GEANT4 Simulation For Imaging of High-Z Materials using Cosmic-Ray Muons

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Outline

- About Muons
- Muon Tomography methods
- Simulation results
- Future experimental plans

Cosmic Ray Muons

Origin: Secondary products of interactions between highly energetic cosmic rays and the nuclei of atmospheric particles.
Mass: Two hundred times heavier than electrons, (~105 MeV/c^2)
Life Time: ~2.2μs
Directionality: They travel in a direction more normal than parallel to Earth's surface; dependent on zenith angle (θ) as ~ ($\cos^2\theta$).
Flux: 1/cm^2/min
Momentum: Varies from 10 MeV/c to 10 GeV/c; peak around 1 GeV/c.
Interactions: Undergo weak interaction; Don't take part in strong interaction. As charged particle, do ionization and Coloumb scattering.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

Cosmic Ray Muons

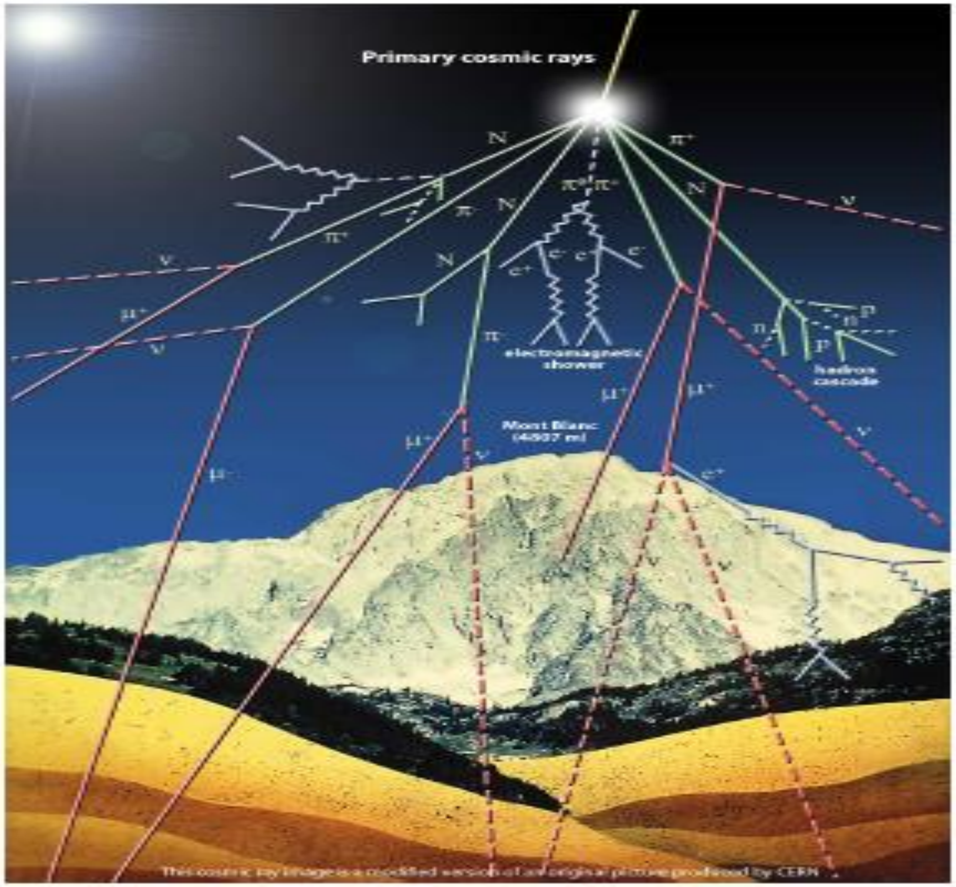


Figure 1: *Cosmic Ray Muon Shower*

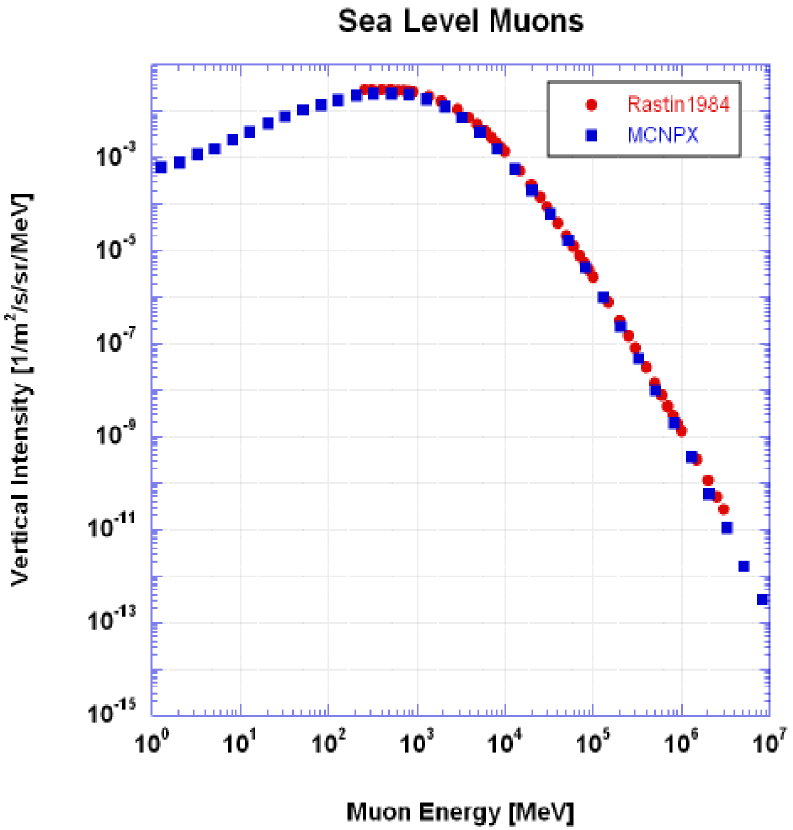


Figure 2: *Muon flux at sea level*

Muon Tomography

Scattering Tomography

For scattering tomography, the deviation through the matter traversed due to scattering is required to be found.

Absorption Radiography

For absorption tomography, the intensity of an image pixel is determined by the attenuation of incident muons caused by absorption in matter.

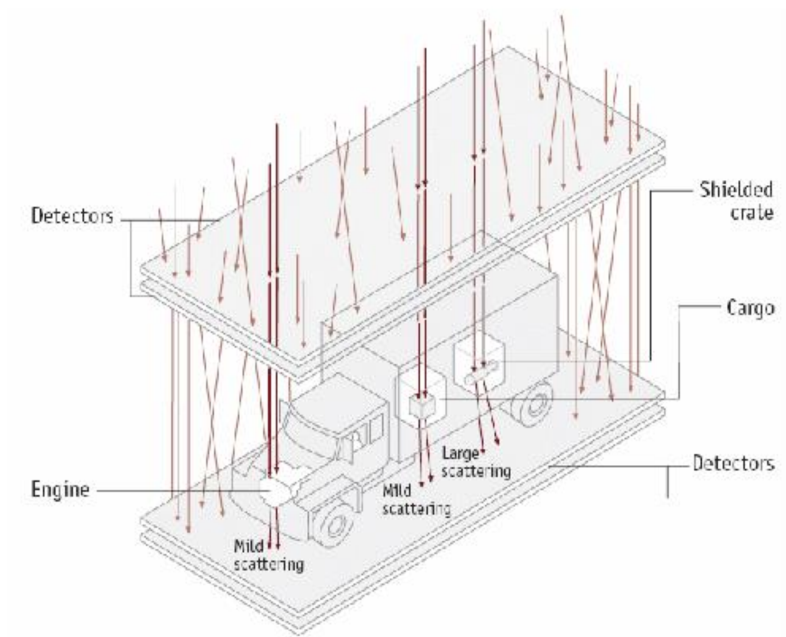


Figure 3: *Muon Scattering Tomography to discriminate High Z material*

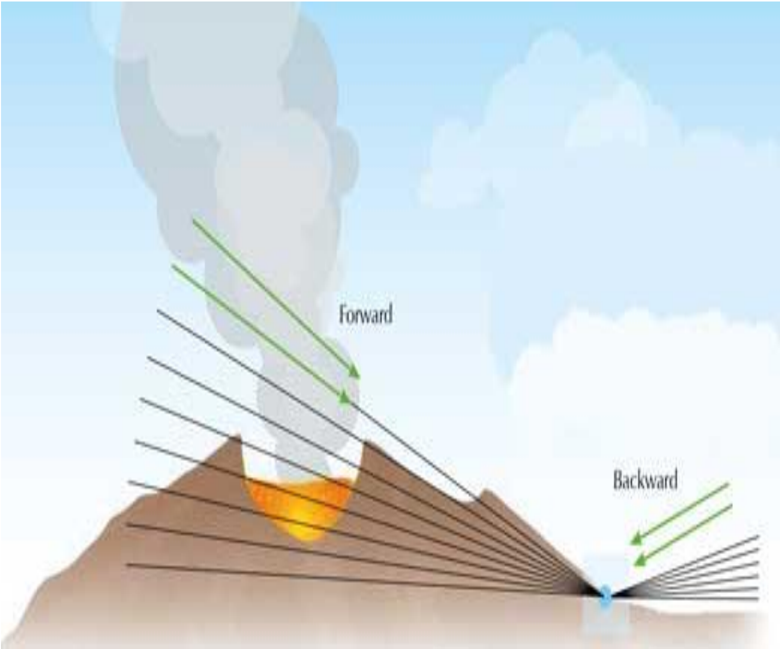


Figure 4: *Muon Absorption Radiography to monitor volcanos*

Muon Scattering Tomography

- Layers of detector volumes are placed above and below the object under inspection.
- This detectors give the position of the muon crossing (x, y) before and after it has passed the target object. The deviation due to scattering is measured.

