Simulations and Cosmic Ray Muon Tomography Reconstruction with Resistive Plate Chambers

Work Done

Assembly of Resistive Plate Chamber.

Data analysis of data collected from experimental setup.

Preliminary track reconstruction using two RPCs.

Geant4 Simulation of Cosmic rays muon tomography setup

Performing the Simulation on different material to understand how scattering varies with Atomic Number (Z)

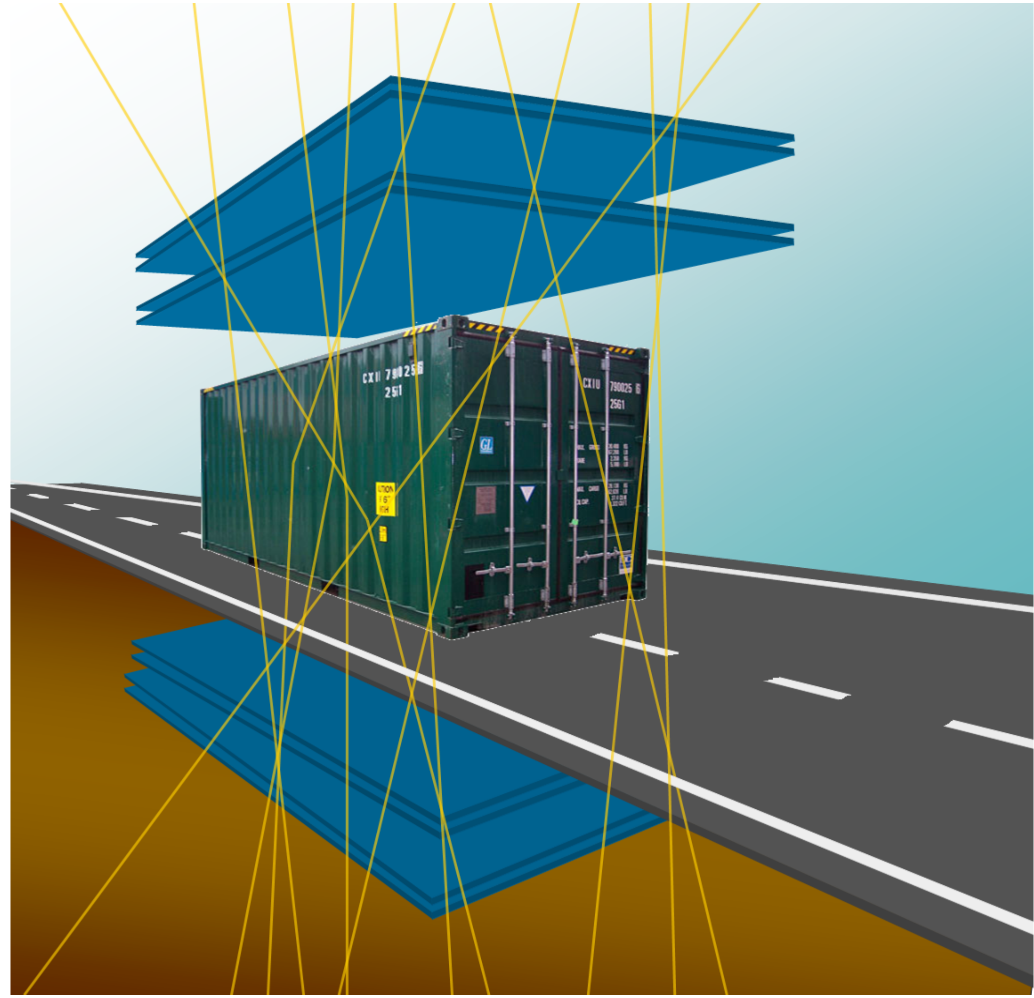
Study the various existing reconstruction algorithm.

Implementation of very preliminary version of Point of Closest Approach (PoCA) algorithm.

Reconstruction using PoCA from Simulated data.

Presentation Overview

- Cosmic-rays and muon tomography
- Simulation of Muon Tomography using Geant4
- Hodoscope Setup at RPC lab
- Construction of Muon Detectors
- Reconstruction algorithms
- Current Status of Project
- Conclusion and outlook



FROM RADIOGRAPHY TO TOMOGRAPHY

- **Radiography**

  Projection on a plane defined by a given direction

  Typical for single source xray

- **Tomography**

  Reconstruct the 3d distribution of the sample by “cutting” it by planes
  With different angle

  Need multi directional source

Three different methods of Muon Tomography with cosmic muons

1) Measure Energy Loss before/after the target :

- detectors are expensive & have limited energy resolution

2) Measure the attenuation

- suitable only for thick/large sized objects

hidden chambers in pyramids (too large)

depth of rocks above an underground tunnel

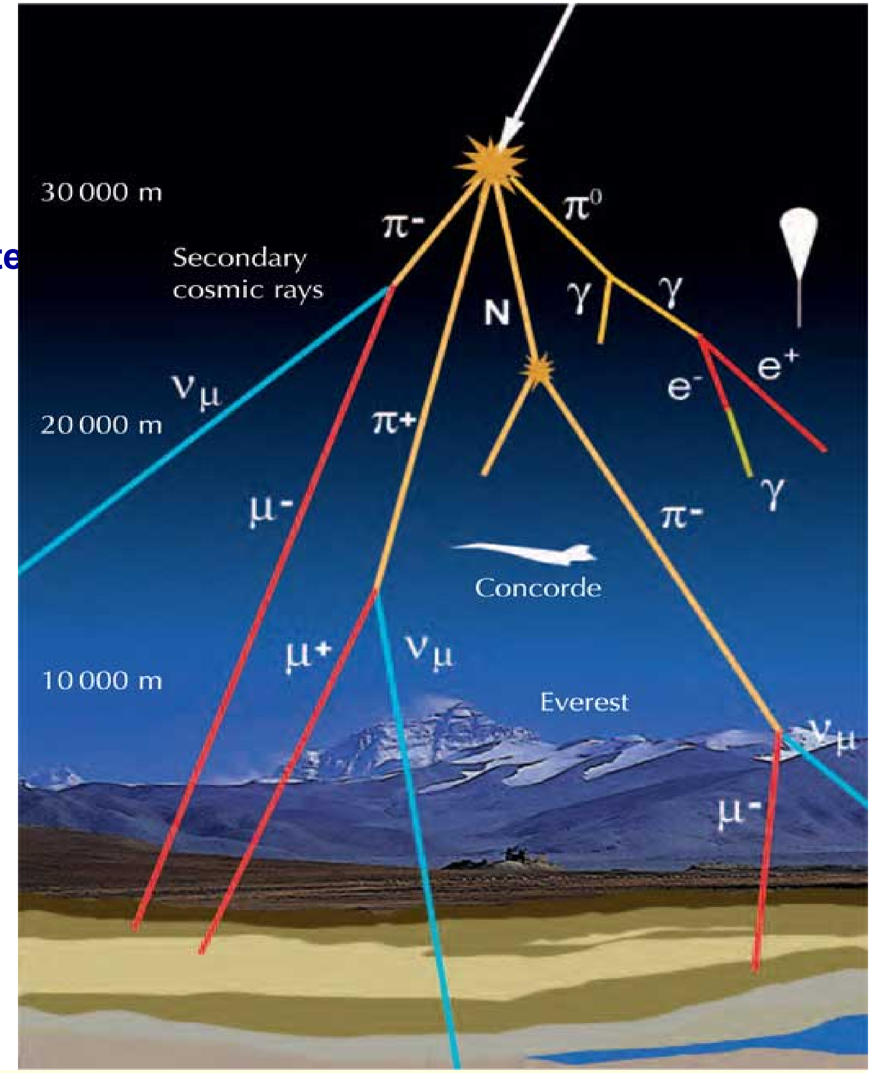
3) Measure the Scattering angle :

suitable for relatively thin/small sized objects

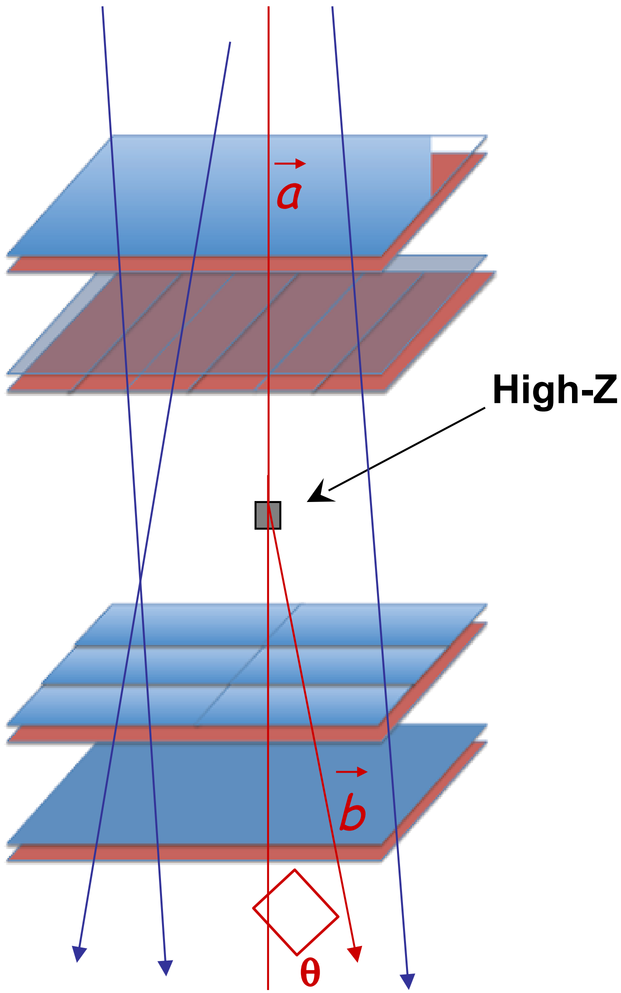
cargos, trucks etc.

