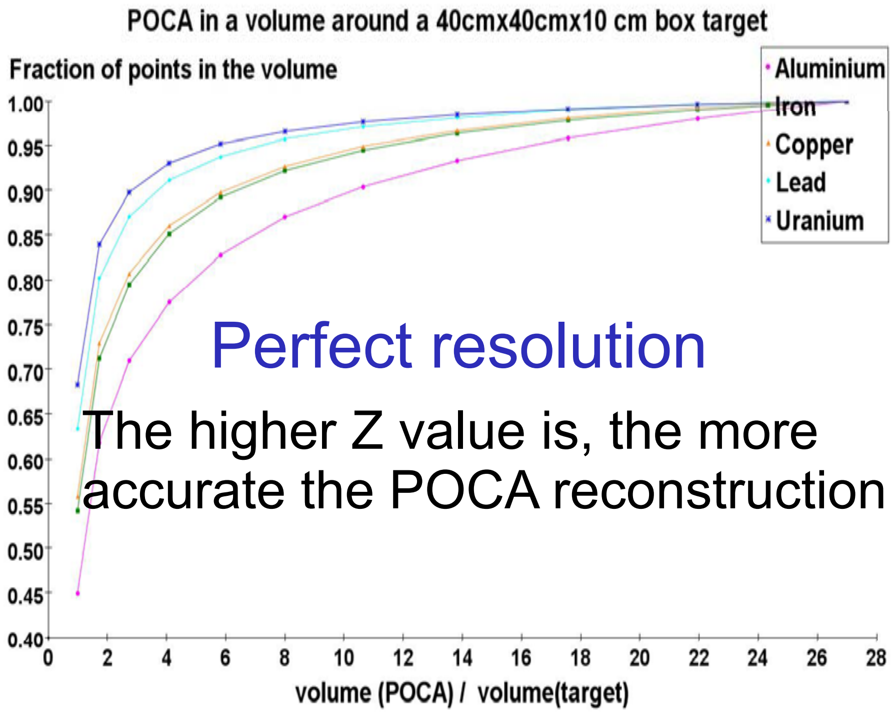
- The POCA points are scattered all around the MTS volume. The statistic is then smaller in the volume defined by the material.