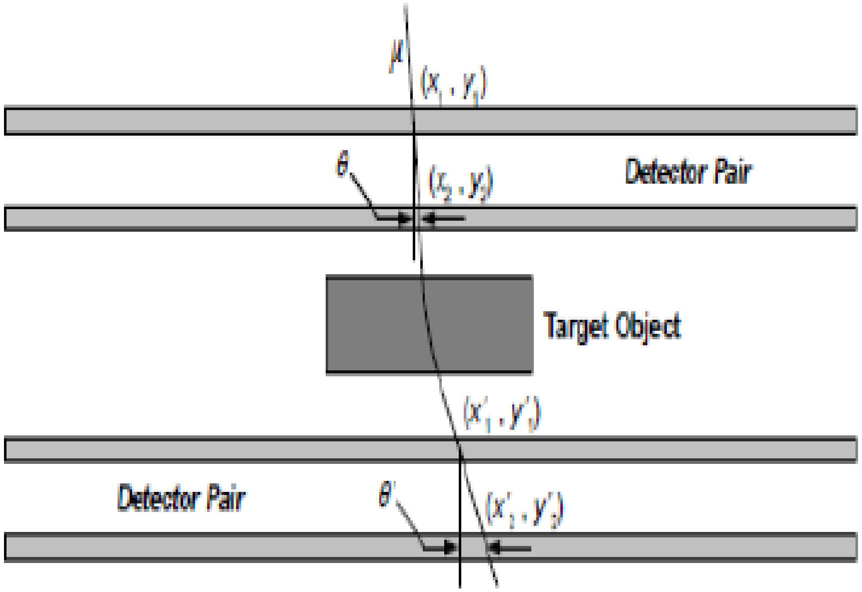


Figure 5: *Muon Scattering Tomography*

How it does:

Muons scatter from the atomic nuclei of the materials, this scattering depends on the atomic number (Z) and density .

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\theta_x^2/2\theta_0^2} \qquad \theta_0 = \frac{13.6\,\mathrm{MeV/c}}{p\beta}\sqrt{\frac{L}{X}} \qquad X = \frac{716.4\,\mathrm{g/cm^2}\,A}{\rho Z(Z+1)\ln\left(287/\sqrt{Z}\right)}$$

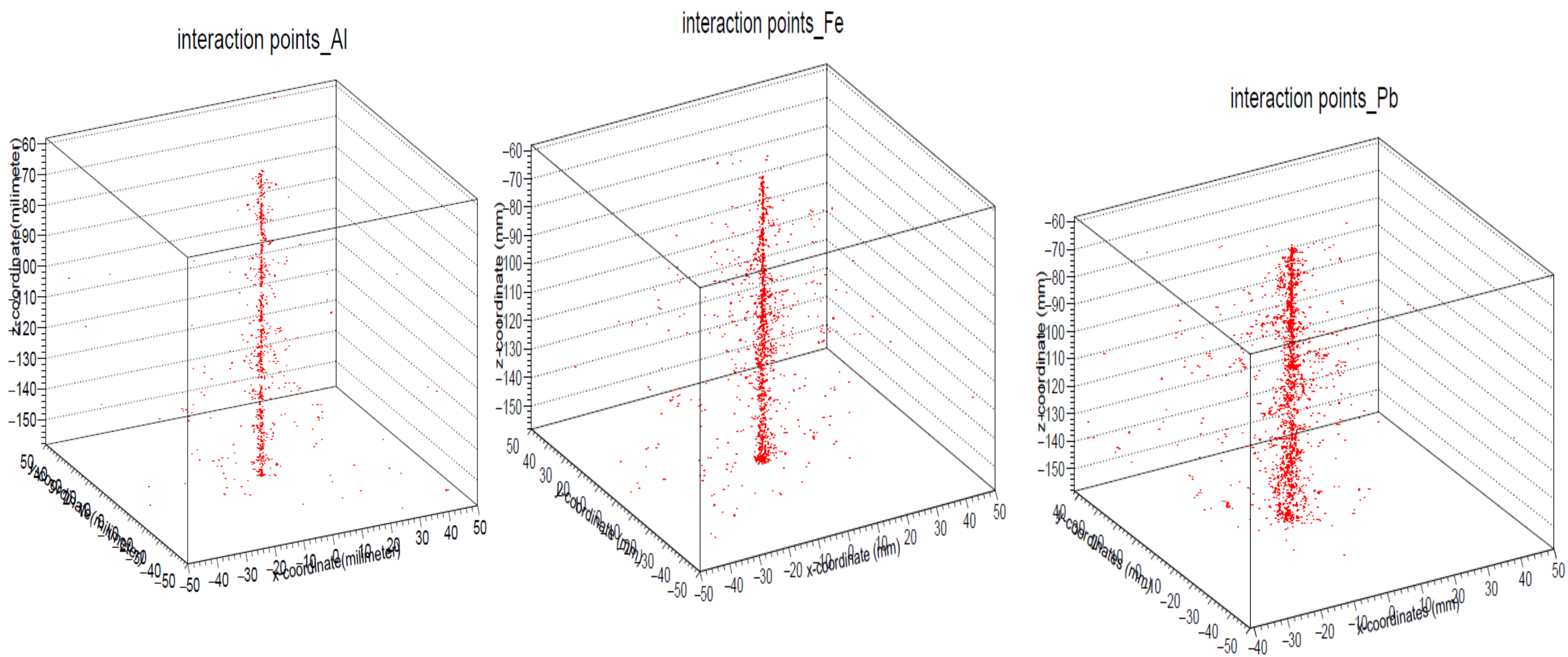
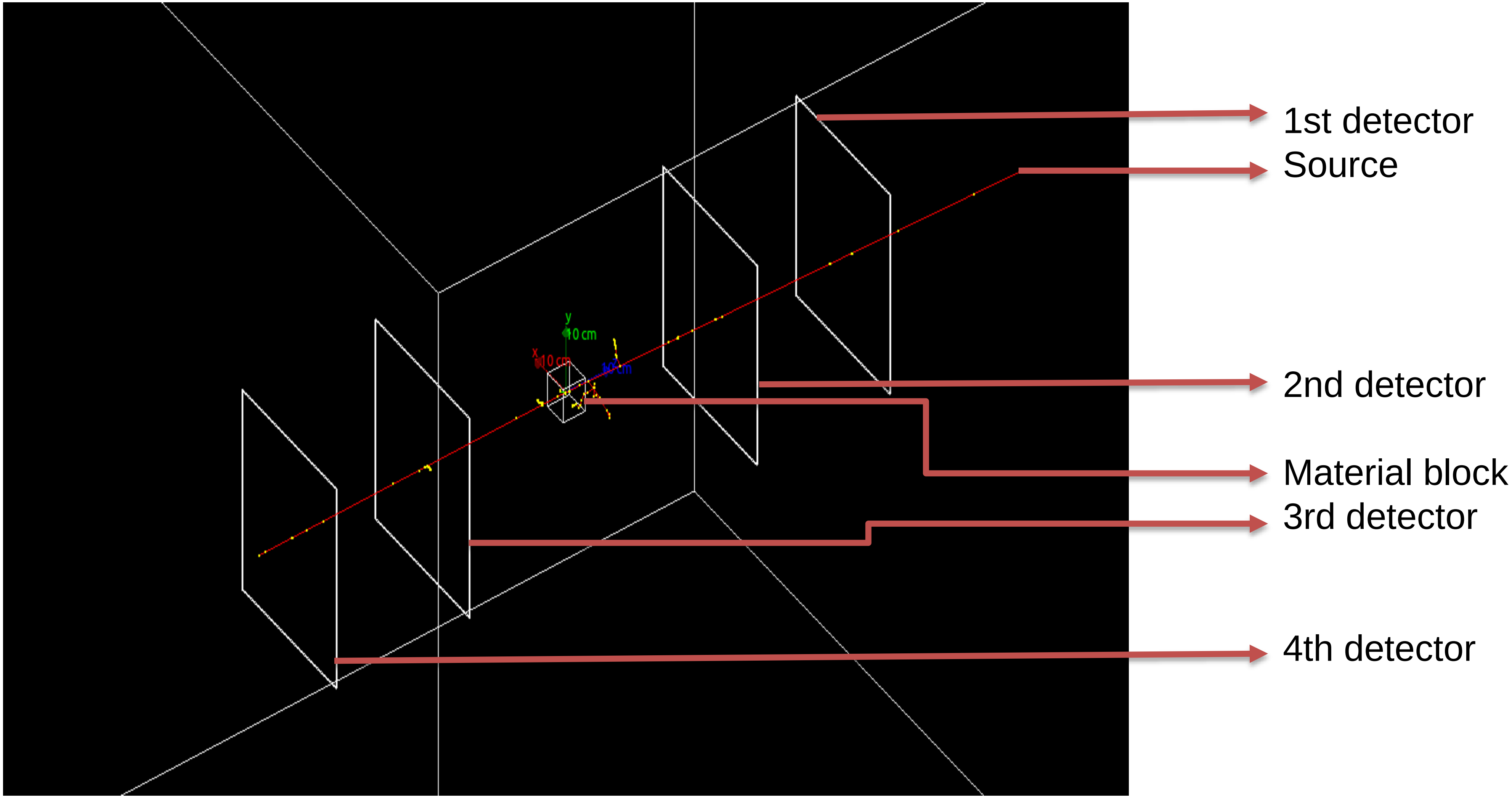


