Geant4 Simulation Of Muon Tomography

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Outline

PART-1
Introduction to Geant4 (Simulation)

Some information about useful classes.

Building a simple geometry (a Cube) using Geant4

Extending the geometry to create a very simple Muon Tomography setup

Data Analysis using ROOT

PART-2
Handons Session

Prerequisites :
Basic knowledge of Linux operating system
Little bit C++

Introduction of basic linux command that will be required during handson practice
(Tutorial Sheet provided)

Instruction to Run the Simulation Program (Tutorial Sheet provided)

Why do we need Simulation

To design the experimental setup

To compare the experimental results to make sure that there is no error in analysis.

To test the required algorithms

To optimize the detector geometry.

What is Geant4

GEANT4 is a toolkit for the simulation of the passage of particles through matter.

Written in C++ (But don’t worry)

Used in nuclear physics, high energy physics, accelerator physics,medical as well as space applications.

Nothing is Free of Cost (Geant does not provide simulation programs)

User has to build their simulation program for specific application.

Features

Provides a complete set of geometries that allow the used to create geometry of any type of detector.

Provides a rich set of predefined materials, Particles etc.

User can track the particle as it passes through matter and EM fields.

Allow to visualize the full detector, and also the events in real time.

Class Structure in Geant4

Mandatory classes

G4VUserDetectorConstruction
Define detector geometries and materials

G4VUserPhysicsList
Define Physics and Processes involved

G4VUserPrimaryGeneratorAction
Generation of Primary event

Action classes (Optional)

G4UserRunAction

G4UserEventAction

G4UserTrackingAction

G4UserSteppingAction

Defining Materials and Geometries

Defining Material

```
G4NistManager* nist = G4NistManager::Instance();
G4Material* world_mat = nist->FindOrBuildMaterial("G4_AIR");
```

There are three steps to define a geometry in Geant4

1) Geometrical Shapes (G4VSolid) : Specify the Shape and its dimensions
2) LogicalVolume (G4LogicalVolume) : Attach the material to the shape
3) PhysicalVolume (G4VPhysicalVolume) : Placement of Logical Shape in the setup

```
G4Box* solidWorld =  new G4Box("World", //Name
                                50*cm, //Half length along X
                                50*cm, //Half length along Y
                                50*cm  //Half length along Z);

G4LogicalVolume* logicWorld =   new G4LogicalVolume(solidWorld,         //its solid
                                                     world_mat,          //its material
                                                     "World");           //its name

  G4VPhysicalVolume* physWorld = new G4PVPlacement(0,                    //no rotation
                                    G4ThreeVector(),  //at (0,0,0)
                                    logicWorld,          //its logical volume
                                    "World",             //its name
                                    0,                   //its mother  volume
                                    false,               //no boolean operation
                                     0,                  //copy number
                                    checkOverlaps);  //overlaps checking
```

Physical Placements (Mother/Daughter relationship)

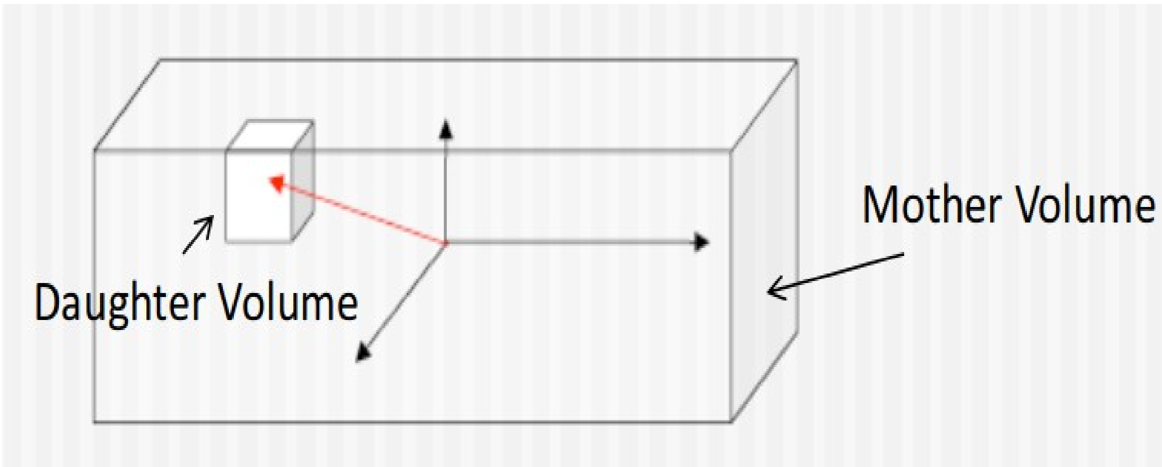
While building the detector geometry, one has to place different geometry one inside the another, and this placement follows Mother/Daughter relationship.

