Improvement of Material Discrimination Using Muon Momenta in MST

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Abstract

- Muons deviate while traversing through the matter due to multiple Coulomb scattering (mcs). Muon Scattering Tomography (MST) exploits the mcs phenomenon for imaging target materials.
- Interesting applications: Imaging cargo-containers, monitoring nuclear waste containers, identifying fissile materials, etc.
- MST simulations have been performed with GEANT4, reconstructed images have been analyzed with t-test and Pattern Recognition Method (PRM).
- An analytical method has been followed to predict incoming momenta of muons and improve the imaging with MST.

MST Principle

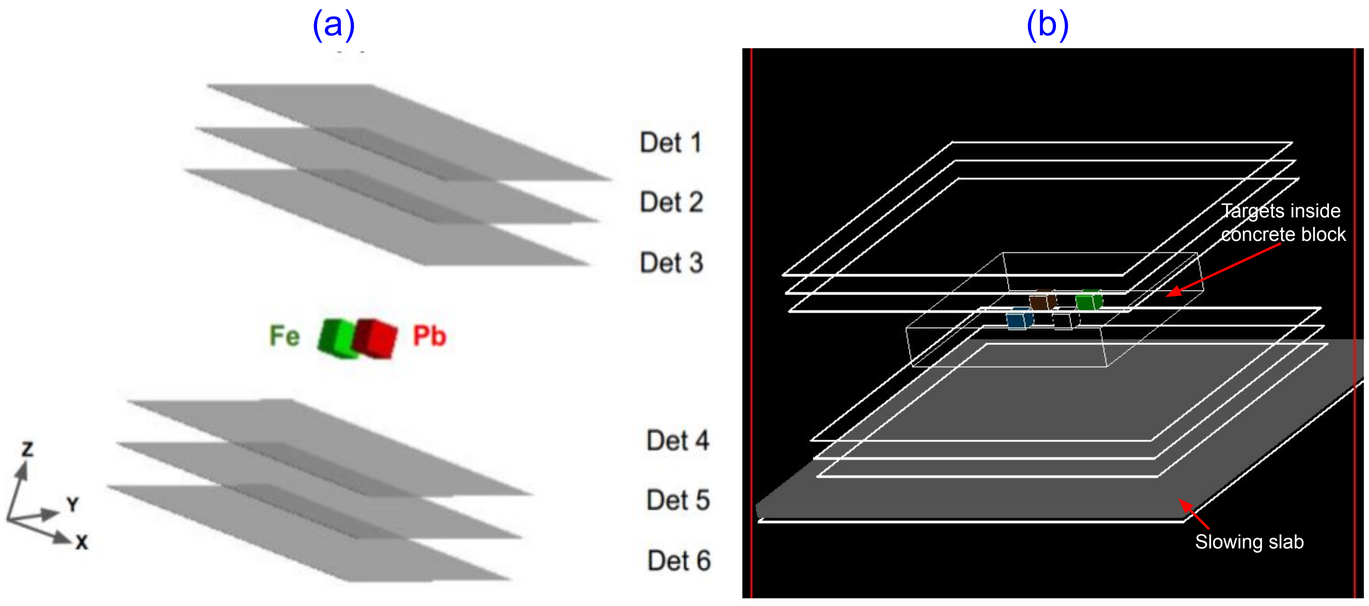
The deviation angle projected on a plane passing through the incoming muon direction has a distribution which is approximately Gaussian for particles of the same momentum, with zero mean and a root-mean-square (σ) according to the formula:

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\theta_x^2/2\theta_0^2} \qquad \sigma \approx \frac{13.6\,\text{MeV}}{pc}\sqrt{\frac{X}{X_0}}$$

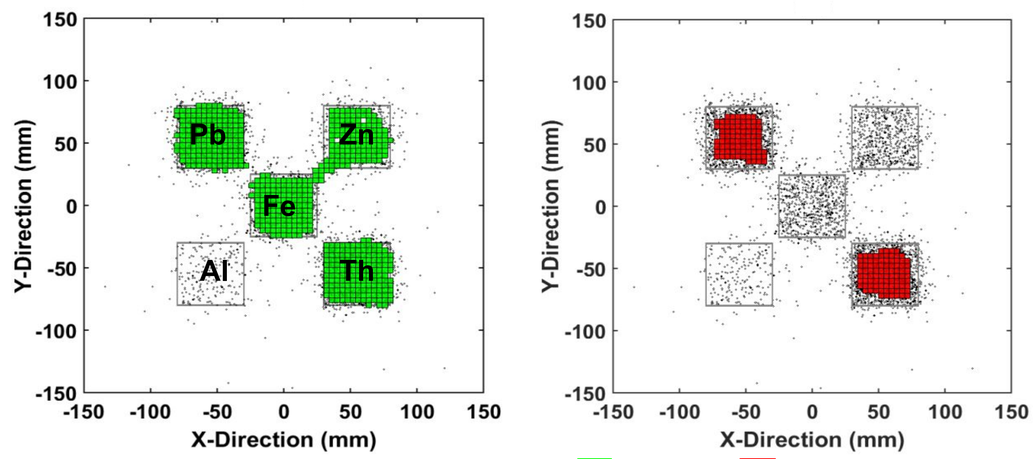
$$X_0 = \frac{716.4A}{\rho Z(Z+1)ln\left(\frac{287}{\sqrt{Z}}\right)}$$