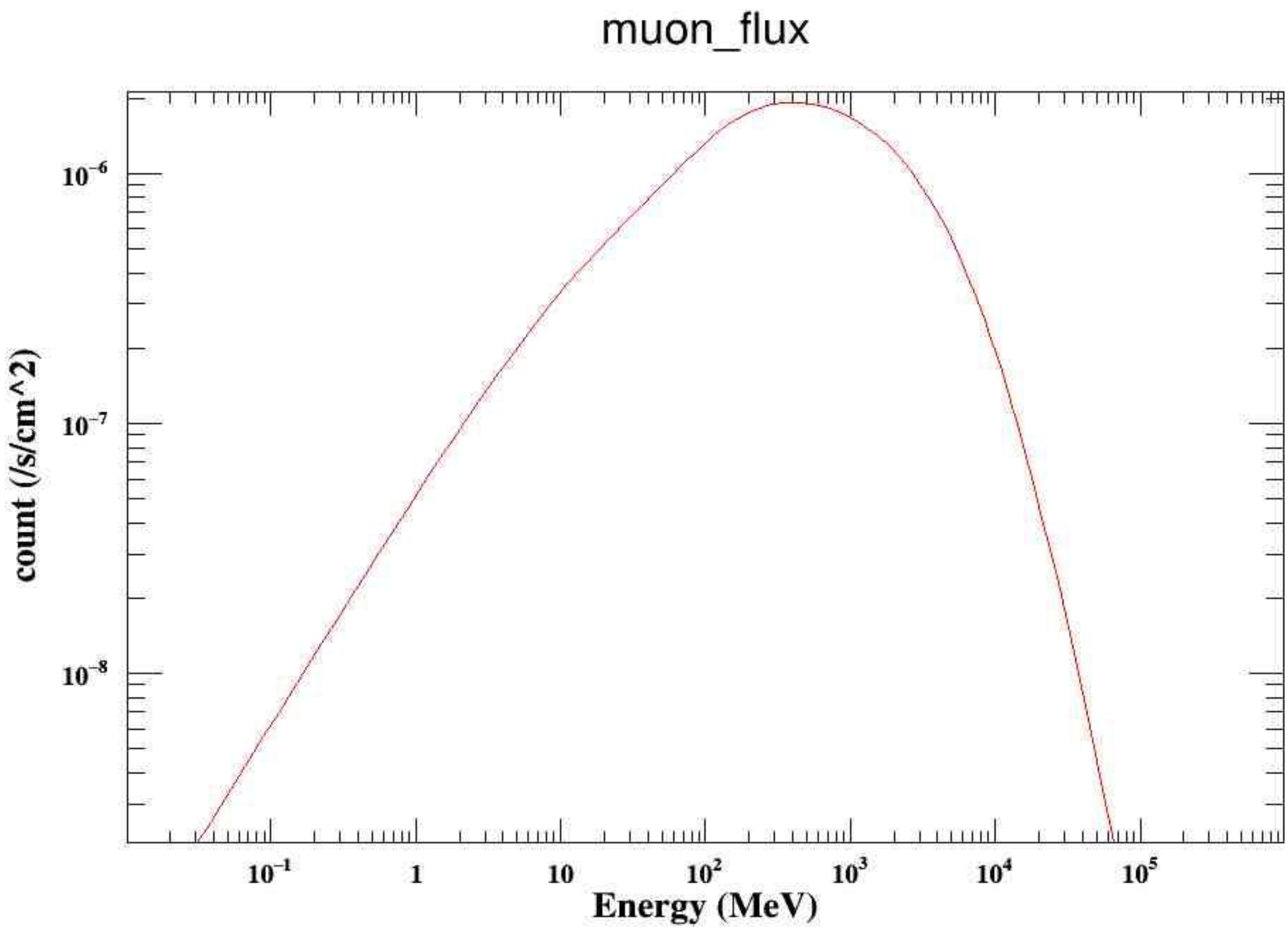
Figure 12: Equal number of muons were incident on same dimensions of different block, (Al, Fe, Pb), and the scattering centers are plotted.

Simulation Scenario



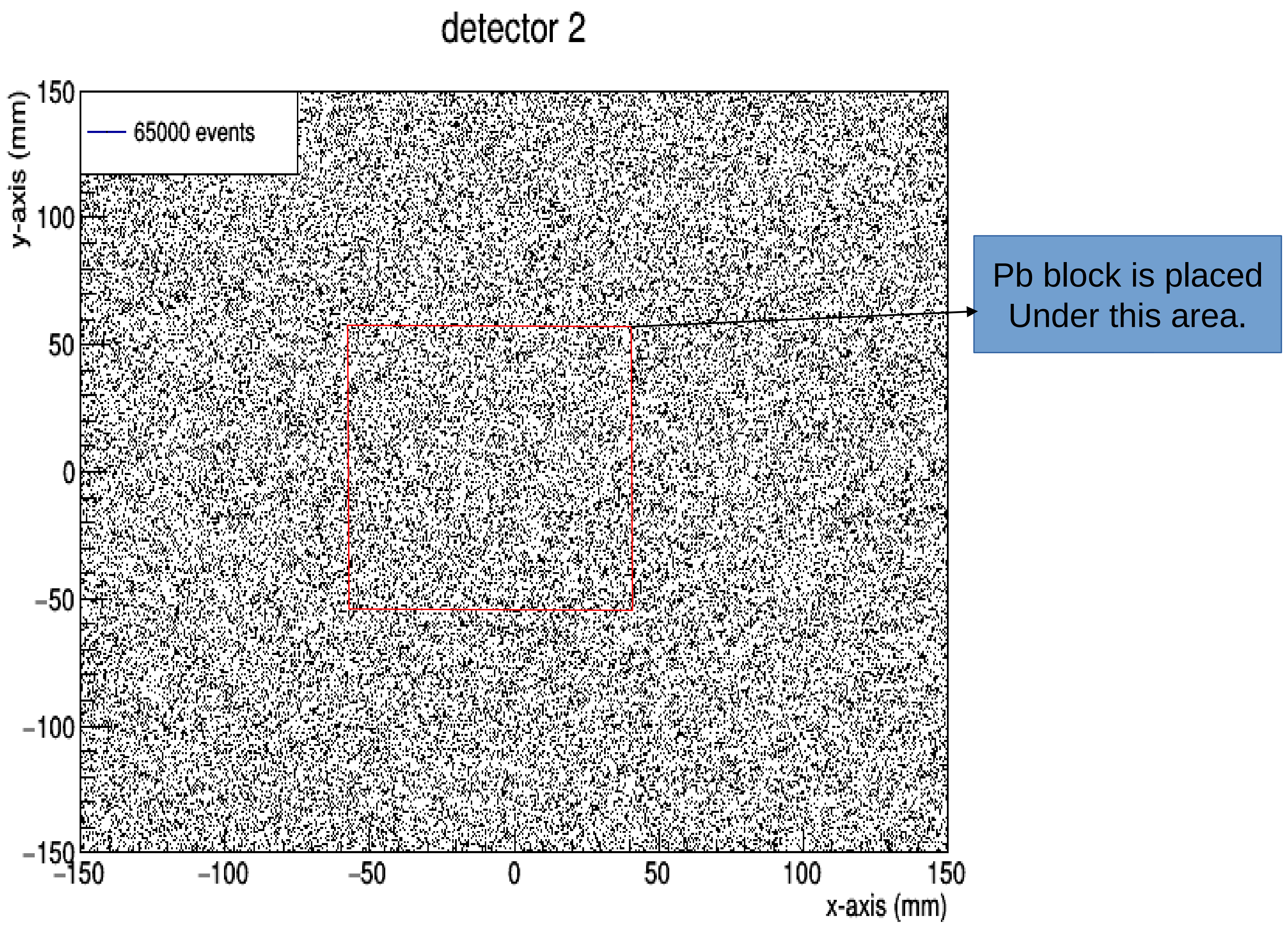
1. The environment contains 4 detector planes planes.
2. Separation between then detector planes is 300 mm. And the same is for the detector plate and material under discrimination.
3. Sources: (“mu-” & “mu+”), energy range: 0.5 GeV to 10 GeV
4. Muons are incident on vertically on the system.
5. Detector plane: 300 mm. X 300 mm.; material; 50 mm size cube