A volume is placed inside its mother volume.

Position and rotation of daughter volume is with respect to mother's coordinate system.

Daughter volumes cannot protude from the mother volume.

Multiple daughter volumes cannot overlap



Generating Primary Event (G4VUserPrimaryGeneratorAction)

This class is responsible for generating primary event

Its allow user to define following

1) Type of Particle gun
2) Location of Particle gun
3) Particle Energy

```
int n_particle = 10;
fParticleGun = new G4ParticleGun(n_particle);
fParticleGun->SetParticleDefinition(G4Electron::ElectronDefinition());

 // Set the kinetic energy to 2 GeV
 // and tell the gun to emit them along the negative z-axis
 fParticleGun->SetParticleEnergy(50. * keV);
 fParticleGun->SetParticlePosition(G4ThreeVector(0., 0., 120 * cm ));
 fParticleGun->SetParticleMomentumDirection(G4ThreeVector(0., 0., -1.));
```

Using Physics process in simulation (G4VUserPhysicsList)

Geant4 provides a wide variety of physics components for use in Simulation, which are coded as Processes

Process class tells the particle, how to interact with Detector material

User can also write his own process class

Geant4 Work flow

Run

In Geant4, a run is a collection ofevents which share the same detector and physics conditions.

•A run consists of one eventloop.

•At the beginning of a run, geometry is optimizedand cross-section tables are calculated according to materials appear in the geometry and thecut-off valuesdefined.

•A run starts withBeamOn()method ofG4RunManager.

Event

An event is the basic unit of simulation in Geant4.•

G4Event class represents an event.

•It has following objects at the end ofits successful processing.

-List of primary vertices and particles(as input)

-Hits and Trajectory collections (as output)

Track

Track is a snapshot of a particle.

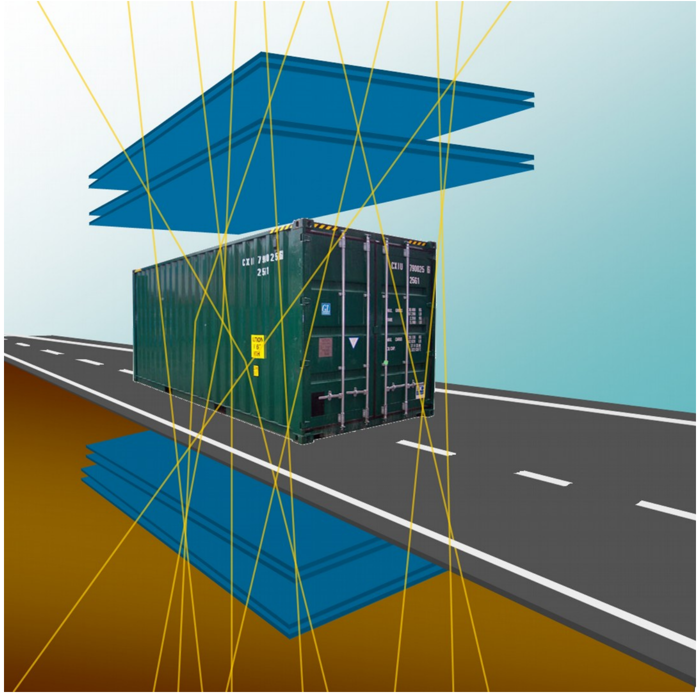
•G4TrackingManager manages processing a track,

A track is represented by G4Track class.