p = Momentum
X_0 = Radiation Length
X = Thickness
A = Atomic Mass
Z = Atomic Number
ρ = Density

MST Setup in GEANT4

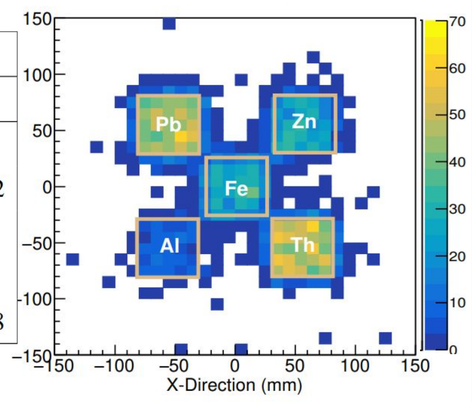


(a) GEANT4 Simulation setup for material discrimination with 6 detectors (b) The setup with a slowing slab of concrete and additional detection layer



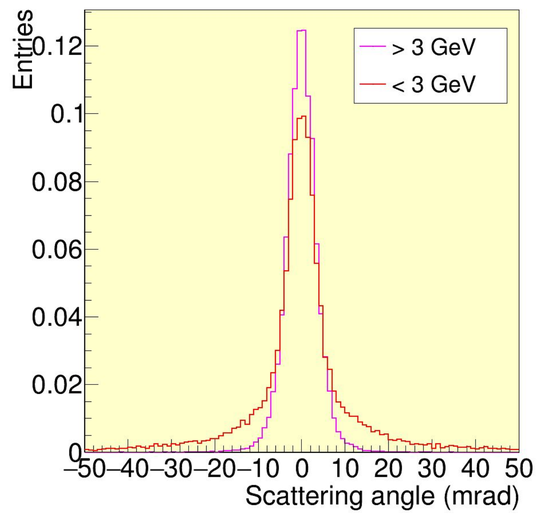
PRM results for 5 blocks with Fe filter and Pb filter

W.r.t Fe			W.r.t Pb		
test	t-value	p-value	test	t-value	p-value
Fe vs. Pb	14.705	1.67e-13	Pb vs. Pb	−0.467	**0.645**
Fe vs. Zn	1.030	**0.313**	Pb vs. Zn	−12.584	4.64e-12
Fe vs. Fe	−0.106	**0.917**	Pb vs. Fe	−6.862	4.26e-7
Fe vs. Th	15.515	5.19e-14	Pb vs. Th	0.499	**0.622**
Fe vs. Al	−15.538	5.03e-14	Pb vs. Al	−24.15	2.39e-18

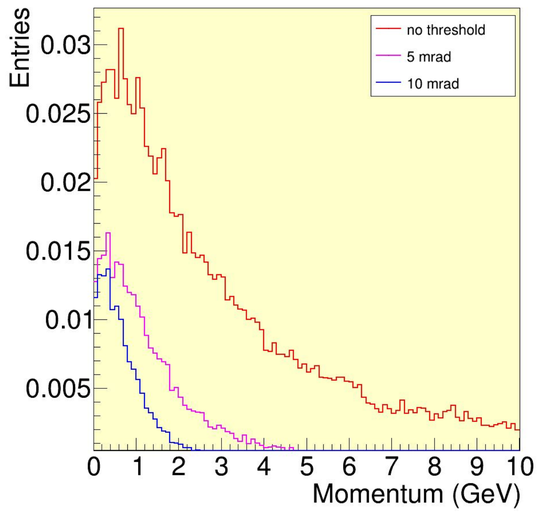


Reconstructed images for five blocks of size 5cm, corresponding t-test results shown in the table

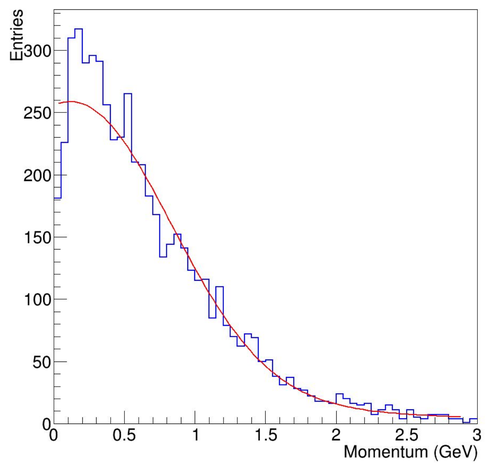
Effect of Momentum



Scattering angle distribution below and above the nominal momentum 3 GeV



Momentum range with different scattering thresholds



Momenta obtained with 10 mrad threshold has been fitted with a combined function

|-| Cosmic-ray muon momenta distribution peaks around 3-4 GeV.