Muon flux at sea-level

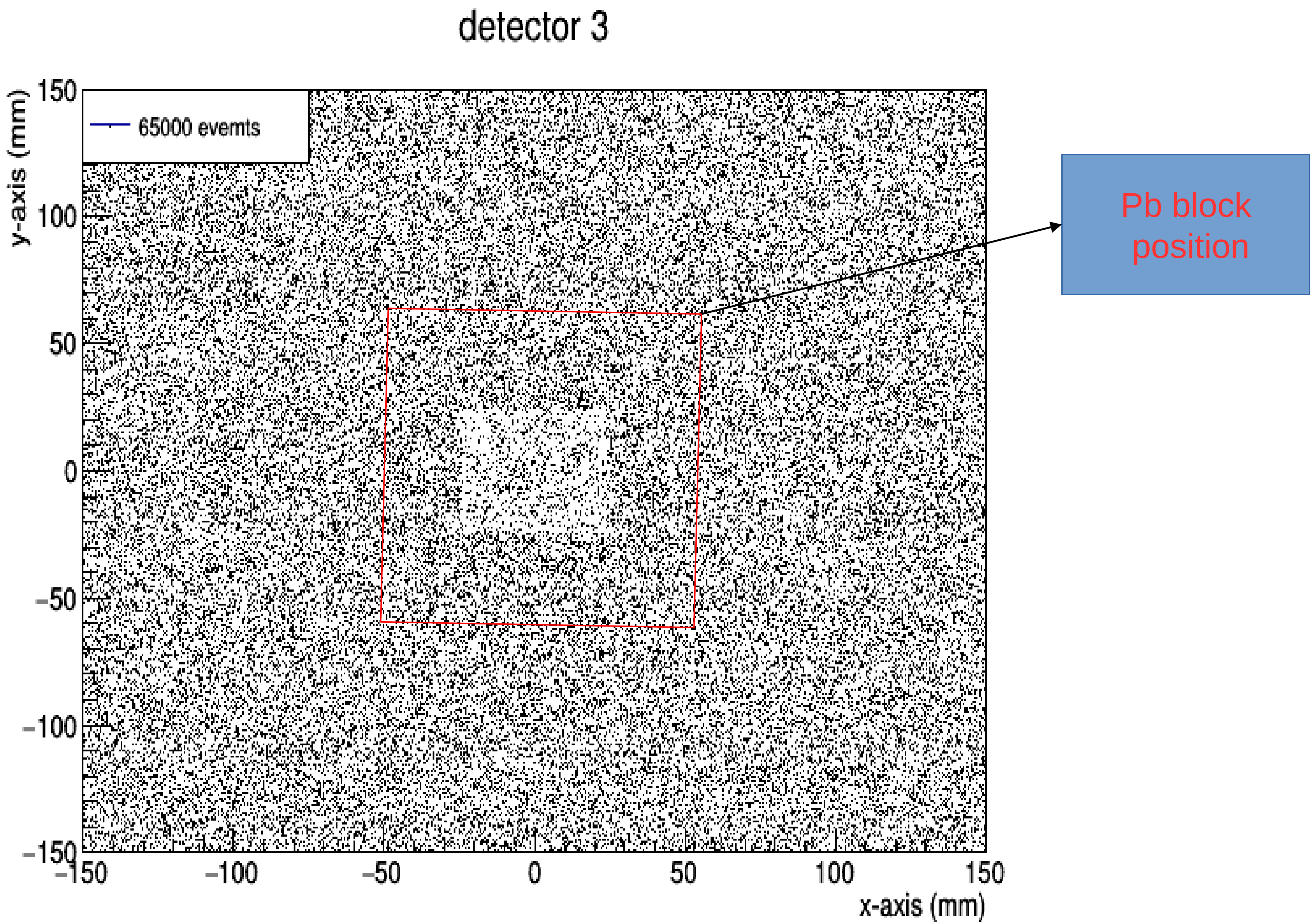


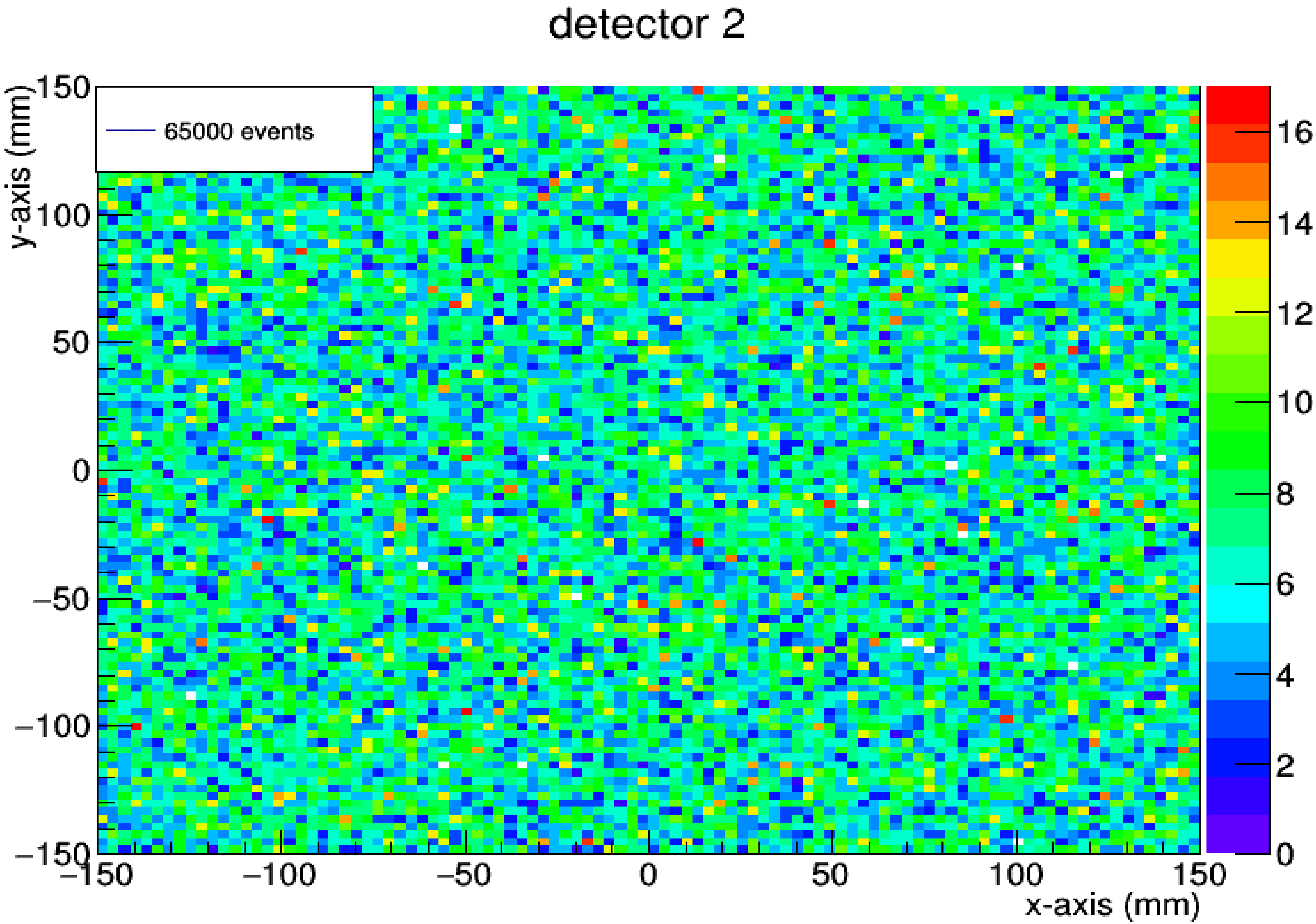
Total muon flux at sea level using EXPAC. http://phits.jaea.go.jp/expacs/