Application : Muon Tomography

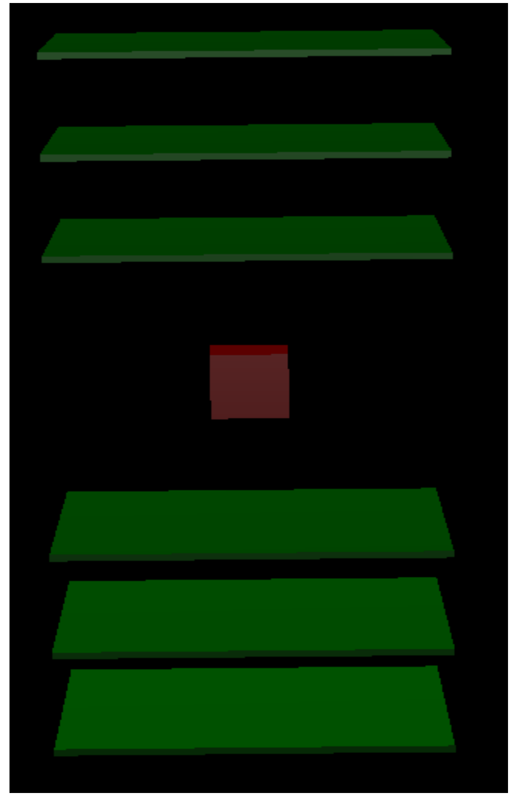
Muon tomography is a technique that uses cosmic ray muons to generate three-dimensional images of volumes using information contained in the Coulomb scattering of the muons.

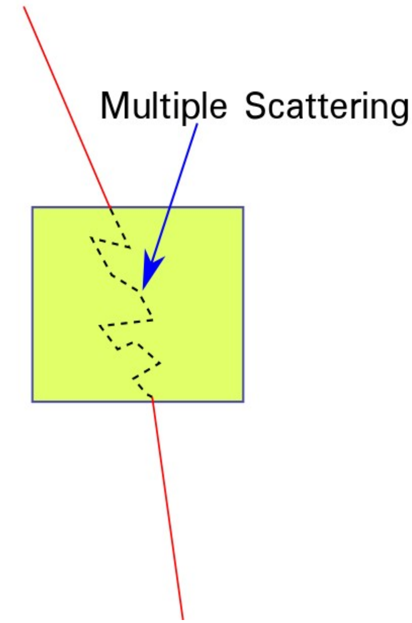
- Secondary cosmic muons: highly penetrating radiations (even more than X-rays)
- Average energy : 3 to 4 GeV
- (Free of Cost) “Natural” radiation
- Muonic interactions well understood, the main physics process under study is Multiple Coulomb Scattering
- Muon scattering strongly dependent on the Z of the material



Geant4 Simulation setup for Muon Tomography

The physics process under study is Multiple scattering





Geometry Setup

Physics list used FTFP_BERT

Particle gun : Muon

Size of Detector : 1m X 1m

Number of Detectors : 6

Size of Scatterer : 20cm X 20cm X 20cm

Muon Energy and angular distribution
3 GeV (ie. Monoenergetic muon)
Firing from a given point vertically down
Firing in all random direction

In reality cosmic muons follow COS$^2\theta$

Scatterer used : Al, Fe, Pb

Shape of Scatterer : Cube

Target : To produce the scattering histogram, to distinguish between different material

Muon Tomography : Material Discrimination and Identification

Materials can be discriminated by calculating the standard deviation of the measurement of scattering of N muons passing through the object.