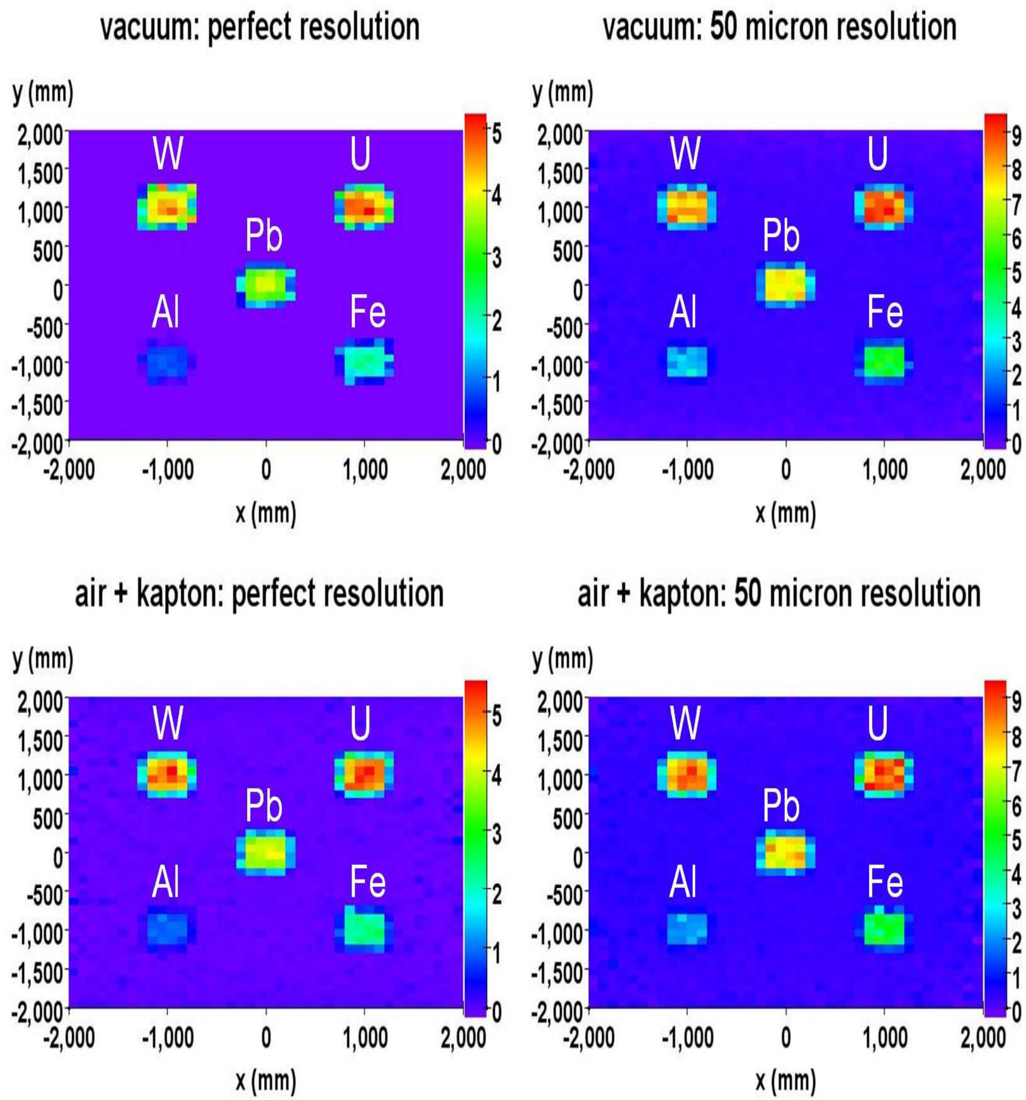
Reconstructed targets



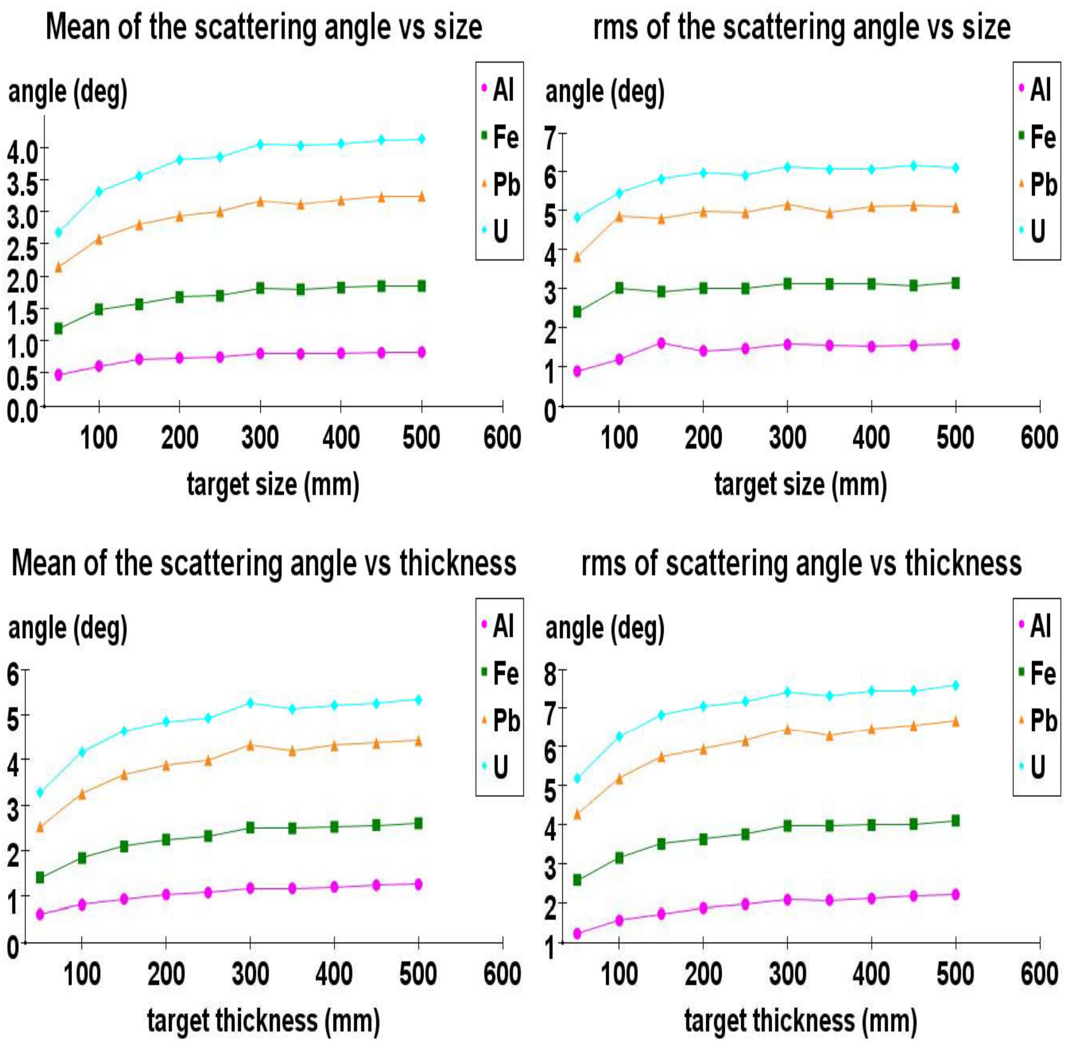