Why Muon Tomography

- Secondary cosmic muons: highly penetrating radiations
- (even more than X-rays)
- Average energy : 3 to 4 GeV
- Flux : approximately 10,000 muons per minute per square mete
- (Free of Cost) "Natural" radiation, hence no additional dose delivered to users and goods
- Muonic interactions well understood
- Muon scattering strongly dependent on the Z of the material
- Each muon may contribute to determine the overall imaging



Muon Tomography



- Muon tomograph: basically made by several detection planes, above and below the volume to be inspected

- Reconstruction of muon tracks allows **to discriminate one material from another, and to identify them**

- Using some good image reconstruction algorithm one can even produce a **3D image as well**

- Performance of the system are given in terms of
  - Sensitive area / volume to be inspected
  - Spatial and angular resolution
  - Time to scan a volume
  - Sensitivity & Efficiency to high-Z objects
  - Discrimination between high-Z vs low & medium-Z

Multiple Scattering : The physics behind muon tomography

Muons, being leptons, interact with matter through the Coulomb force.

The muon passing through the material is deflected by many small angles, scatters off the nuclei of the material

The angular scattering distribution is approximately Gaussian (with long tails), but the central 98% is well described by gaussian with zero mean and standard deviation is given by

$$\sigma_{\Theta} = \frac{13.6MeV}{\beta cp}\sqrt{\frac{L}{X_0}}\left[1 + 0.038ln\left(\frac{L}{X_0}\right)\right]$$

Geant4 Simulation

The physics process under study is Multiple scattering

Physics list used FTFP_BERT

Size of Detector 1m X 1m

Number of Detectors : 4

Muon Energy chosen : 2 GeV (ie. Monoenergetic muon)

Scatterer used : Al, Fe, Pb (4 cm, 5cm, 10 cm, 12 cm , 15 cm)

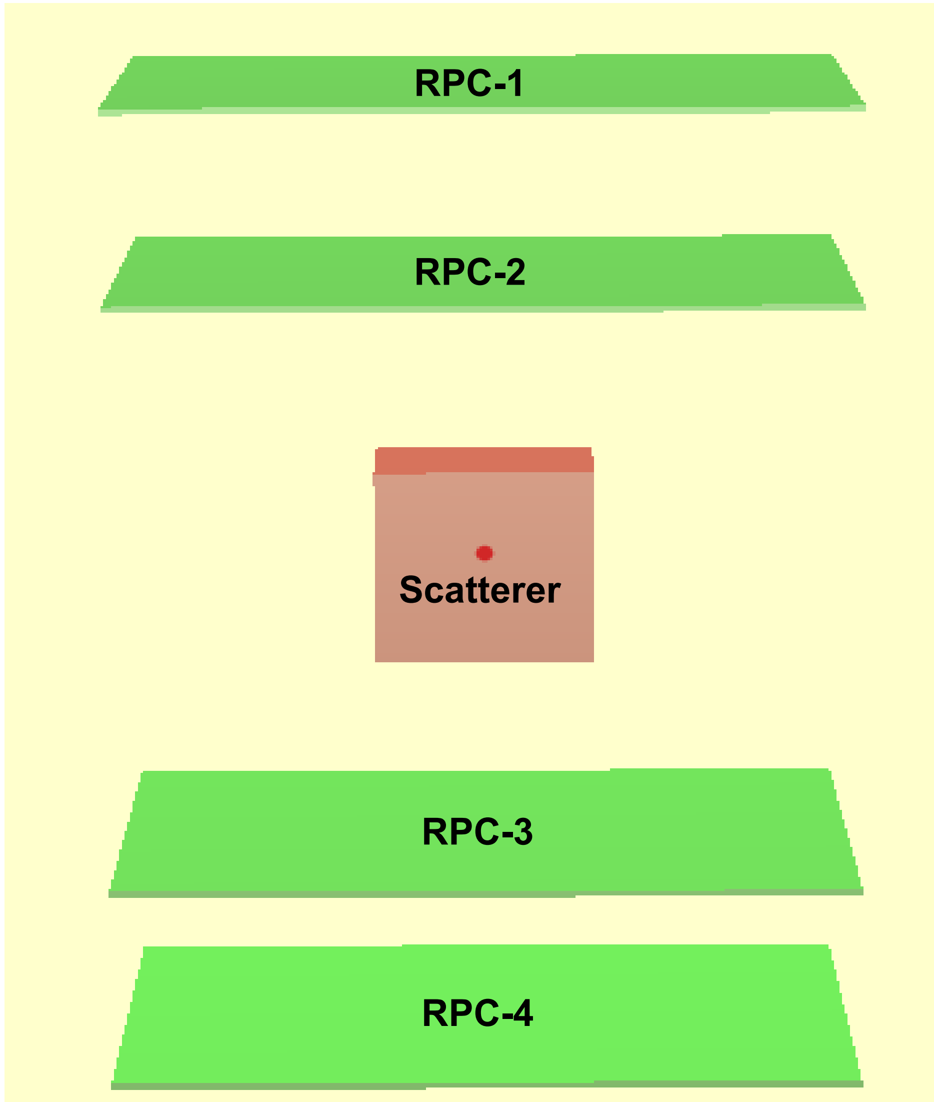
Shape of Scatterer : Cube

In the first stage simulation are done with following assumption :
1) Detectors are 100% efficient.
2) And give the exact hit point.

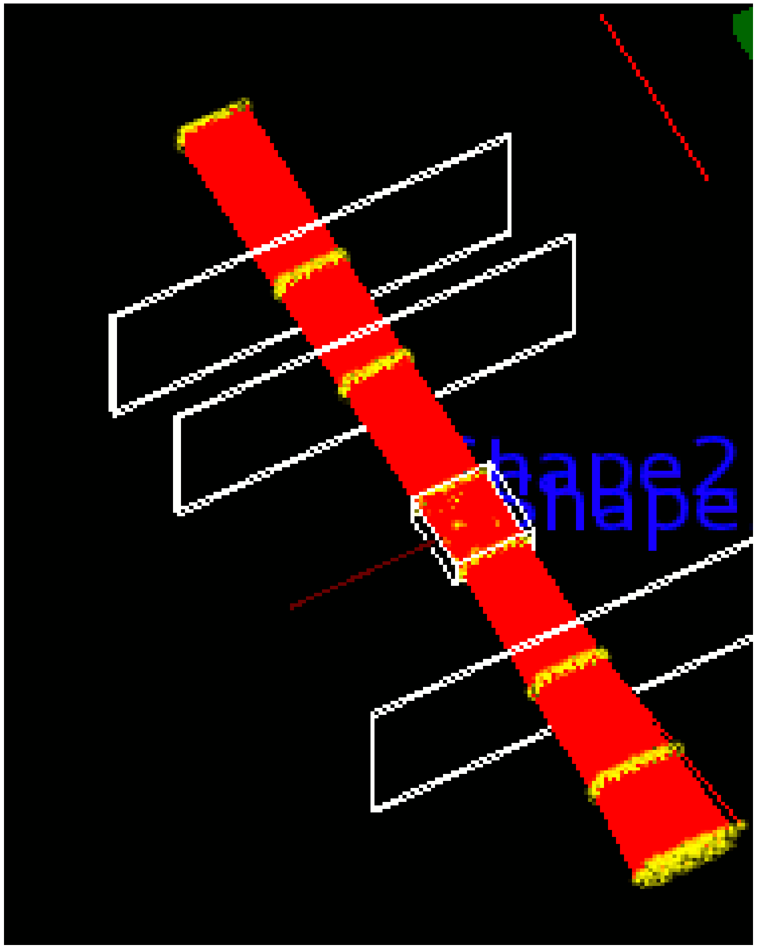
These assumption are taken to work parallely on Reconstruction algorithm.

In the next stage we will try to remove these assumption, so that we can get simulated data which is more closer to reality.

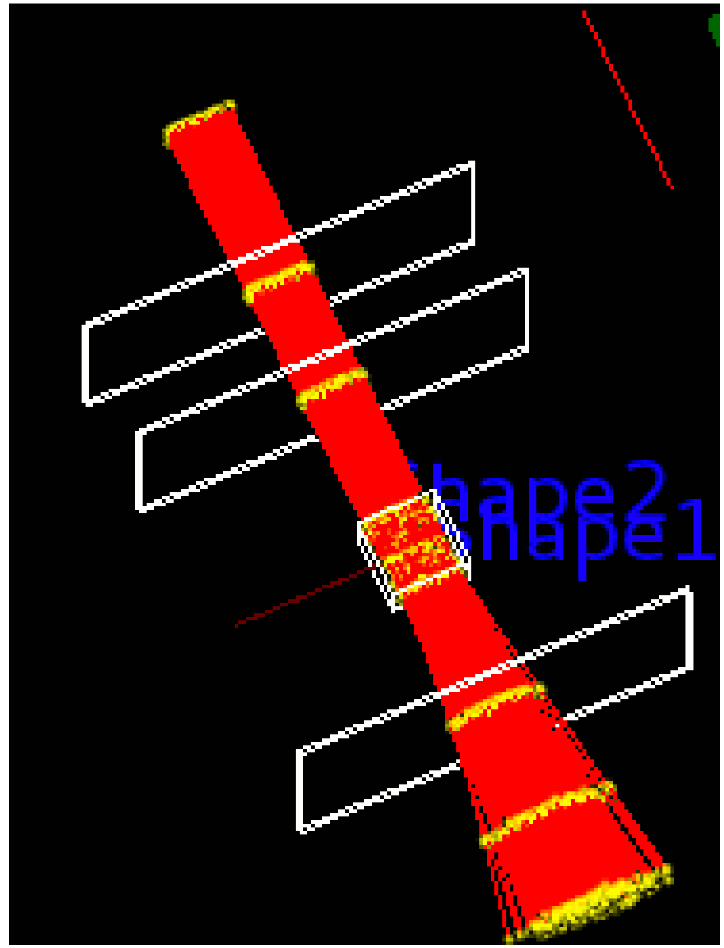
Simulation with different scatterers (Pb , Fe and Al) cube of varying sizes (10cm, 15cm, 20cm...)