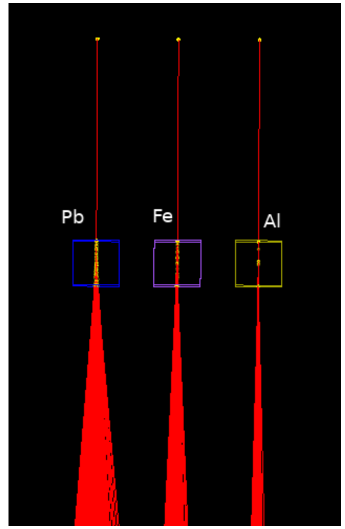
This can tell that one material is having more Z relative to other, but cannot tell what actually is the material.

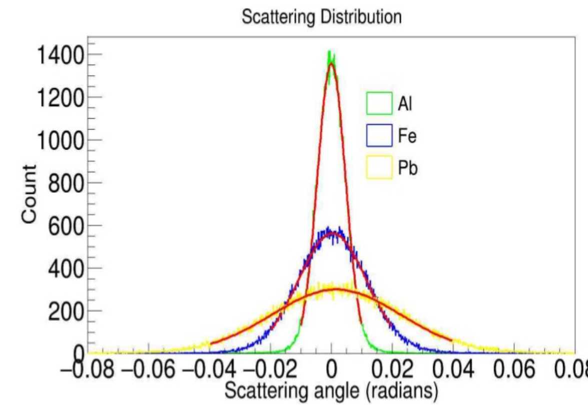
Two material of different thicknesses may give same scattering angle distribution.

To detect the correct material one has to estimate some material property.

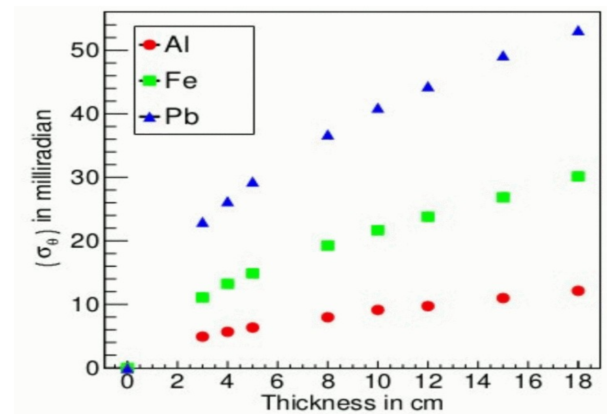
Radiation Length can be one such good property

Try to calculate the radiation length of Al, Fe and Pb, and compare them with theoritical values





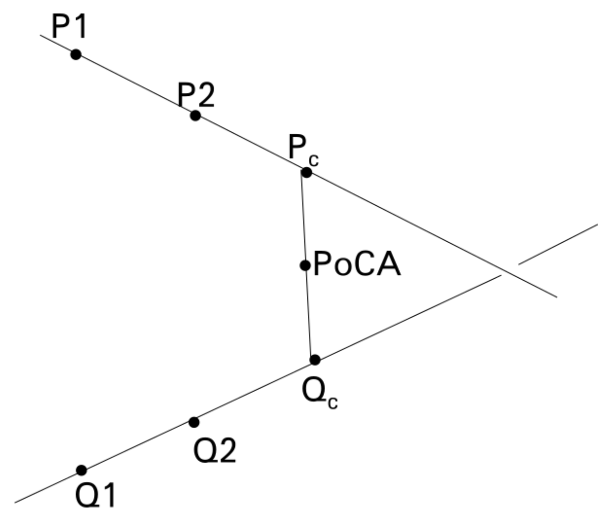
Materaial	Radiation Length
Al	8.897 cms
Fe	1.797 cms
Pb	0.561 cms



$$\sigma \simeq \frac{1}{p}\sqrt{\frac{L}{X_o}}$$

Lets do some reconstruction

The two most famous reconstruction algorithms for muon tomography are
1) Point of Closest Approach (PoCA)
2) Maximum Likelihood Expectation Maximization (MLEM)