Perfect resolution

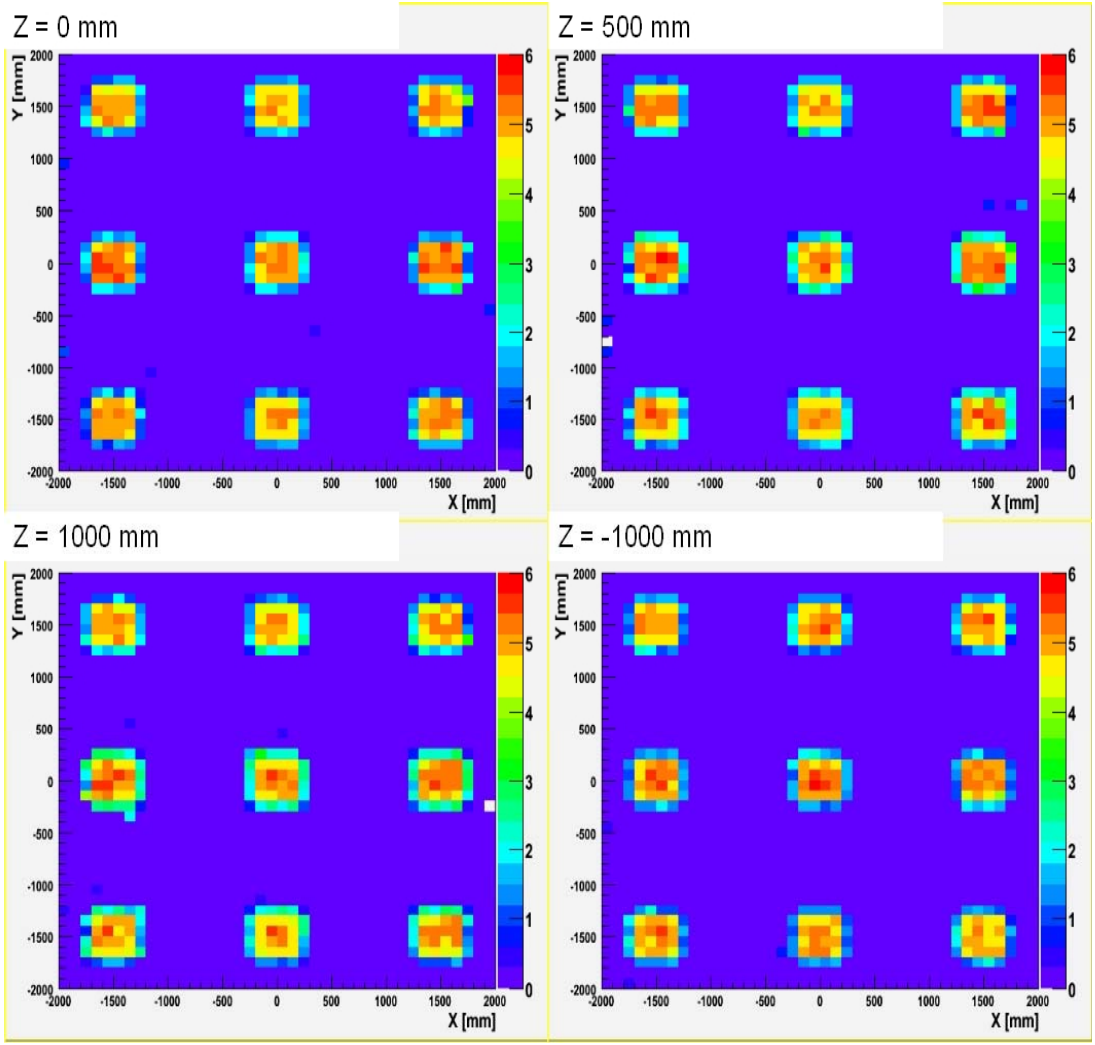
The higher Z value is, the more accurate the POCA reconstruction