Scattering difference with Iron and Lead Cube of 20 cm

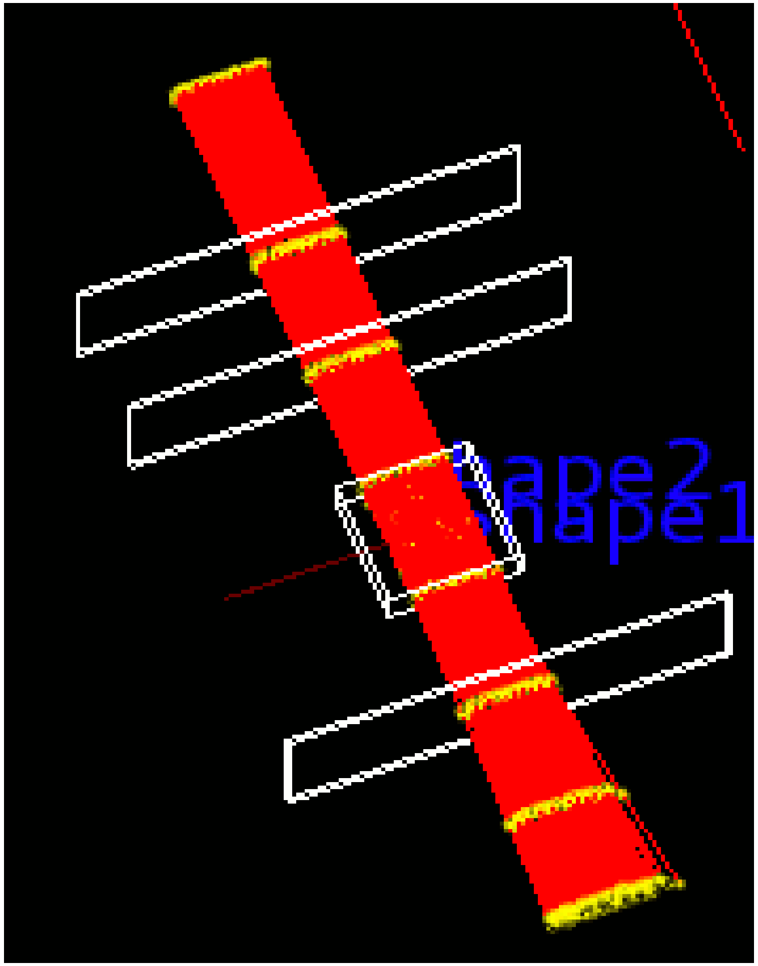


Iron Cube of 20 cm

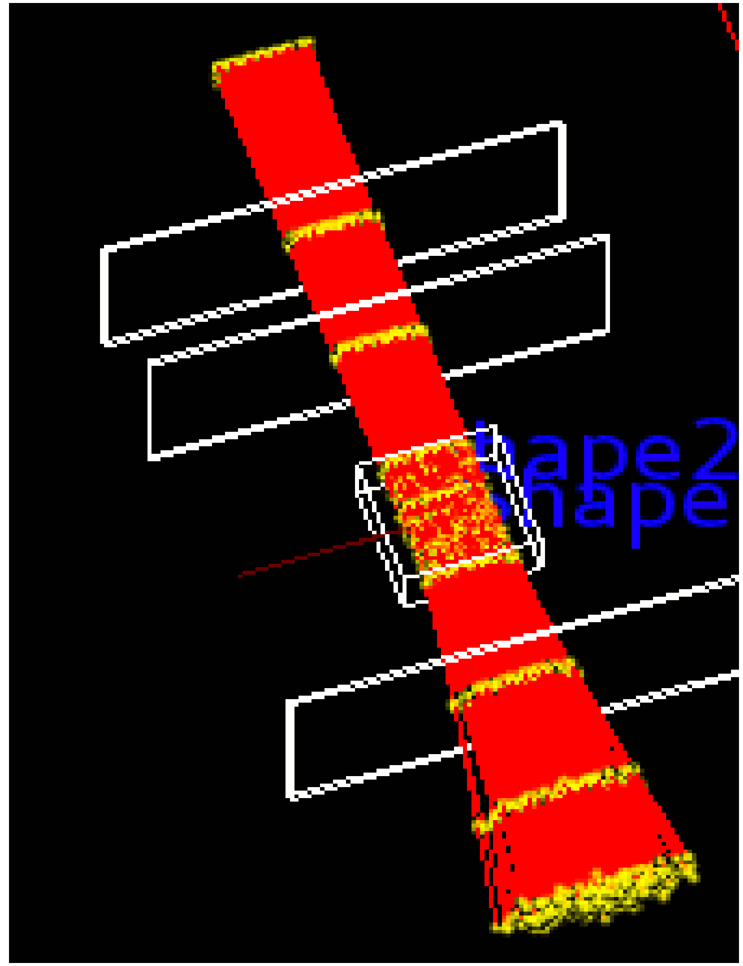


Lead Cube of 20 cm

Scattering difference with Iron and Lead Cube of 30 cm



Iron Cube of 30 cm

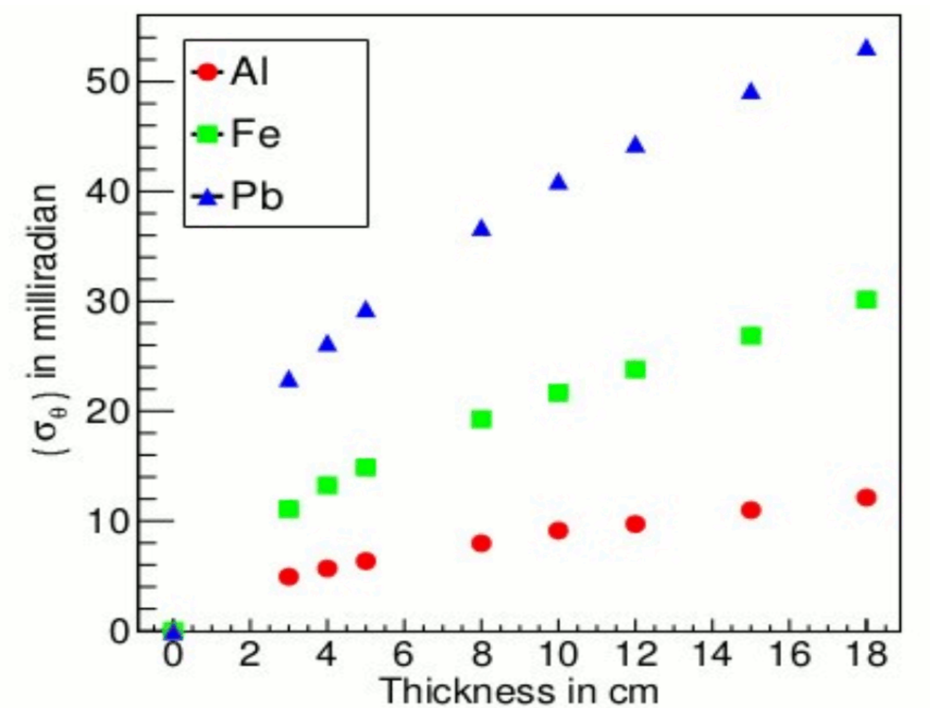


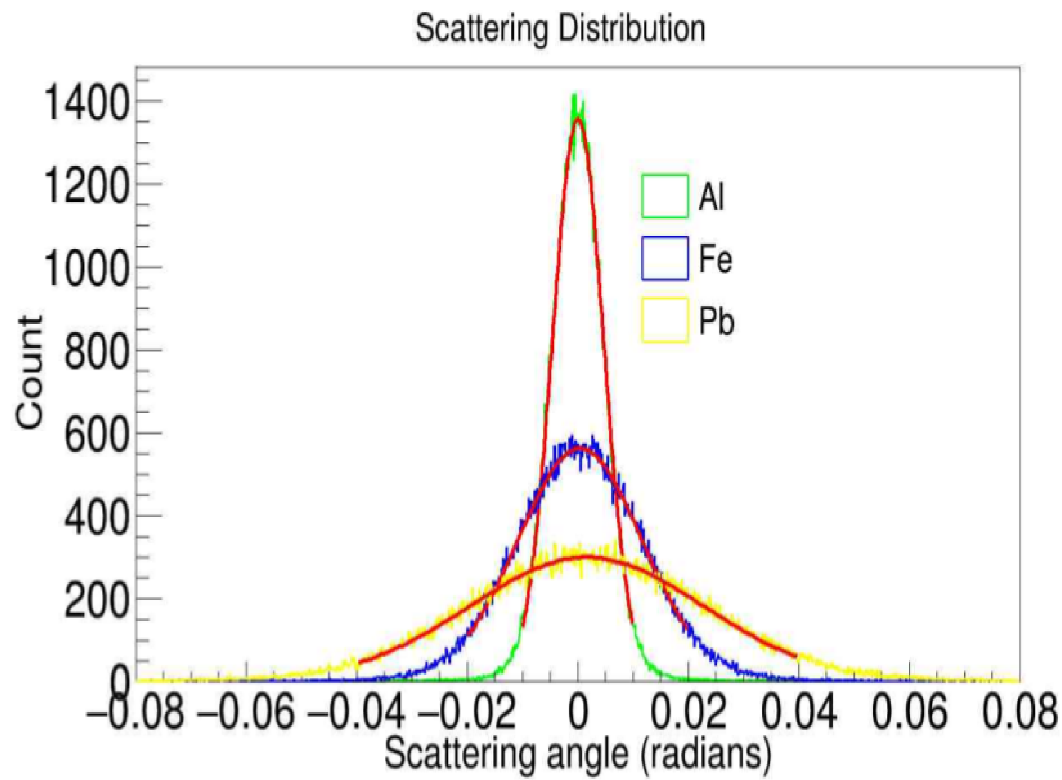
Lead Cube of 30 cm

Material Discrimination and Identification

As a first step 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





Proceedings of DAE Symposium on Nuclear Physics (Vol. 61, 2016)

Material Discrimination and Identification Cont..