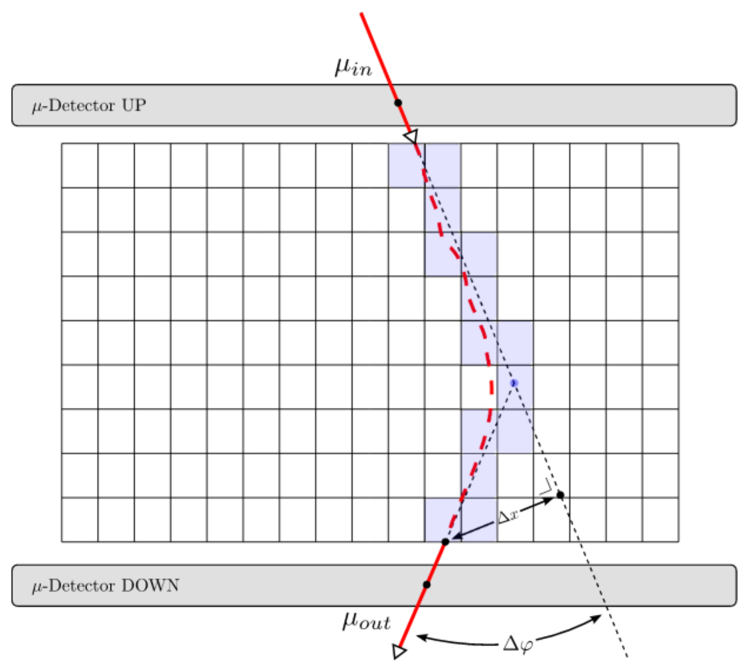


PoCA is simplest and purely geometrical algorithm

Pros : Its very fast and and quickly gives you the location of object.

Cons : It does not takes any multiple scattering physics into consideration, as a result of this assigns the full scattering to single PoCA point.

Also gives a alot of false positives, and hence some postprocessing filteration algorithm are required