Systematic effect on the mean angle

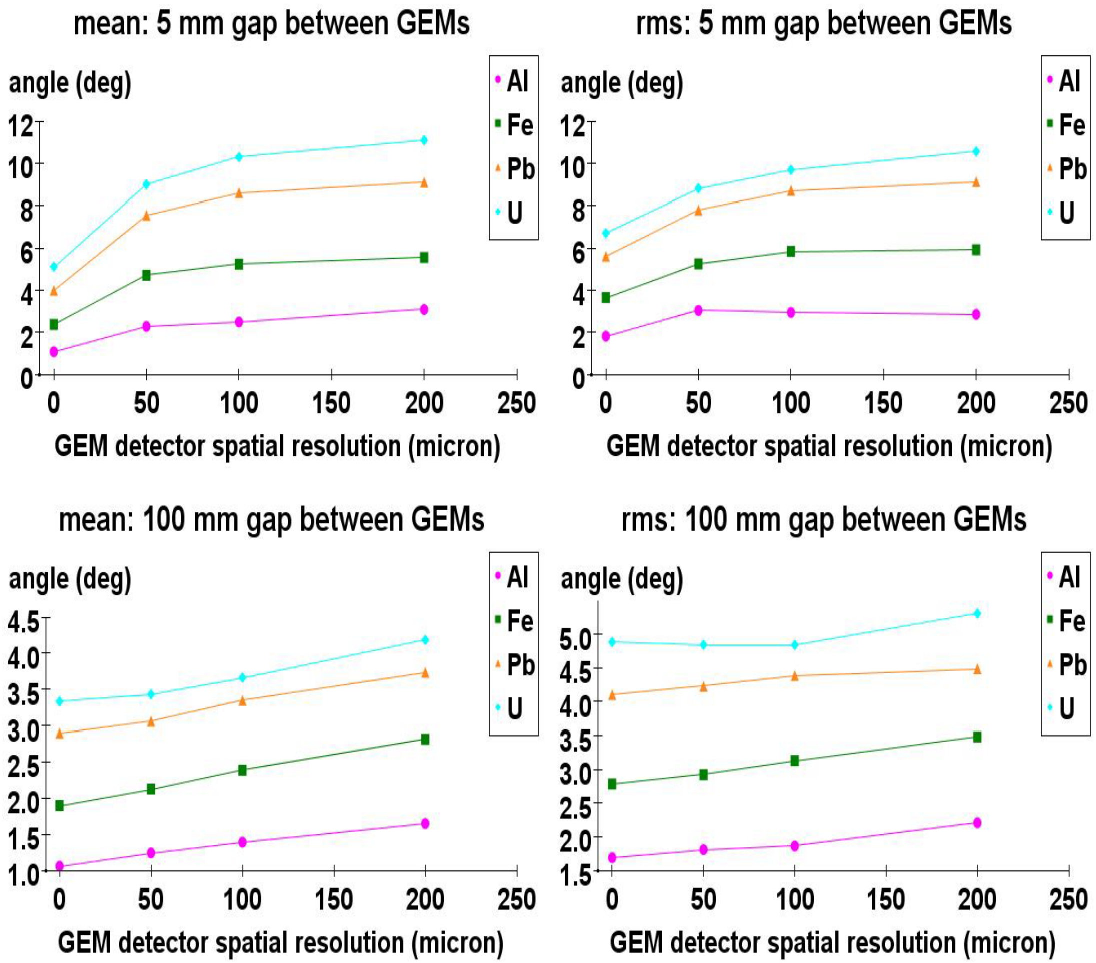


Effect of the target dimensions

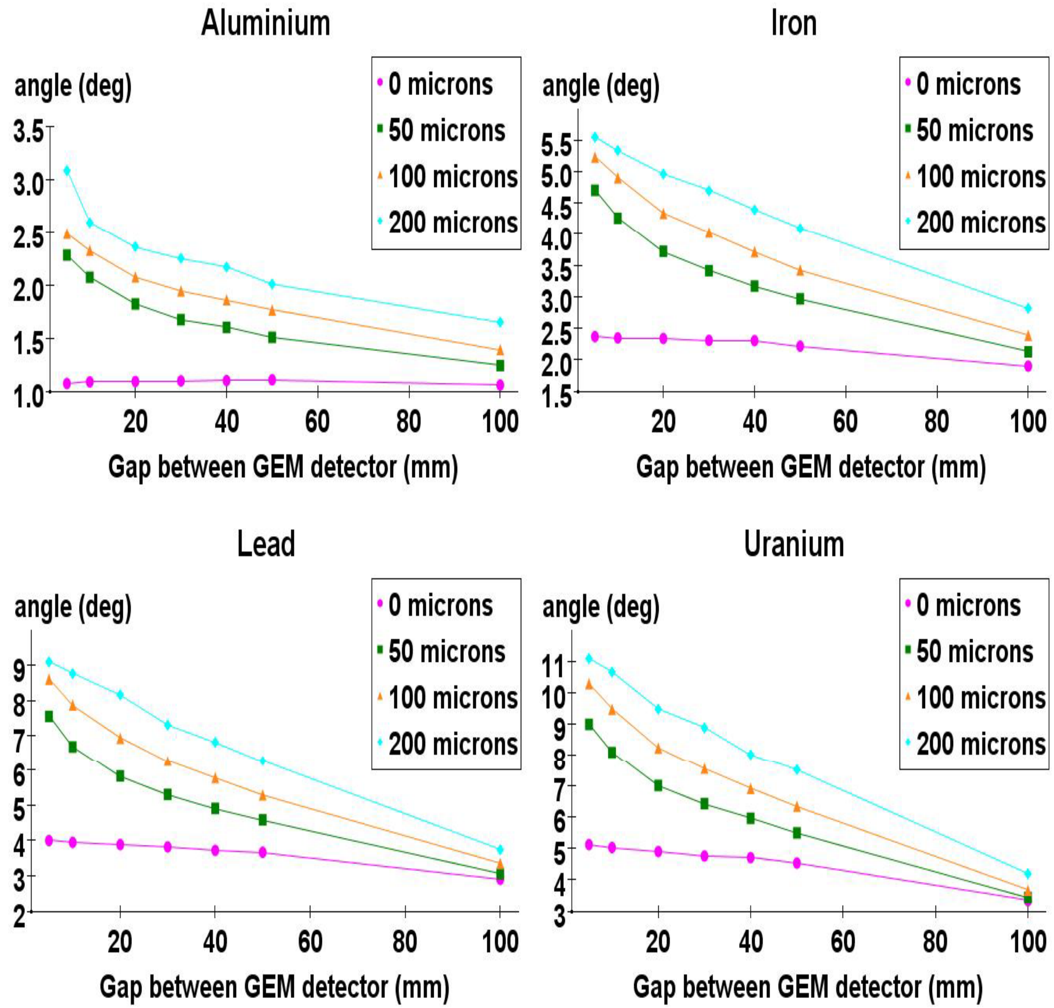


Effect of the position of the targets in the MTS volume: Uranium

Systematic effects on the mean angle



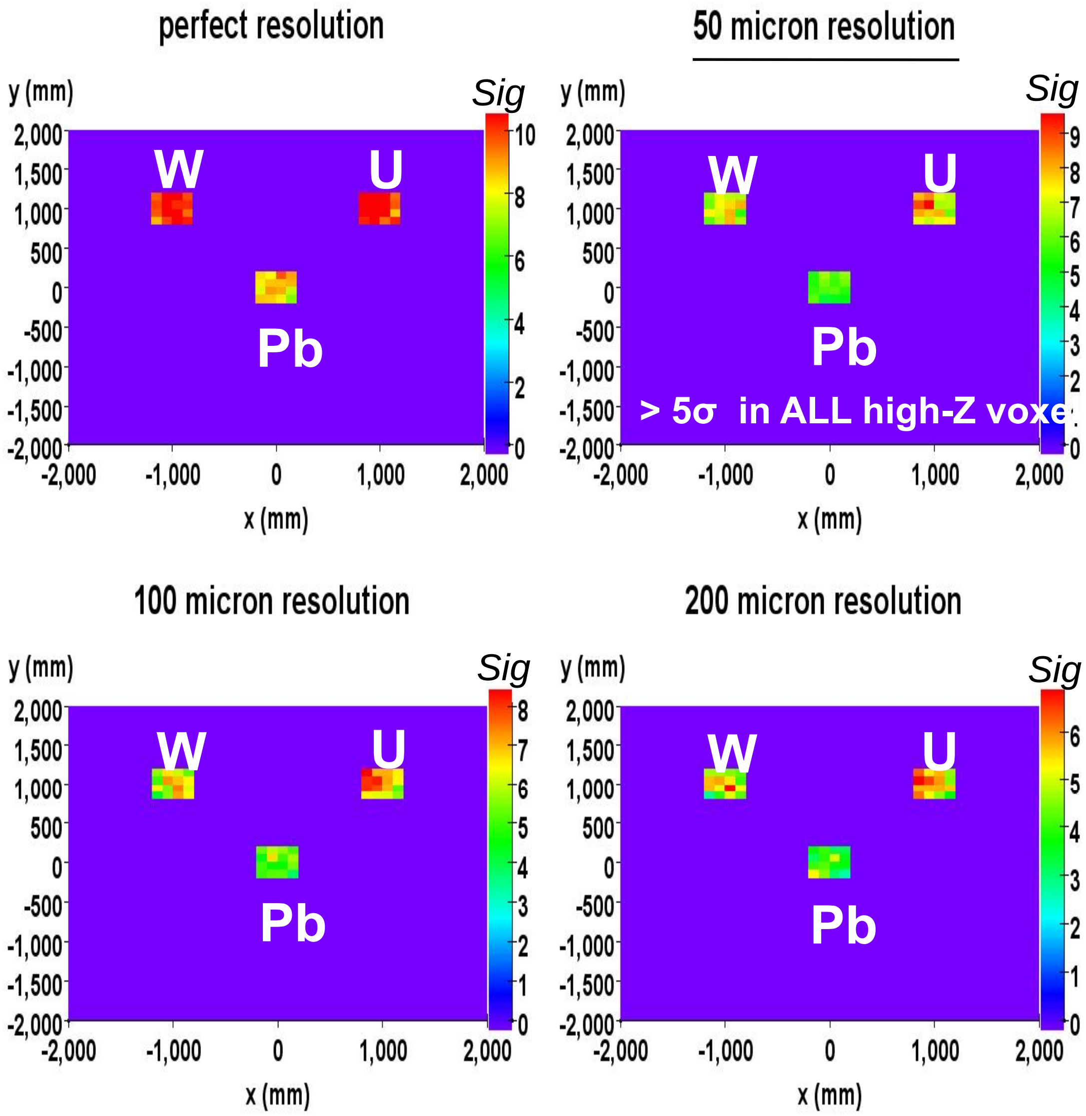
Effect of the detectors resolution



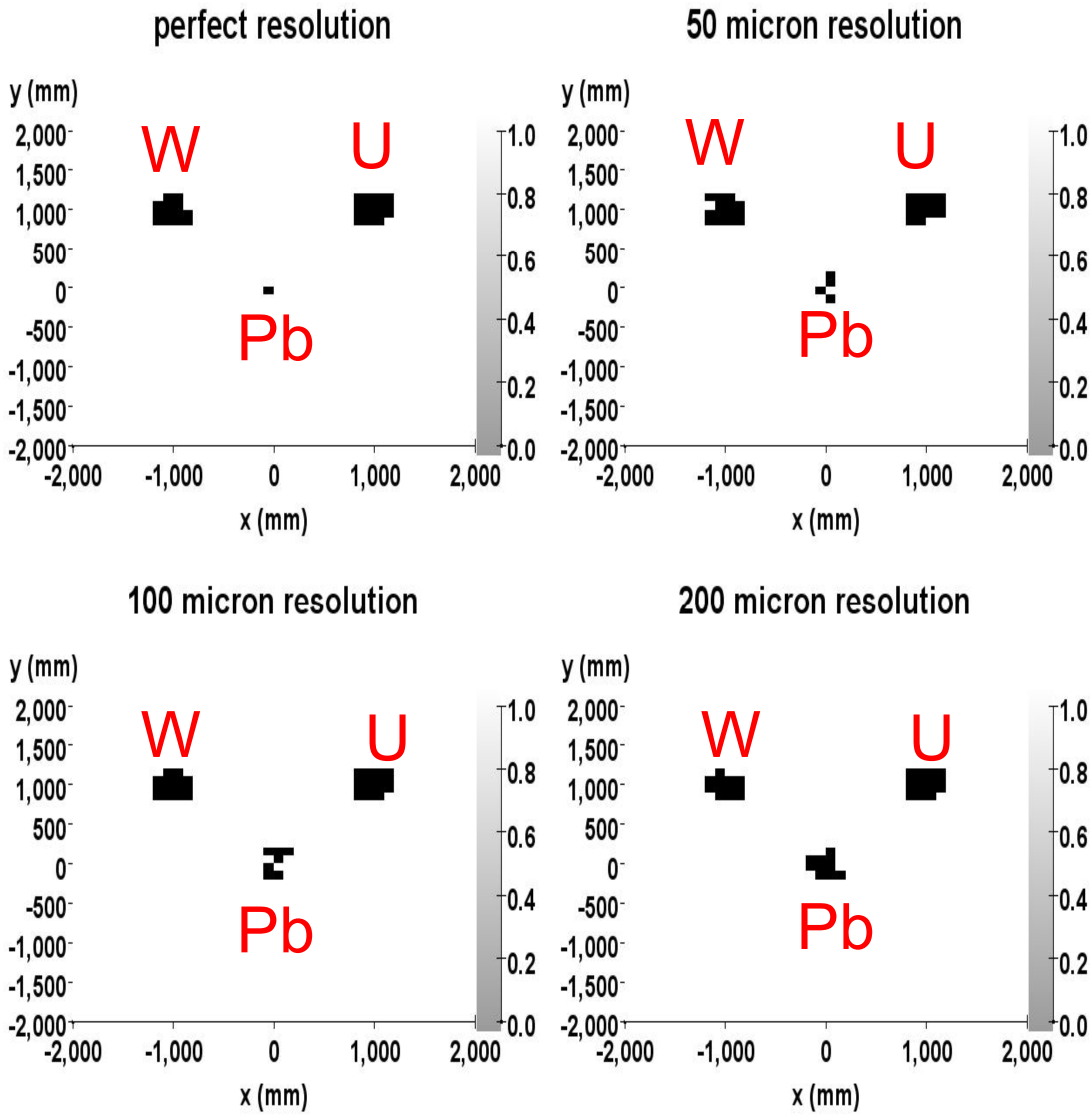
Effect of the gap between the detectors

Significance of Excess and U hypothesis test: 10 min Exposure @ 99% confidence

Excess above Fe background