But cannot tell what actually is the material !!

It may happen that two material of different thicknesses may give same scattering angle distribution.

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

We have chosen the **Radiation Length**

We have worked with three materials **Al, Fe and Pb** in our simulations.

To make our calculation easier we are using simplified form of previously mentioned formula

$$\sigma_{\Theta} = \frac{13.6MeV}{\beta cp}\sqrt{\frac{L}{X_0}}$$

As per the literature the radiation lengths of the materialsused in simulations are as follows :**Al : 8.897 cms, Fe :1.757 cms, Pb : 0.5612 cms.**

Table specifying standard deviation of scattering angle distribution for different materials of different thicknesses

Length (cms)	Al (X_0 **8.897** cms)	Fe (X_0 **1.797** cms)	Pb (X_0 **0.5612** cms)
10	5.30088	11.9285	**21.1063**
15	6.49223	14.6093	25.8498
20	7.49658	16.8694	29.8488
25	8.38143	18.8605	33.3719
30	9.1814	20.6607	36.5571
34	9.77435	**21.995**	38.918

Proceedings of DAE Symposium on Nuclear Physics (Vol. 62, 2017)

Material Identification using Radiation Length

Here we have considered only one material of known thickness at a time.

In the first case we have taken Fe of **34 cm** thickness.

The standard deviation of scattering angle that we get from simulations is around **22.36 mrad**

In the second case we have taken Pb of 10 cm thickness.

The standard deviation of scattering angle that we get from simulations is around **21.217 mrad**

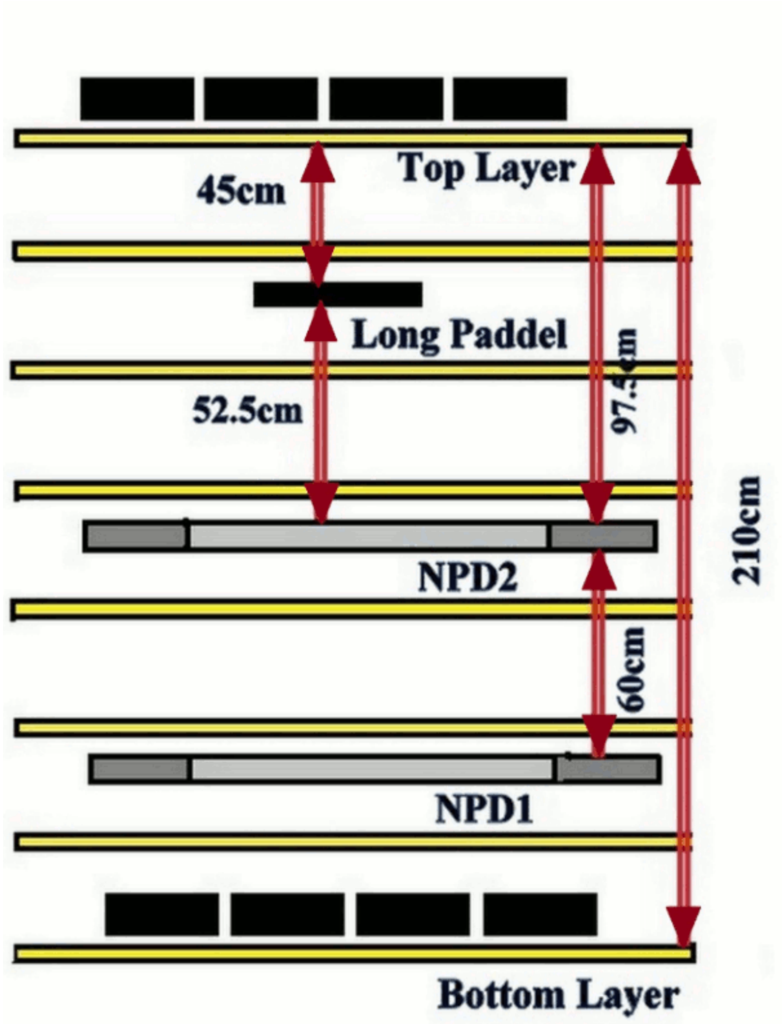
Using formula 2 we have calculated theradiation length $X_{0\ i}$ in both the cases.

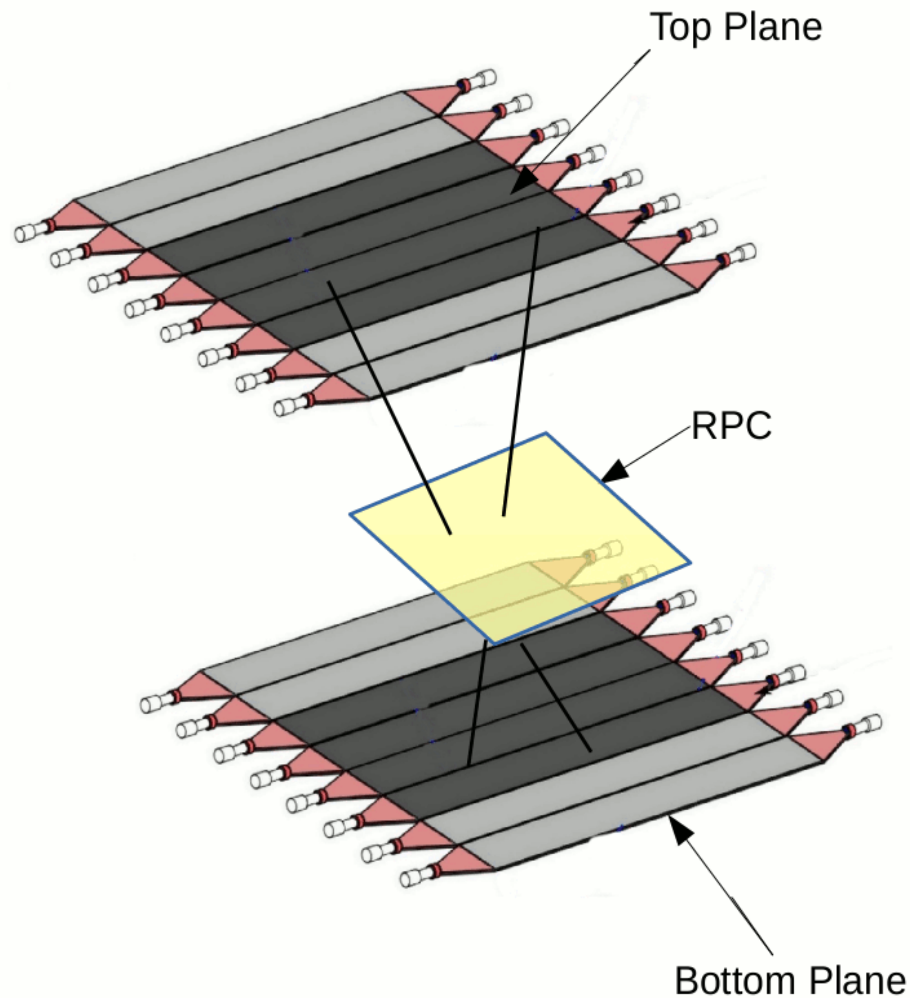
The values of radiation length for Fe comes out to be **1.7001 cms**

And for Pb it comes out to be **0.5553 cms**

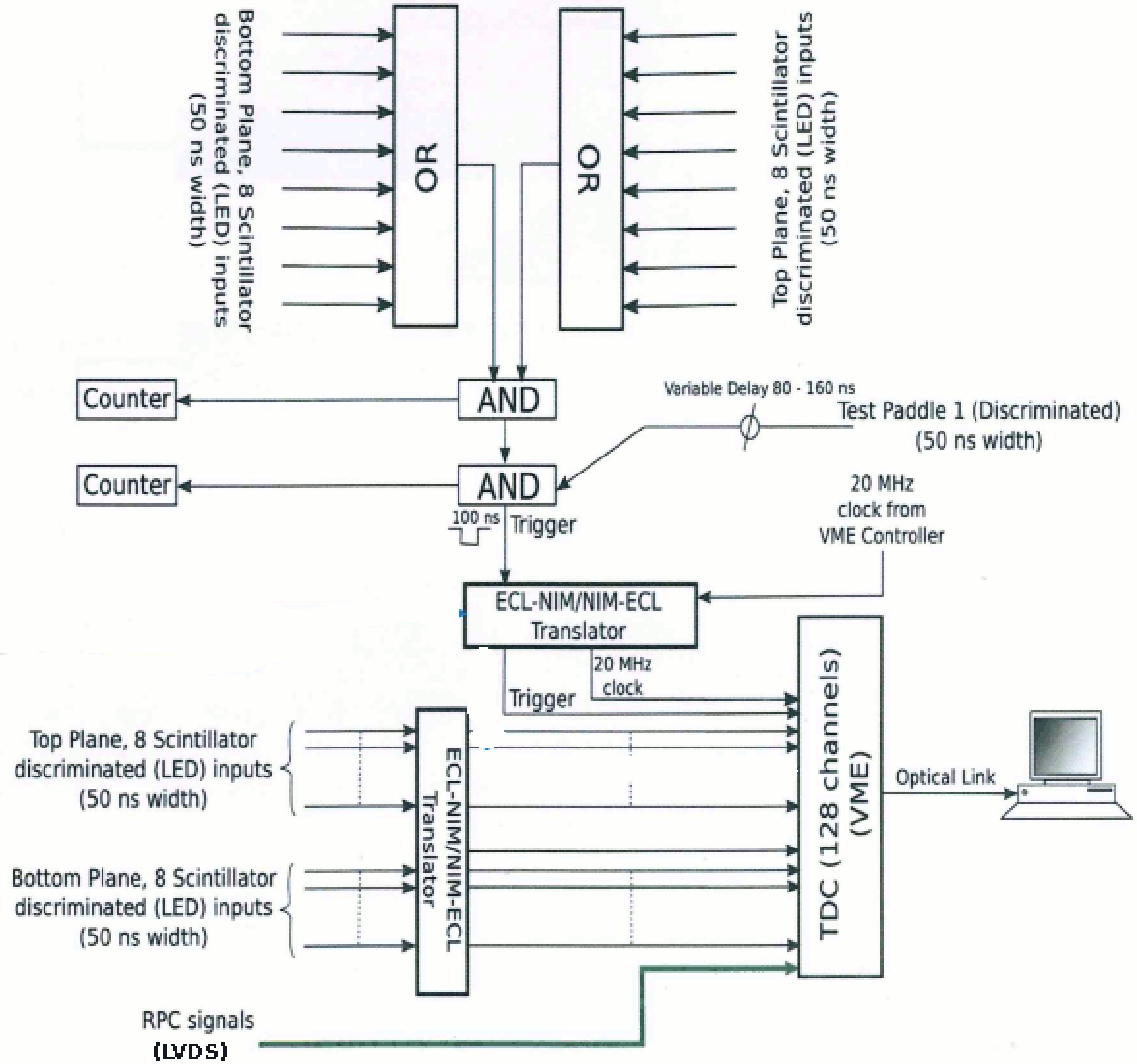
Both these values matches closely with the theoretical values