Simulation of Pb block of 50 mm size

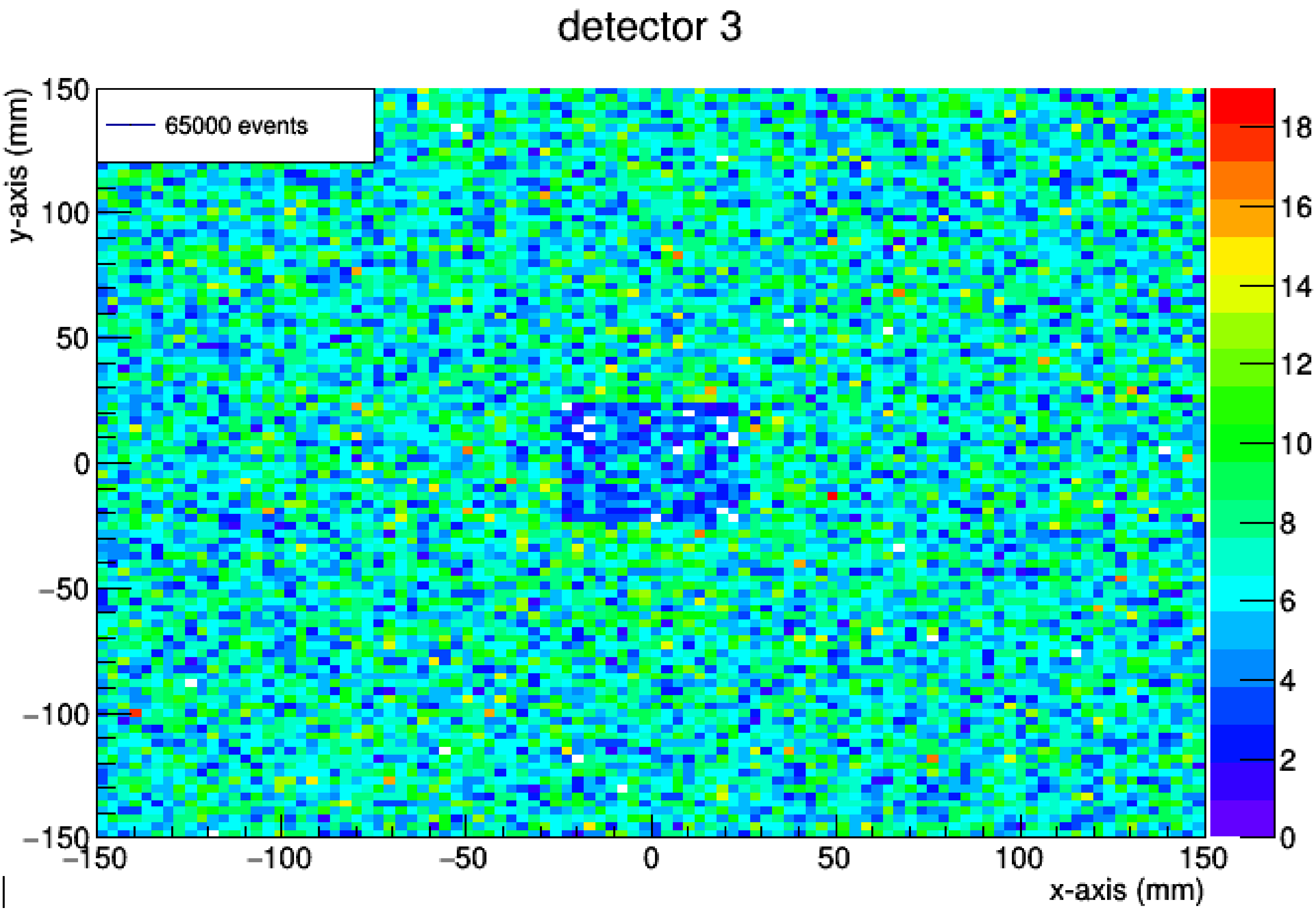


Simulation of Pb block of 50 mm size



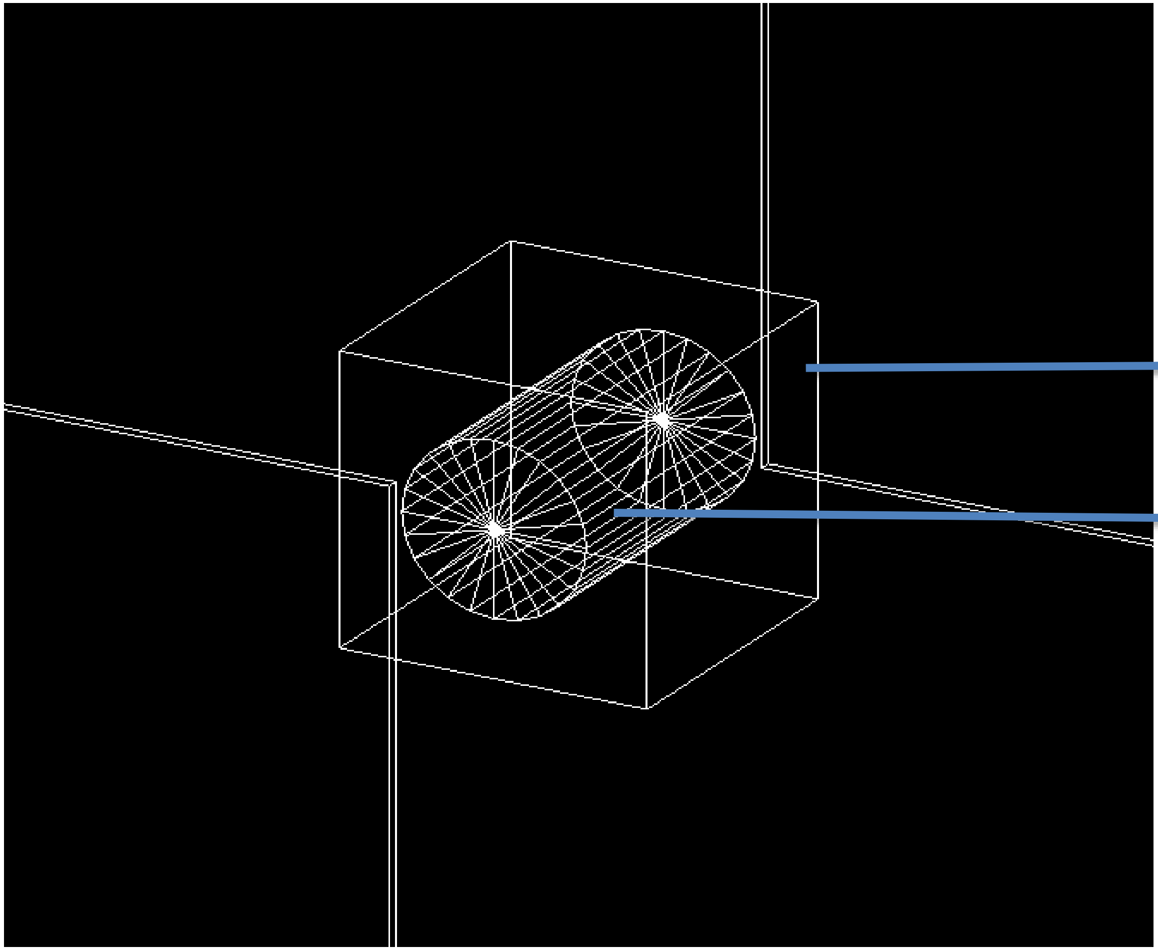


And of detectors position resolution comes to 3 mm X 3mm.



And of detectors position resolution comes to 3 mm X 3mm.

A Different Geometry



Pb cube of 50 mm side.

Cylinder of 30 mm radius cut

Inside the cube a cylinder of radius 30 mm was bored.