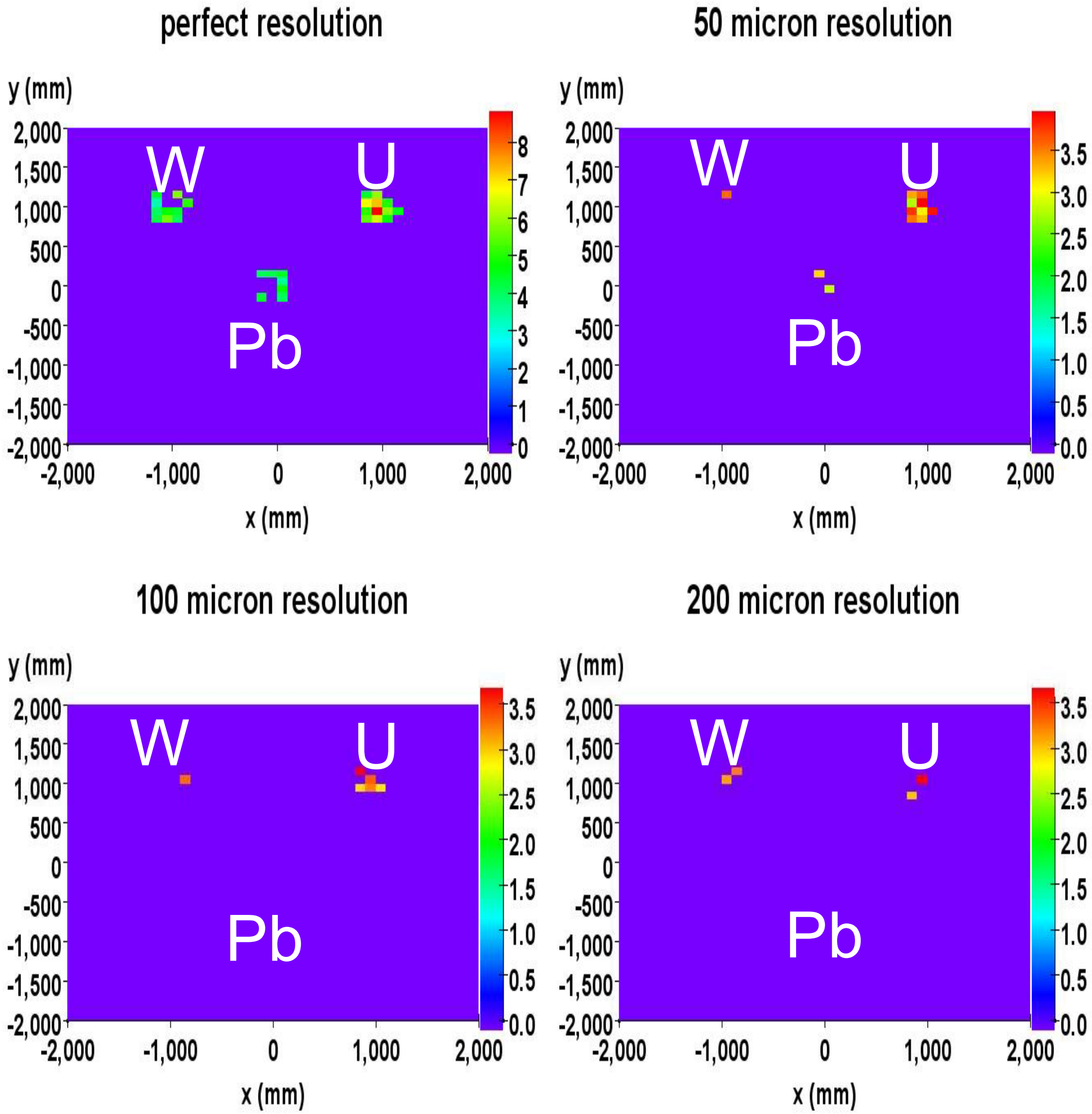


U hypothesis

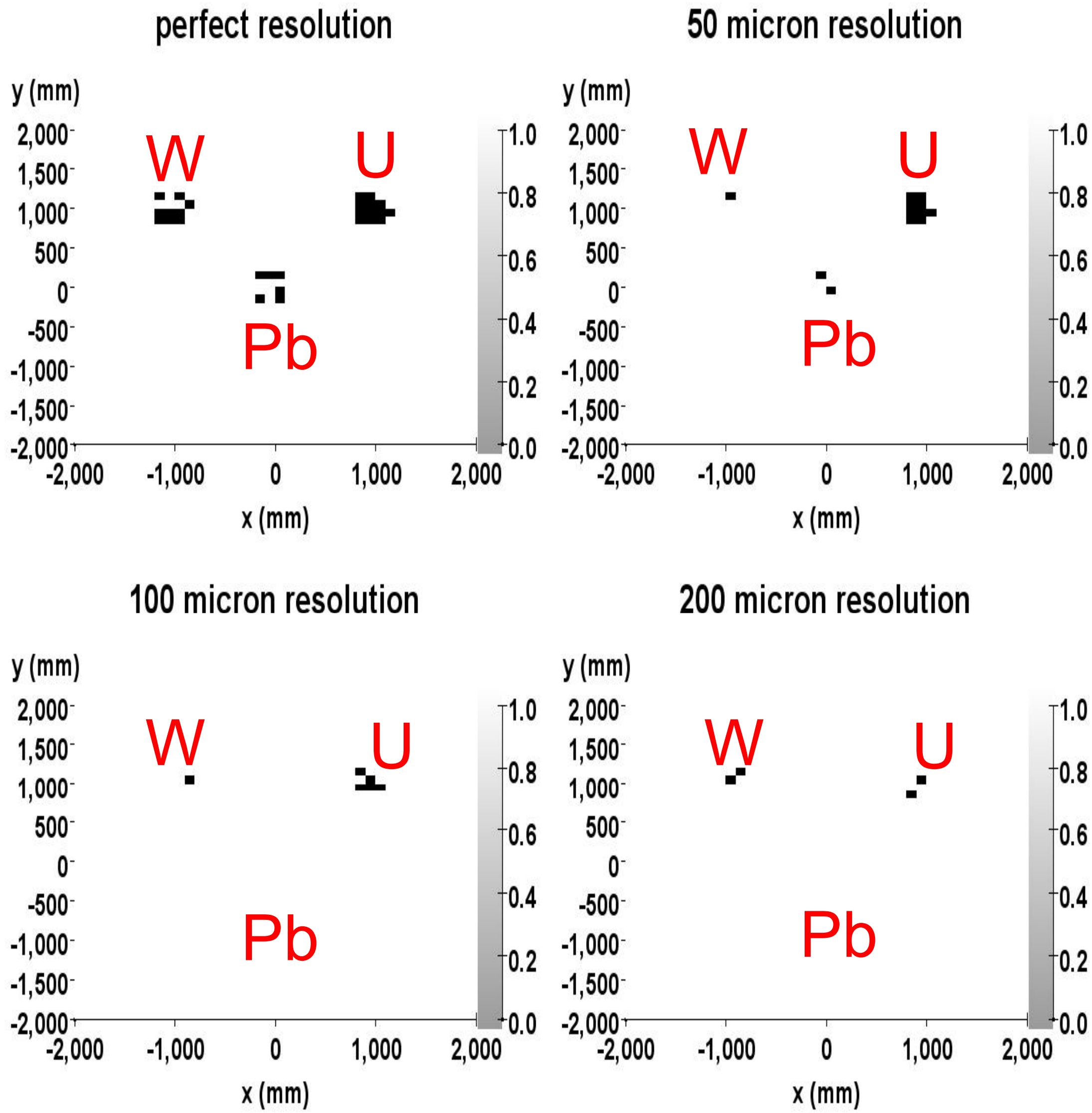


Significance of Excess and U hypothesis test: 1 min exposure @ 99% confidence

Excess above Fe background

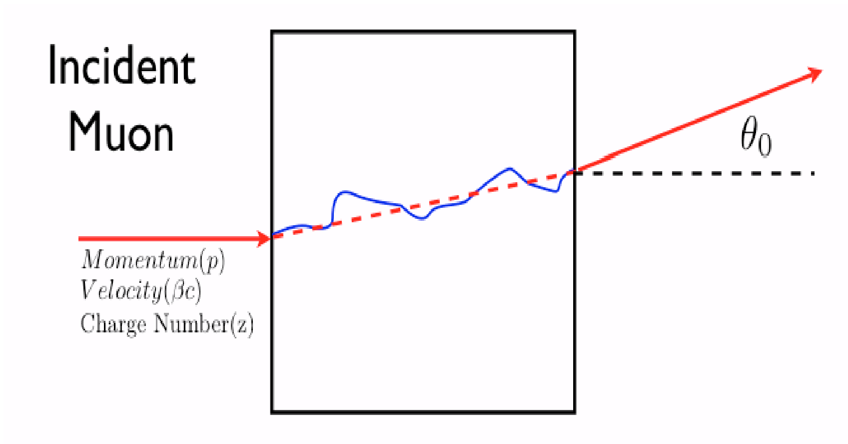


U hypothesis

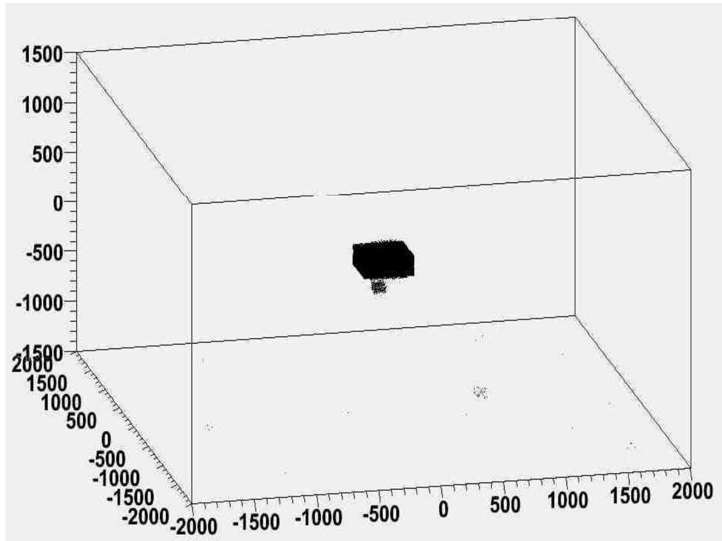


Advanced reconstruction: Expectation Maximisation Algorithm (EM)

- Reproducing Los Alamos Expectation Max. algorithm (L. Schultz et al.)
- **Input**: Use lateral shift Δx_i in multiple scattering as additional information on top of scattering angle θ_i for each (i-th) muon track