Schematic of setting the muon trigger with scintillator paddles in the hodoscope



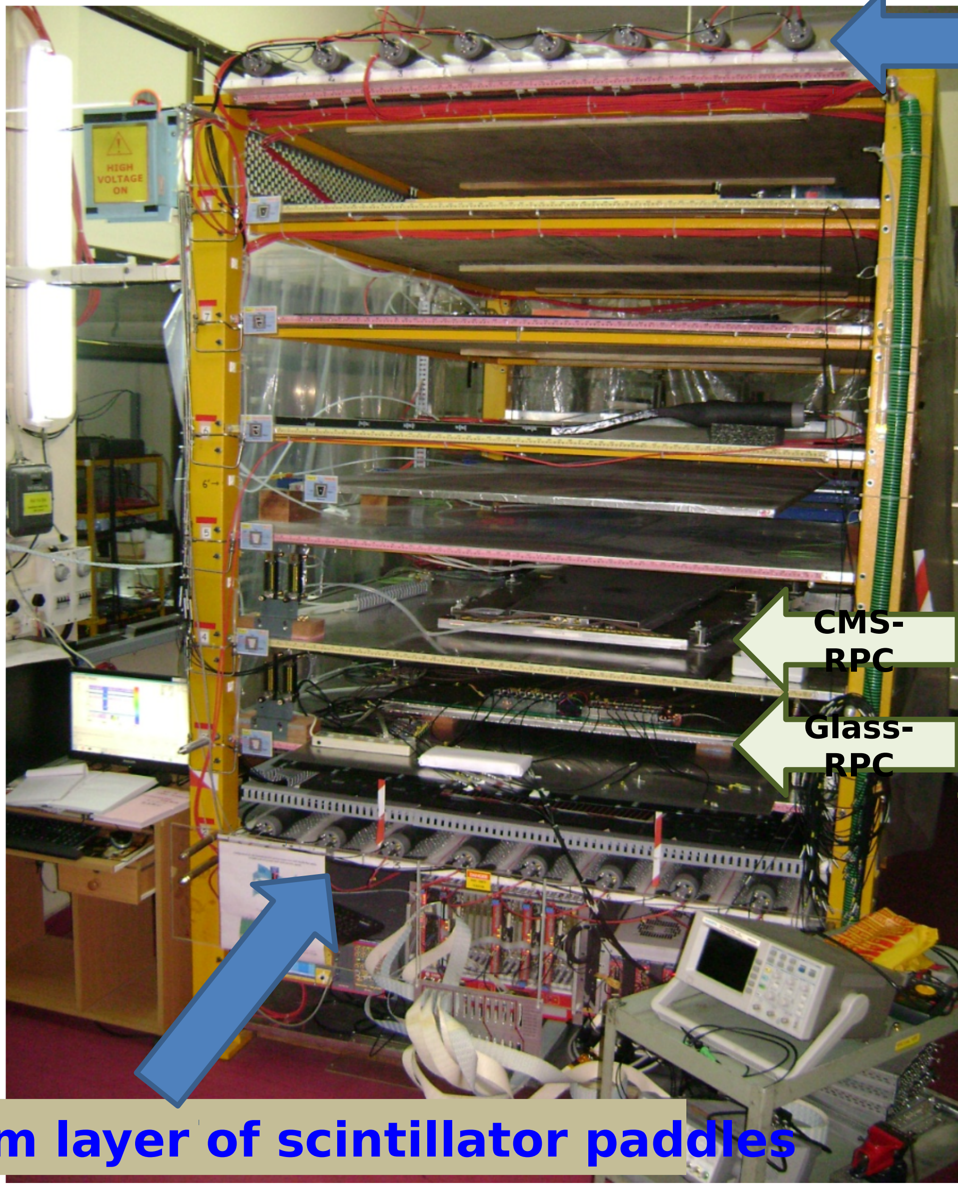


Electronic Setup



Hodoscope at NPD-BARC
Characterisation of RPCs with Cosmic Muons

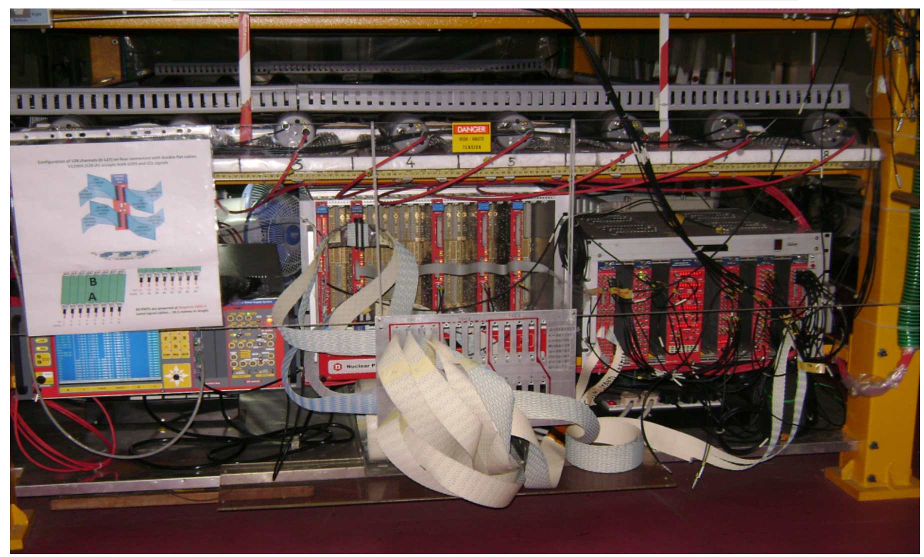
p layer of scintillator paddles



ottom layer of scintillator paddles

1. Characterization of CMS RPCs
2. Muon Tomography (400 ch electronics)
3. Experiments for TSOs
4. Project Trainees

VME-DAQ and TDCs (V1190A)



Publication on Hodoscope

Pramana – J. Phys. (2016) 87: 92
DOI 10.1007/s12043-016-1294-7

CrossMark

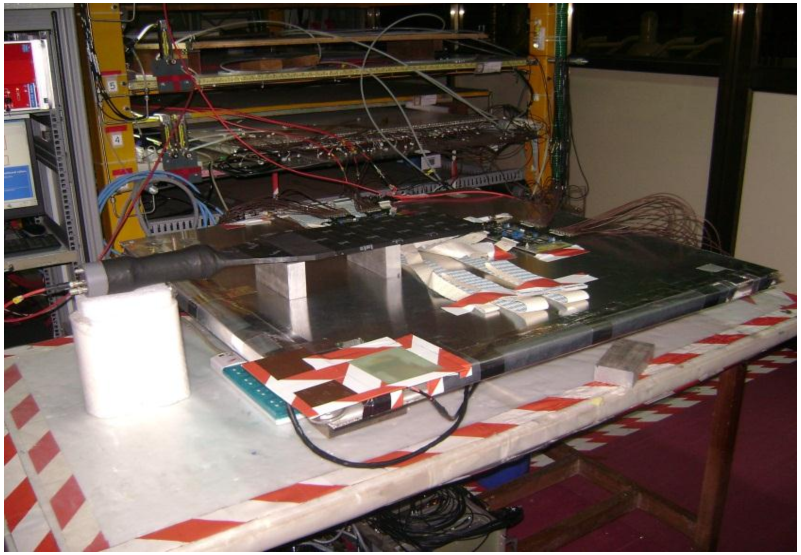
Plastic scintillator-based hodoscope for the characterization of large-area resistive plate chambers