Hits on detector planes

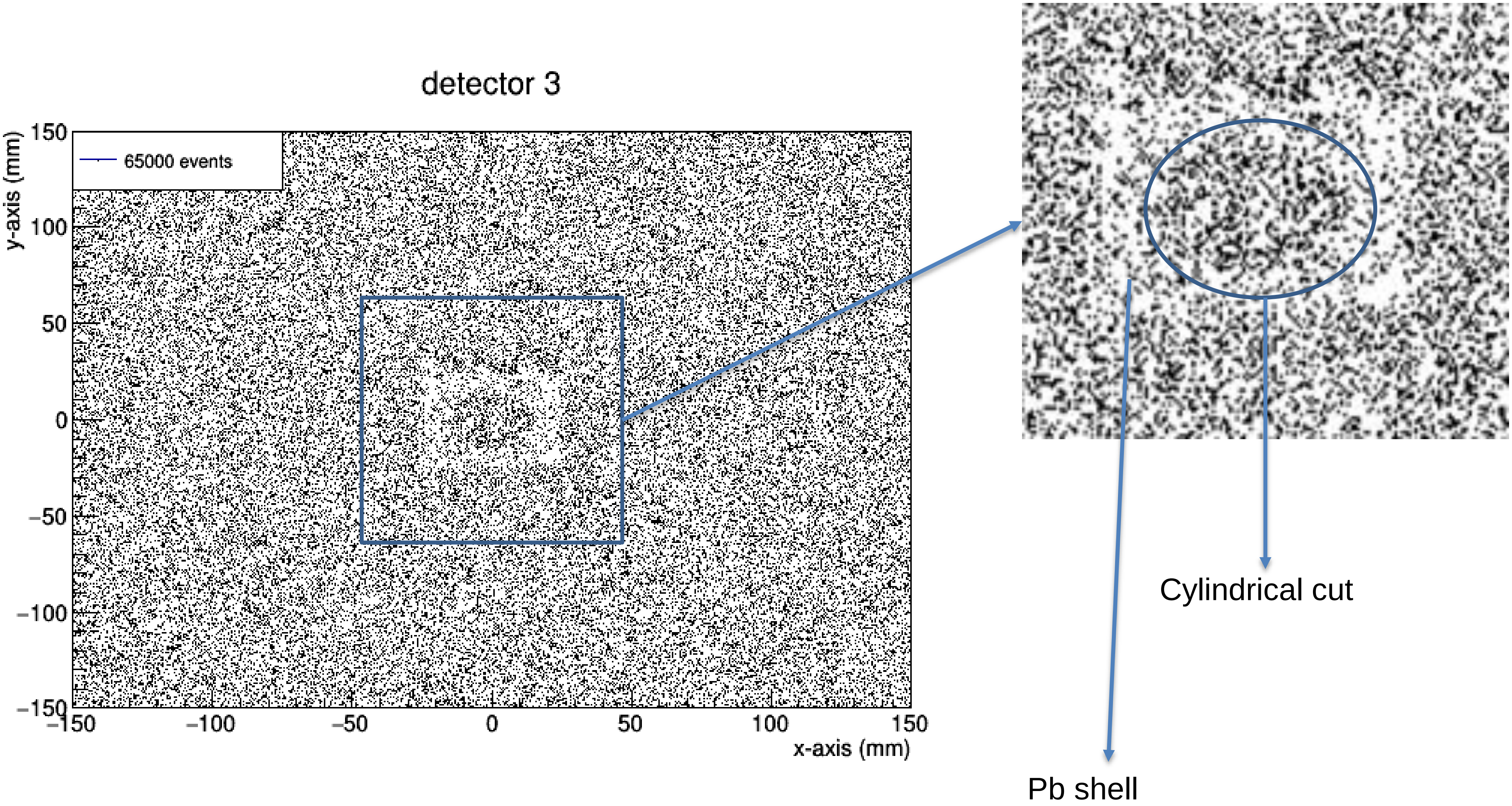
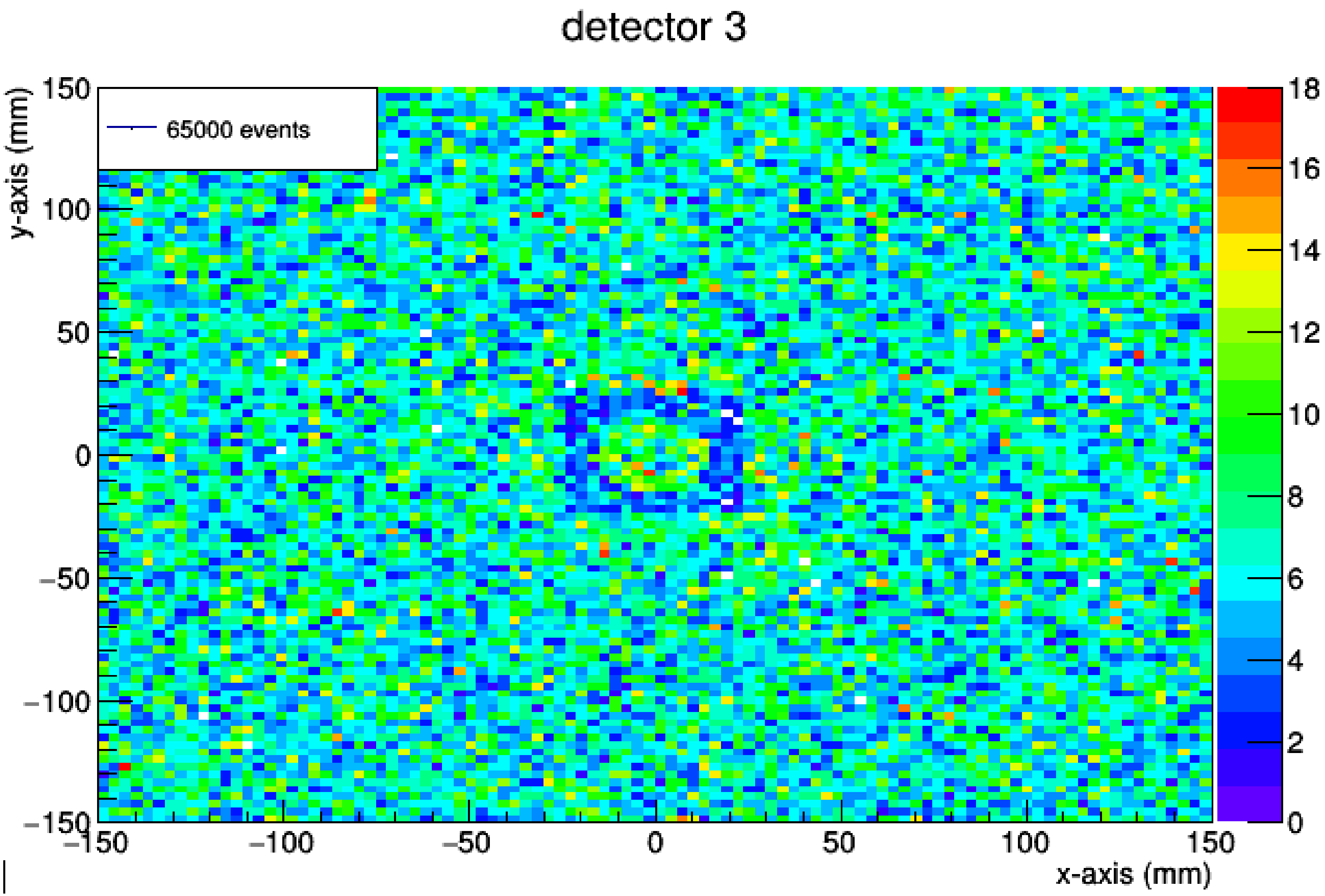
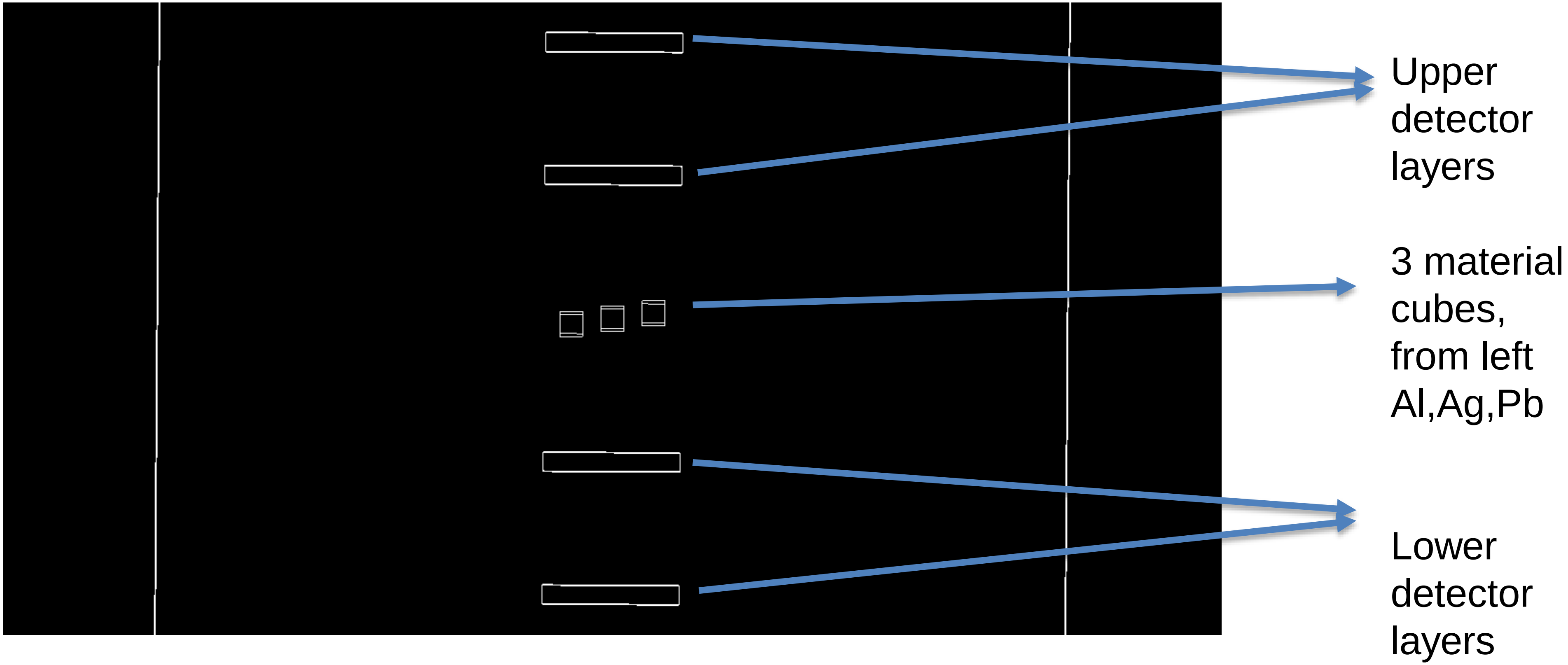