- **Output**: Scattering density λ_k for each (k-th) voxel of the volume
  - λ relates the variance of scattering with radiation length (or Z value) of the respective material
- **Procedure**: Maximize log-likelihood for assignment of scattering densities to all independent voxels given observed μ tracks
  - Analytical derivation leads to an iterative formula for incrementally updating λ_k values in each iteration



Multiple Coulomb Scattering



Plans for the next months

- Start the building a our first GEM detector:
  - Working on a with 10 cm x 10 cm foils prototype.
  - Readout and electronics development.
  - Expect our first MTS prototype some time next year.

- Continue simulation work:
  - Improvement the EM algorithm for the reconstruction.
  - Get involve MPGD detector simulation (GEANT4, Garfield integration).

Conclusion

- We report advanced simulation results of Muon Tomography detection technique.
  - Large size and excellent spatial resolution tracking detectors are needed for the MTS.
  - We proposed to use large size GEM detectors.
  - Big challenges ahead in terms of statistics (low rate cosmic muons) and resolution.
- Plan to switch from simulation to building a MTS prototype
  - Get a small size GEM detectors working.
  - Build a medium size MTS prototype and compared with simulation.
  - Still some simulation and algorithm development needed.
  - Our group is new in MPGDs so we need all expertise from you to meet our challenges of building a MTS with large size MPGDs.