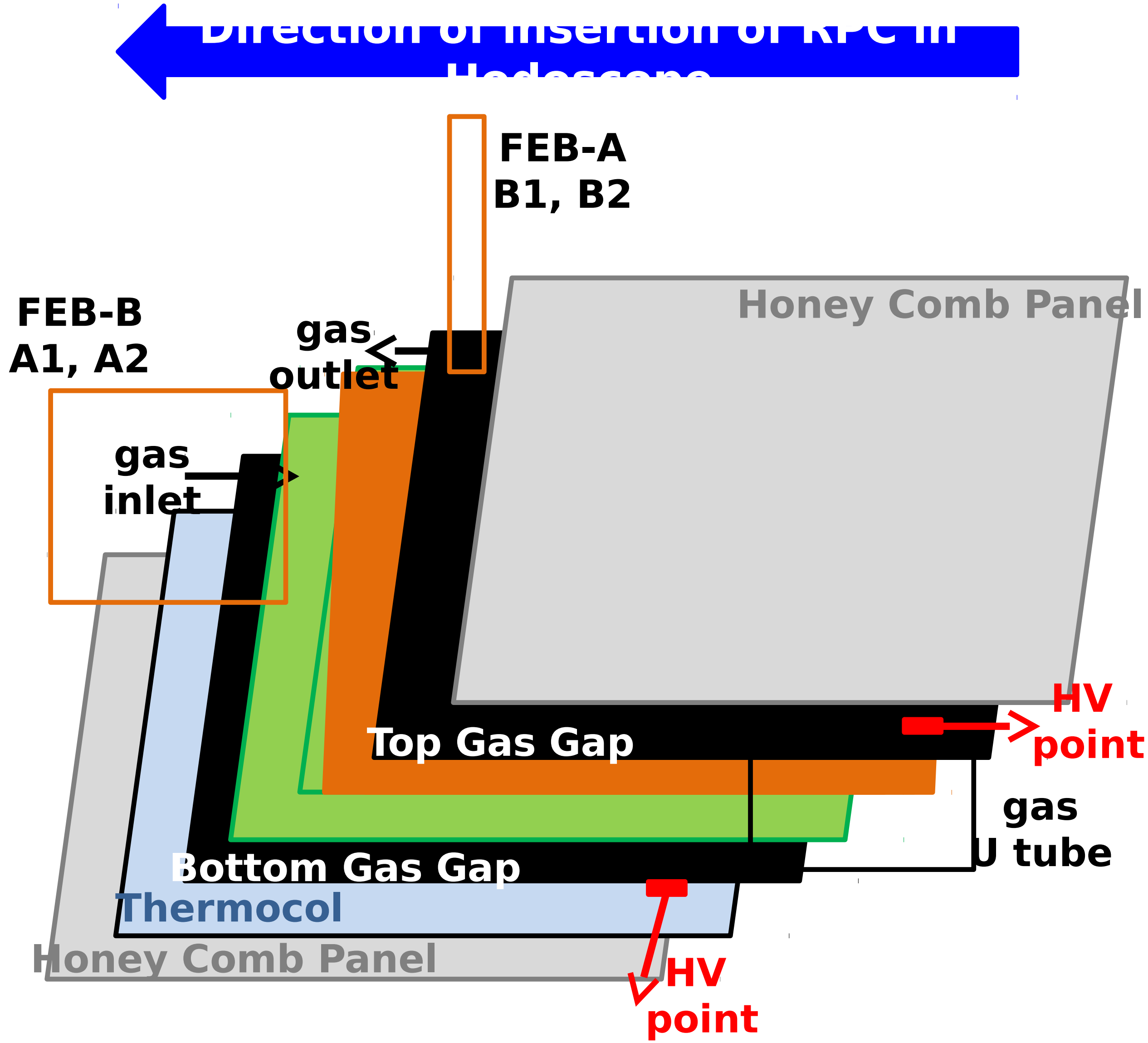
V K S KASHYAP[1,2,*], C YADAV[1], S T SEHGAL[1], R SEHGAL[1], R G THOMAS[1], L M PANT[1,2] and A K MOHANTY[3]

[1]Nuclear Physics Division, Bhabha Atomic Research Centre, Mumbai 400 085, India
[2]Homi Bhabha National Institute, Anushaktinagar, Mumbai 400 094, India
[3]Saha Institute of Nuclear Physics, Kolkata 700 064, India
*Corresponding author. E-mail: kashyap@barc.gov.in

MS received 12 August 2015; revised 29 December 2015; accepted 7 March 2016; published online 3 November 2016