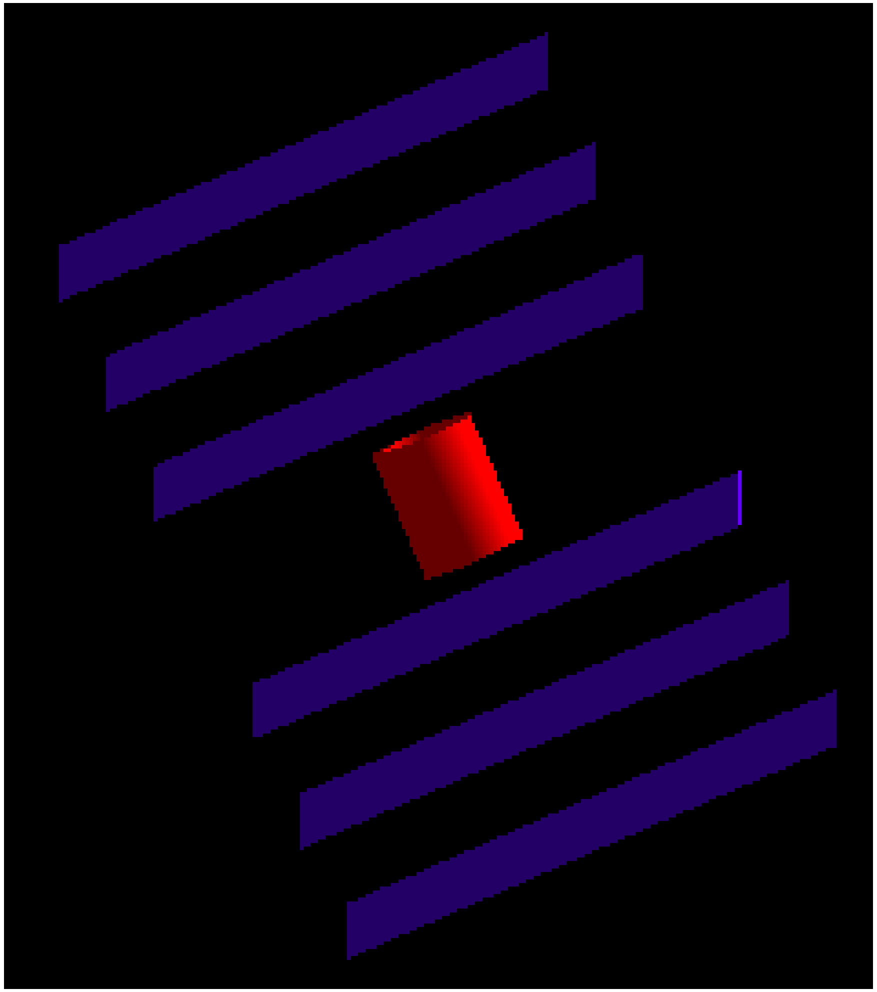


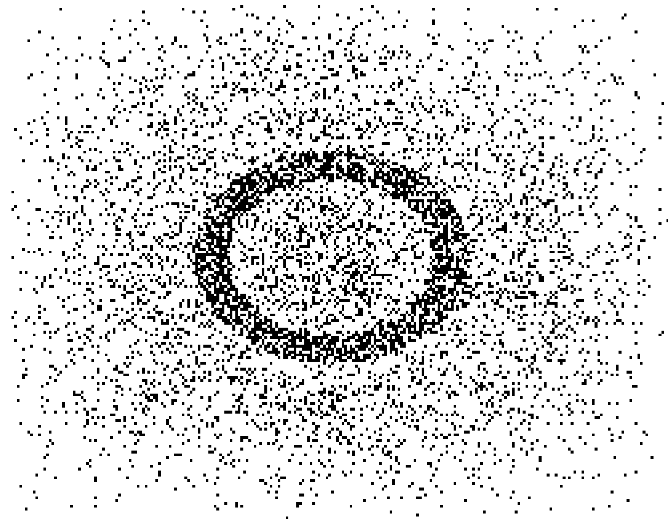
MLEM is an iterative algorithm, and works by dividing the volume of interest into Voxels

Pros : Makes use of Multiple scattering physics and assign scattering value to the voxel that comes along the Muon Path.

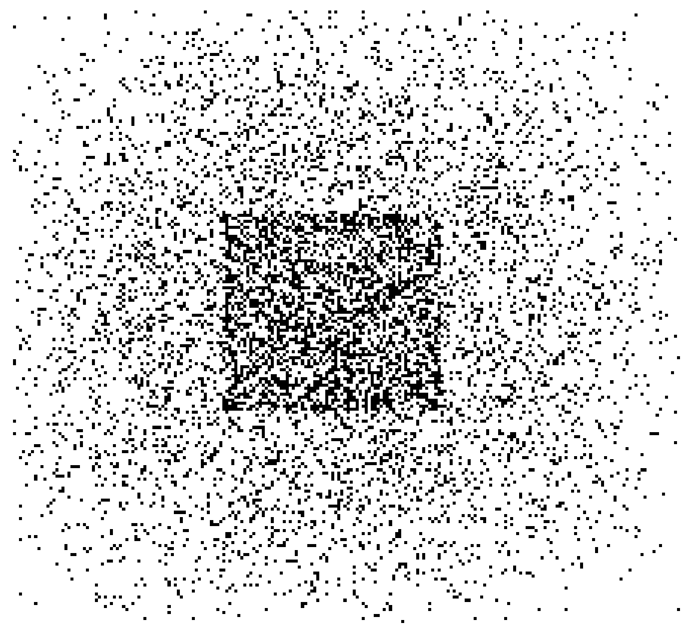
Cons : Needs more computation power and time to converge.

PoCA Reconstruction Results





Top View of
Hollow tube



Top View of
Cube