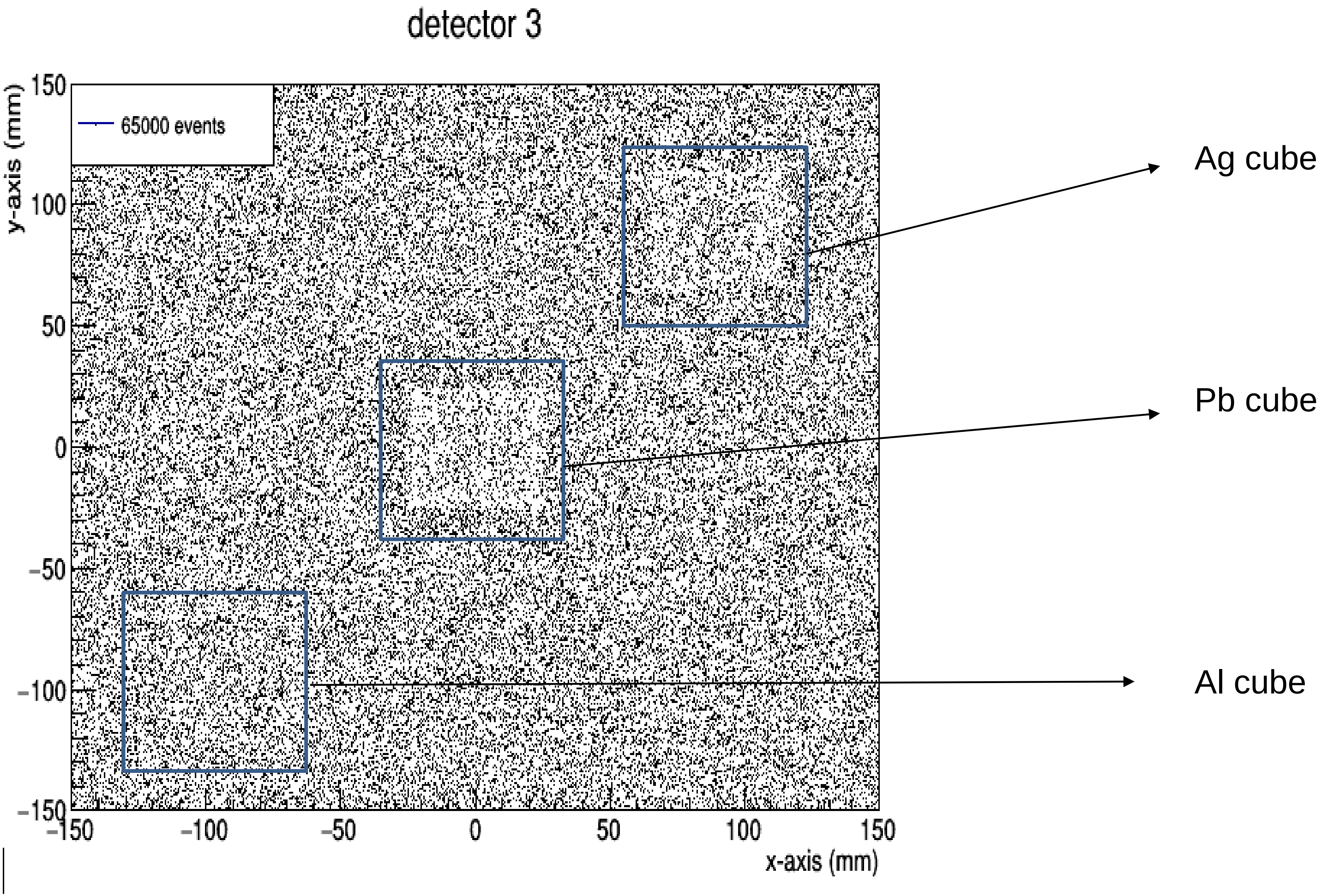
Image from the detector with spatial resolution 3mm X 3mm

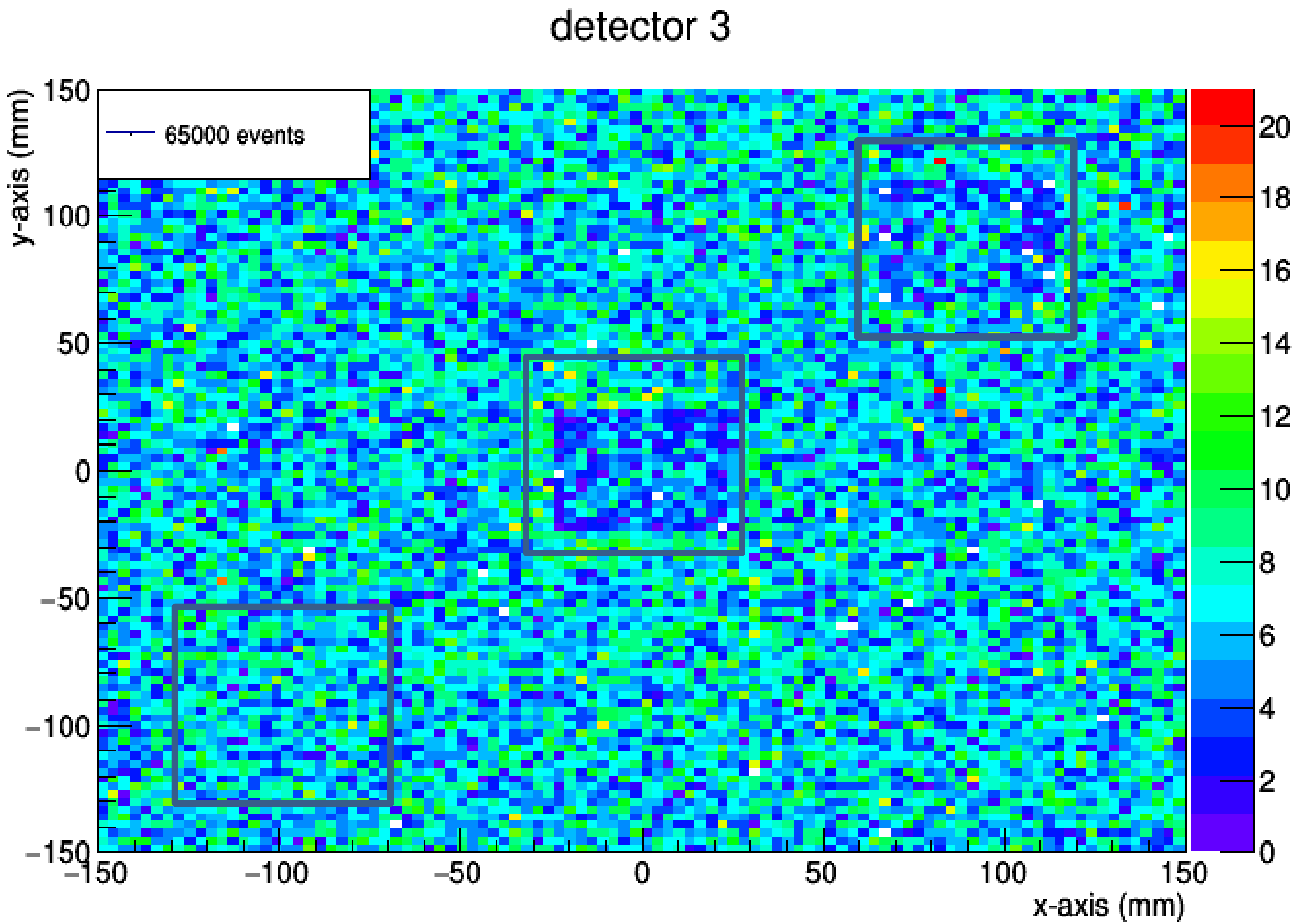


3 different materials:



Cubes of same dimension (50 mm side) of Al, Ag, Pb are placed.


detector 3
65000 events
y-axis (mm)
x-axis (mm)
150
100
50
0
−50
−100
−150
−150
−100
−50
0
50
100
150
Ag cube
Pb cube
Al cube



detector 3
65000 events
y-axis (mm)
x-axis (mm)
150
100
50
0
−50
−100
−150
−150
−100
−50
0
50
100
150
20
18
16
14
12
10
8
6
4
2
0

Some simulation results

- The dependence of the scattering distribution on atomic number Z and density ρ

Material	Atomic Number(Z)	Density (gm/cm^3)	Mean Scattering angle (mrad)	RMS width σ (mrad)
Aluminium	13	2.7	6.12	3.61
Iron	26	7.87	15.27	8.51
Silver	47	10.49	22.72	12.12
Caesium	55	1.87	10.29	5.67
Tungsten	74	19.37	38.78	20.56
Lead	82	11.35	28.53	15.39
Thorium	90	15.4	29.85	16.38
Plutonium	94	13.6	40.78	21.29

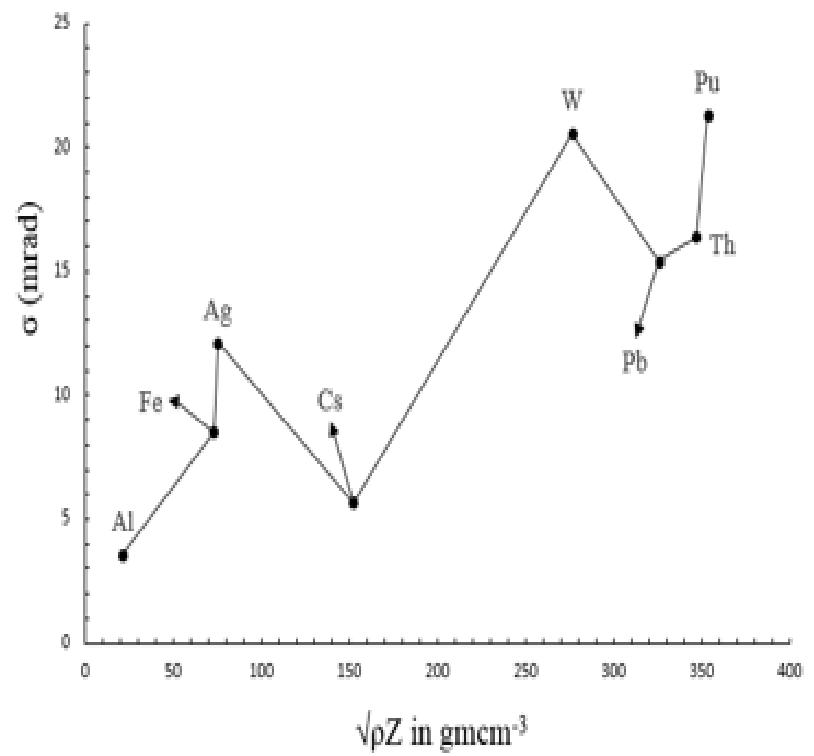


Figure 10: Variation of scattering angle with Z and ρ

Detector Requirements

- •The accuracy and reliability of the measurement are strongly dependent on design of the setup and the choice of the detectors.
- •Nanosecond coincidence timing resolution will be required for registering a muon event.
- •Sub-millimeter range position resolution will be required for distinguishing medium Z and high Z material, for which scattering angle will be of the order of 10 mrads.
- •The detector separations greatly affects δx for the same scattering angle.
- •As the energy of the muons increases, better time resolution will be required for distinguishing two muon events.