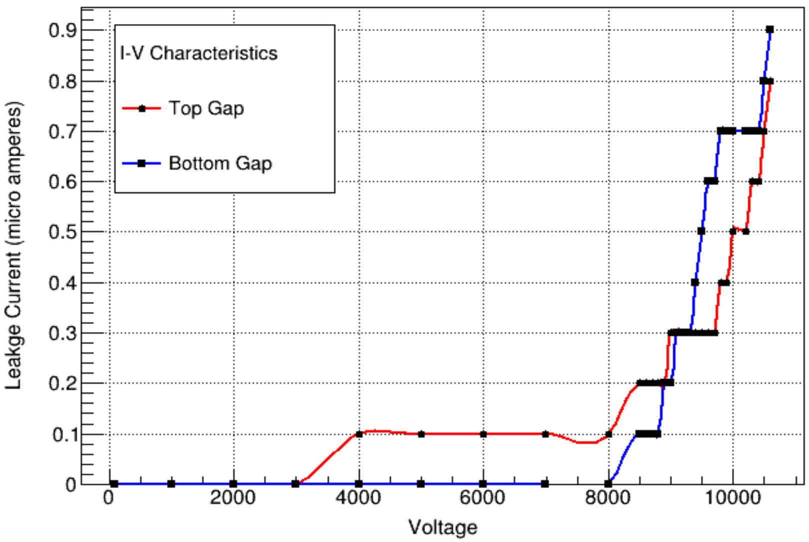
Construction of Muon Detectors



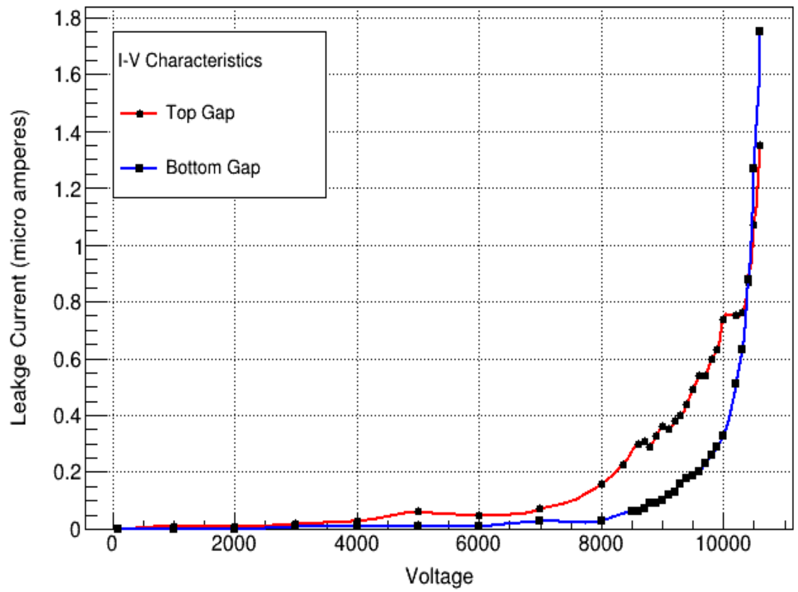


I-V Characteristics of Gaps of RPCs

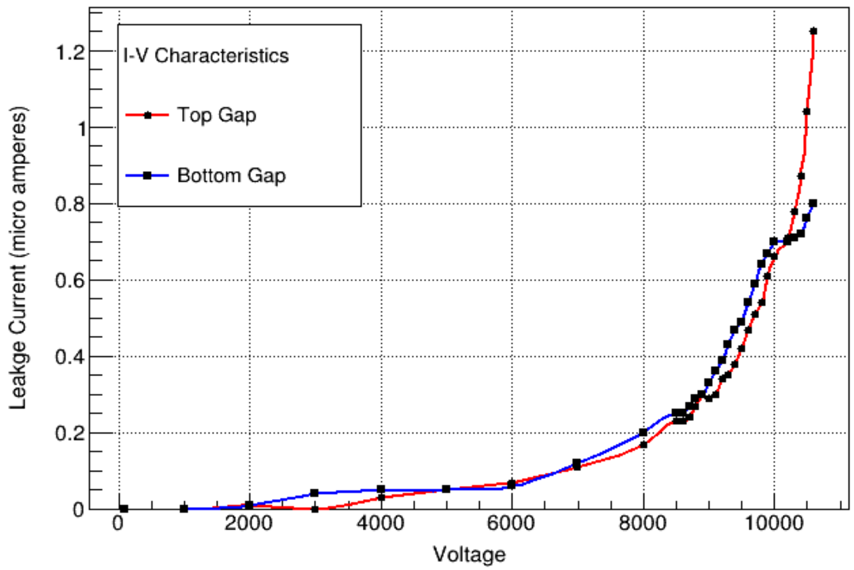
RPC-1



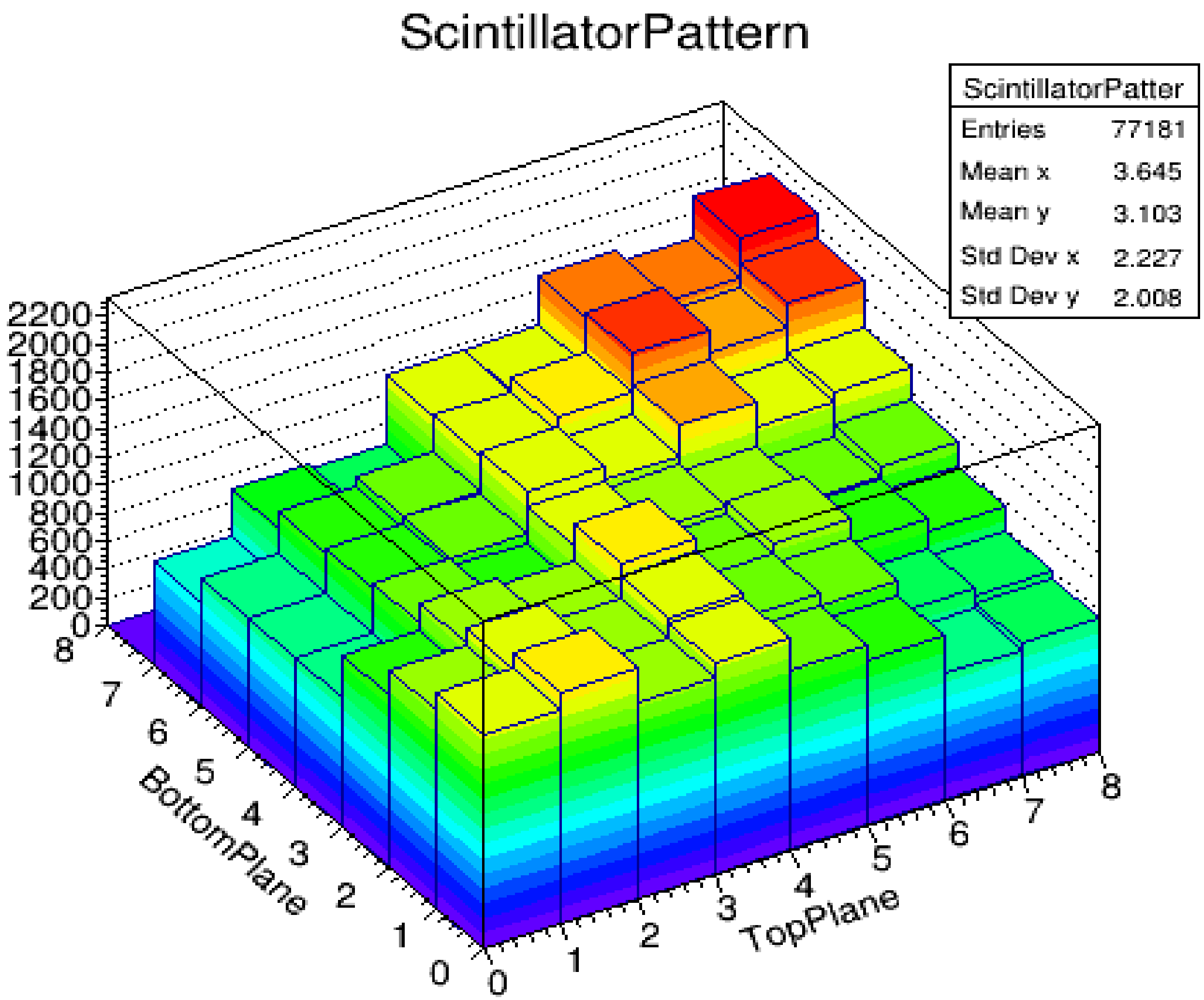
RPC-2

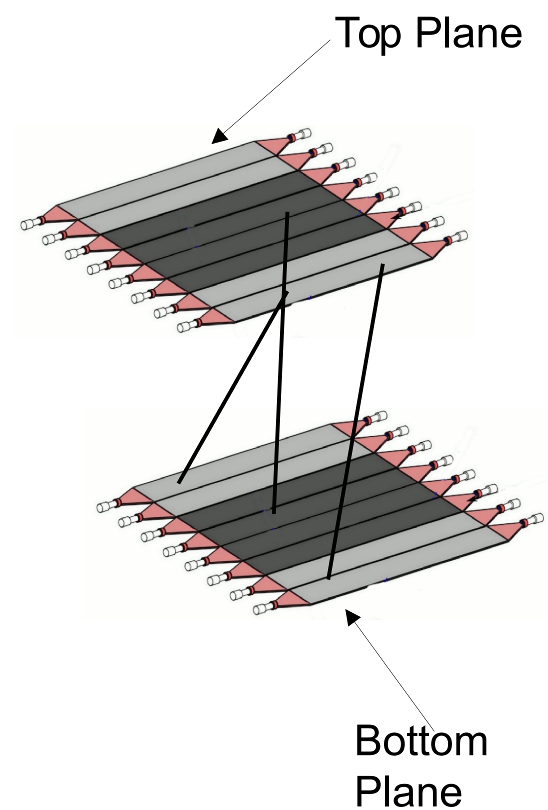


RPC-3

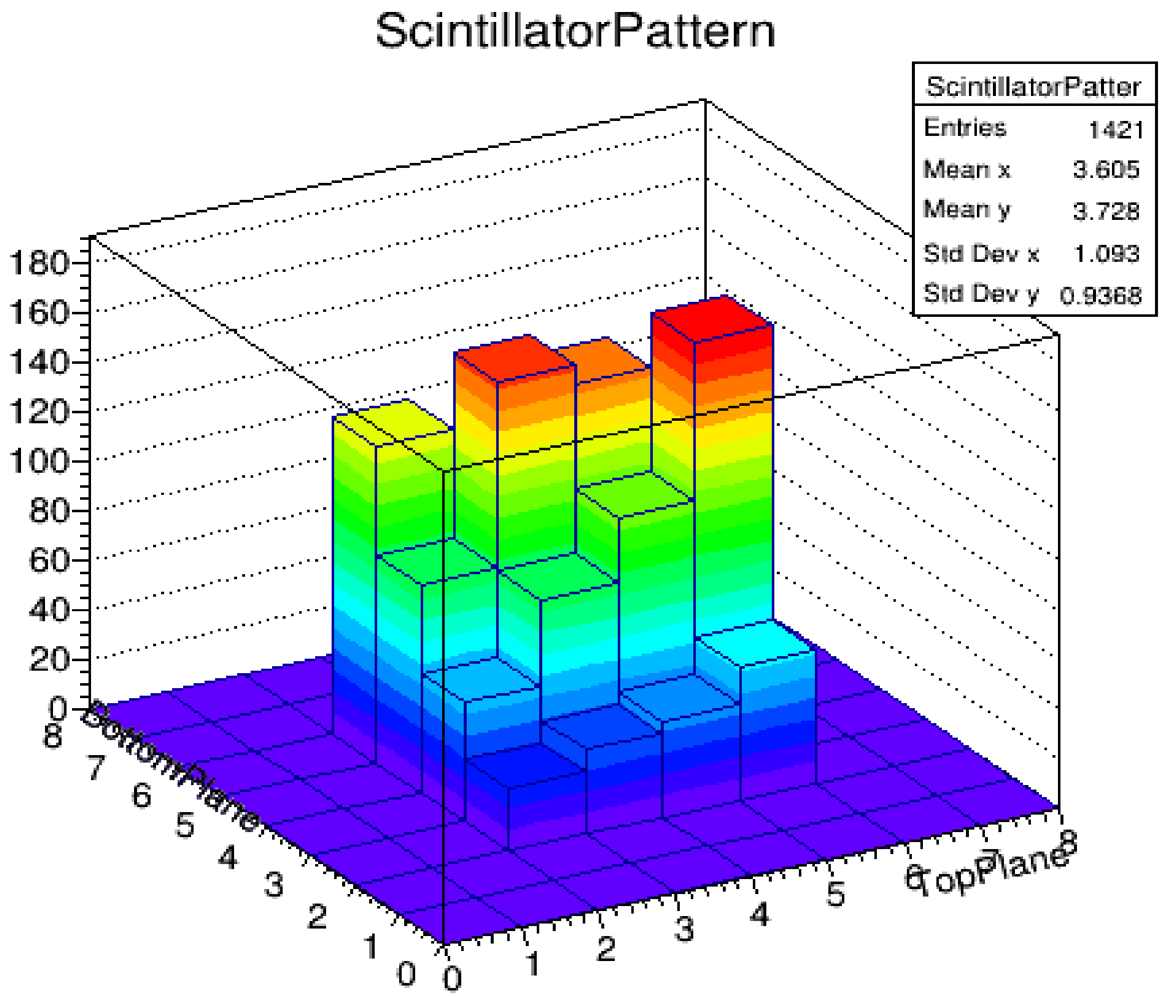


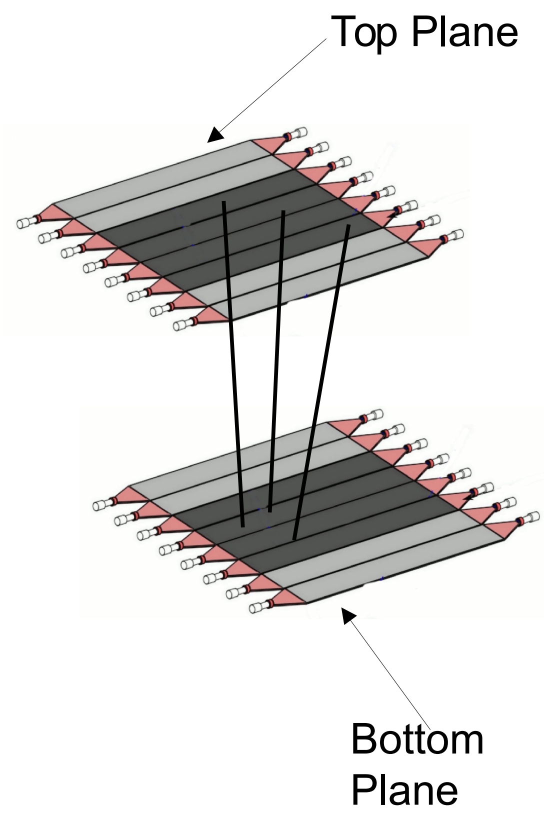
Top and Bottom Scintillator Plane Pattern