|-| Momentum of incoming muon affects mcs significantly.

$$S = \sum_{k=1}^{\rho_c} \theta_k \frac{p_k}{p_n}$$

|-| The weighting parameter S depends on scattering angles θ_k, true value of momentum p_k
Nominal weighting momentum: p_n
Number of entries to the pixels: ρ_c
|-| Without any momenta information

$$S = \sum_{k=1}^{\rho_c} \theta_k$$

|-| With the reconstructed momenta p_{re} information

$$S = \sum_{k=1}^{\rho_c} \theta_k \frac{p_{re}}{p_n}$$

|-| Several techniques to obtain p_{re};

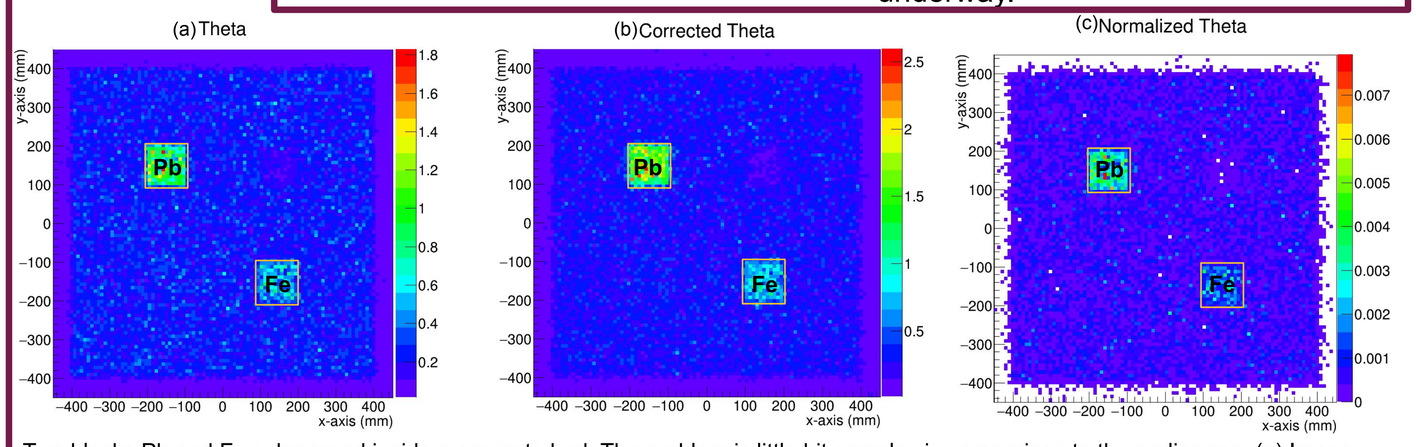
- Time of Flight information.
- Spectrometer with alternate layers of known target

|-| An alternate approach has been considered, where with min. Scattering threshold momenta range is obtained.

|-| For 10 mrad threshold the range is between 0-3000 MeV. For Random value of p_{re} generated from fitted function.

|-| For events < 10 mrad, p_{re} values are used to generate the S-map.

|-| A range-fit approach with scattering angle and χ^2 fit of the track with incoming muon momenta is underway.



Two blocks Pb and Fe submerged inside a concrete bed. The problem is little bit complex in comparison to the earlier one. (a) Image obtained without momentum information. (b) With true momentum information. (c) Normalized plot with reconstructed value of momentum

Summary

- MST simulation has been done in GEANT4 to discriminate high-Z materials.
- PRM has been used to learn from known samples of given size and to recognize targets in unknown region of interest.
- The discrimination has also been done based on of a t-test.
- Cosmic-ray muon momentum has been studied to improve imaging results. A minimum scattering threshold is applied to reduce background noise.
- An analytical fit-based approach has been followed to estimate muon momenta.
- The obtained results have been compared with images with true momenta, improvement needed to reconstruction muon momenta.
- Work is going on to exploit the scattering angle vs. momentum range relationship to improve results.

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References:
1. S. Tripathy et. al.,Material discrimination in cosmic muon imaging using pattern recognition method JINST 15 (2020) 06, P06029
2. L.J. Schultz, et al., Image reconstruction and material Z discrimination via cosmic ray muon radiography, 687 (2004). DOI 10.1016/j.nima.2003.11.035