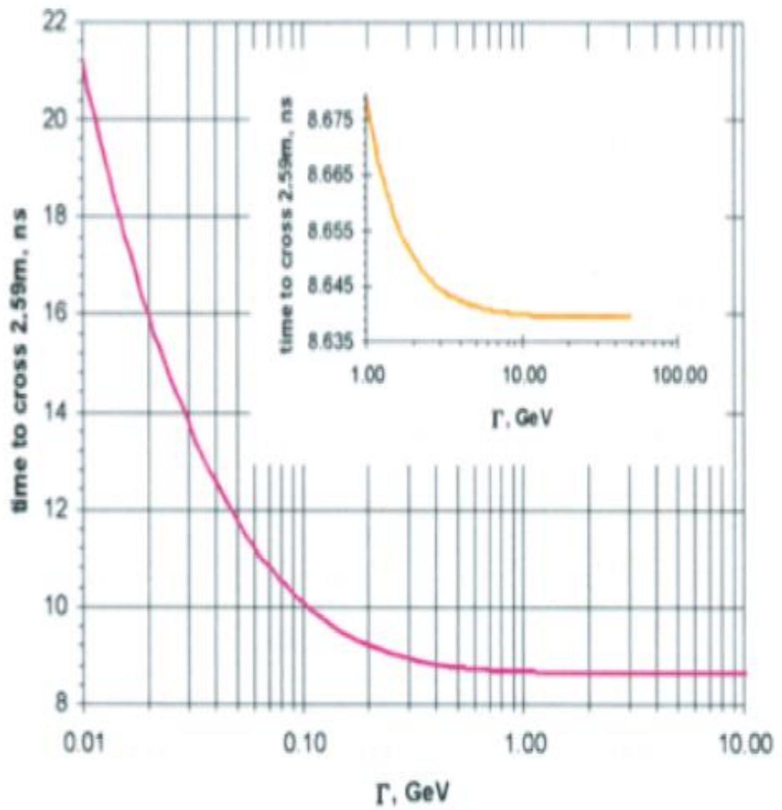
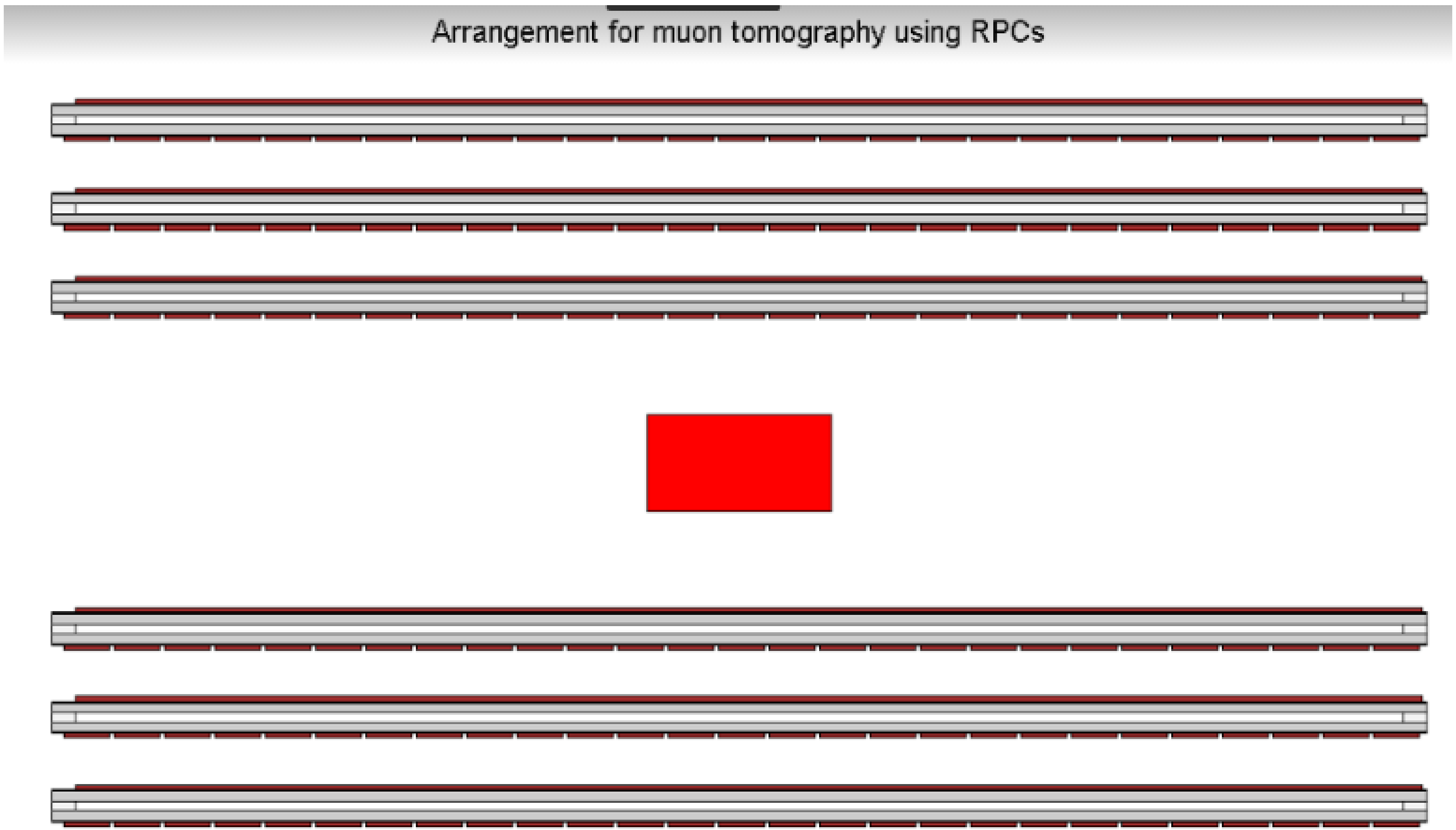


Figure 5: The purple curve suggests that distinguishing between sub-GeV and GeV or higher energy muons would require timing resolutions on the order of nanoseconds, whereas the inset (orange) curve suggests that differentiating between several GeV and tens of GeV muon energies would necessitate picosecond-like time resolution.

Preparing the experimental set-up



Summary

1.The image for a Pb object of 5 cm dimension is clearly visible in simulations.
2. However in the same scenario, lower Z materials like Al are not distinguishable.
3. Without any danger of radiation, Muon imaging method promises to be a perfect method for distinguishing contraband materials from normal materials.
4. The effect of variation of material size, separation between detectors has to be experimentally verified.
5. Initially a tracker based on several layers of Bakelite-RPC detectors is planned to be set-up, in future detectors like micromegas / GEM will be investigated for their application in MT.
6. Development of read-out electronics and data acquisition system for the experiment is underway.

References:

- Garutti E., Gruner.F, Lecture on Medical Physics
- P. Jenneson, W. Gilboy, S. Simons, S. Stanley, and D. Rhodes, Imaging large vessels using cosmic-ray muon energy-loss techniques, Chemical Engineering Journal 130, 75-78 (2007).
- MedicineNet.com
- F. Flakus, Detecting and measuring ionizing radiation - a short history, IAEA Bulletin 23, 31-36 (1981).
- King, N.S.P., et al., An 800-MeV proton radiography facility for dynamic experiments, *Elsevier Science* (1999).
- C.L. Morris, Tomographic imaging with cosmic ray muons, Science Global Security 16, 1, 37 (2008).
- C. L. Morris, Tomographic Imaging with Cosmic Ray Muons. JINST(2008)
- George E. P. , Cosmic Rays measure overburden of tunnel, commonwealth Engineer (455)
- Alvarez. E W (1970) Search for hidden chambers in pyramids using cosmic rays Science 167:832
- Borozdin, K. N., Hogan, G. E., Morris, et al., "Radiographic Imaging with Cosmic Ray Muons", Nature, **422,** 277 (2003).

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