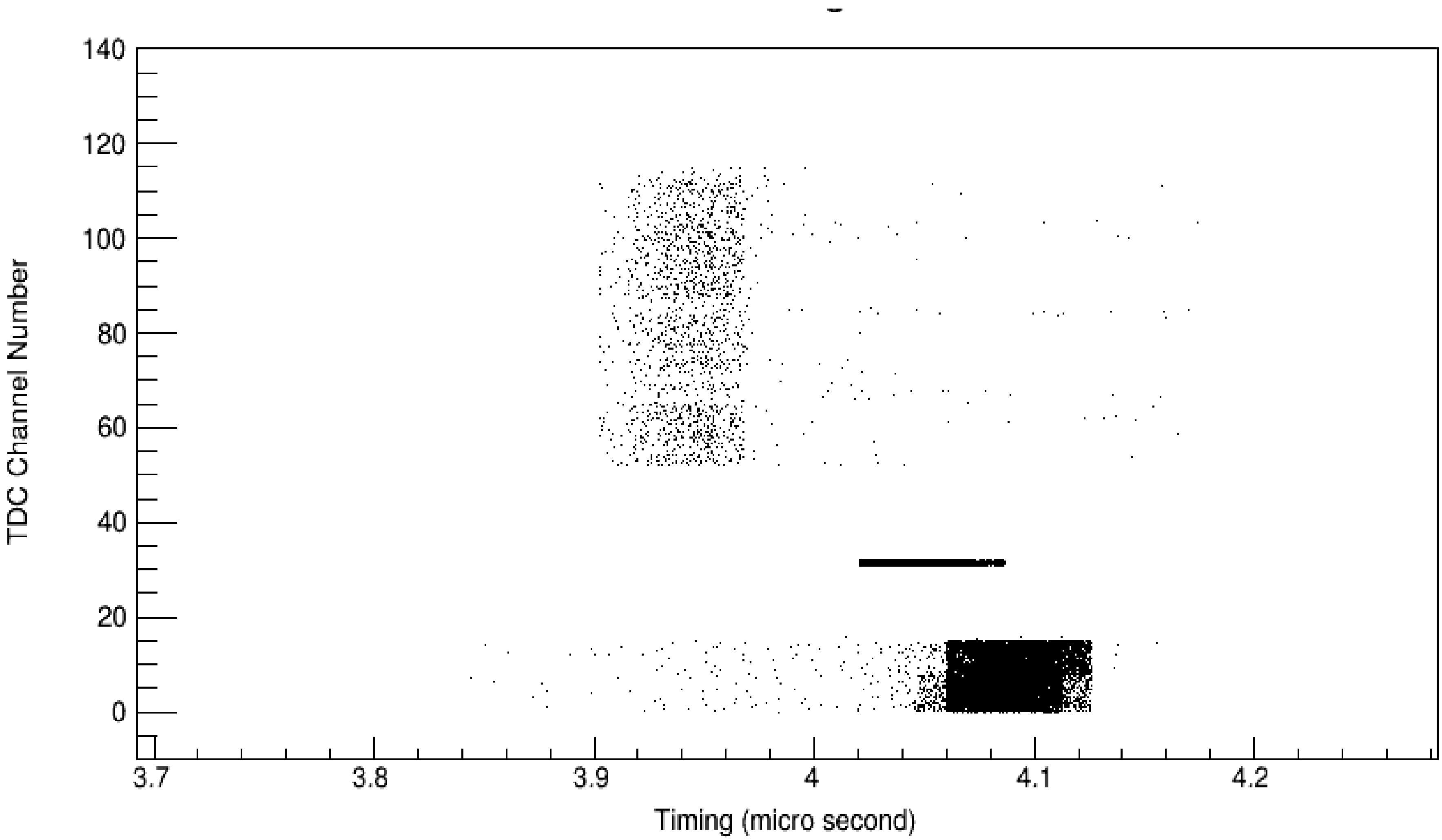


Top and Bottom Scintillator Plane Pattern (only middle four are swtiched ON)

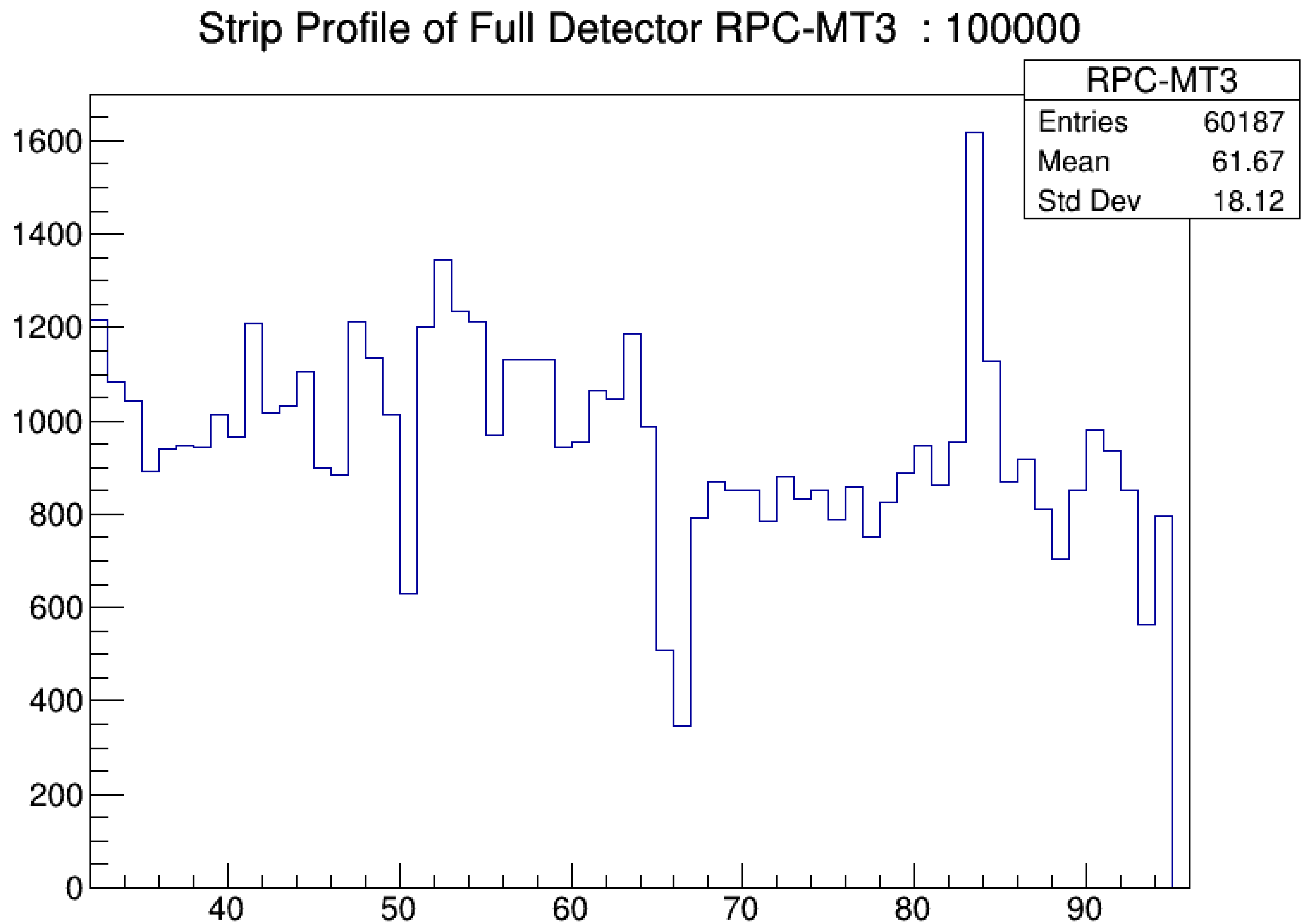




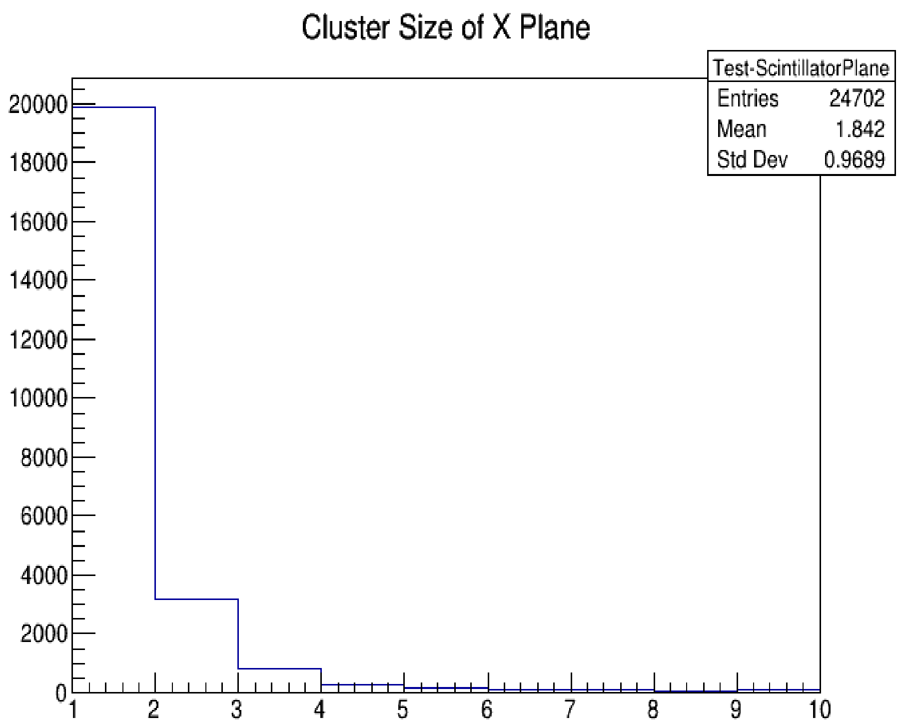
Calibrated Timing Histogram to select the desired window width with respect to Trigger

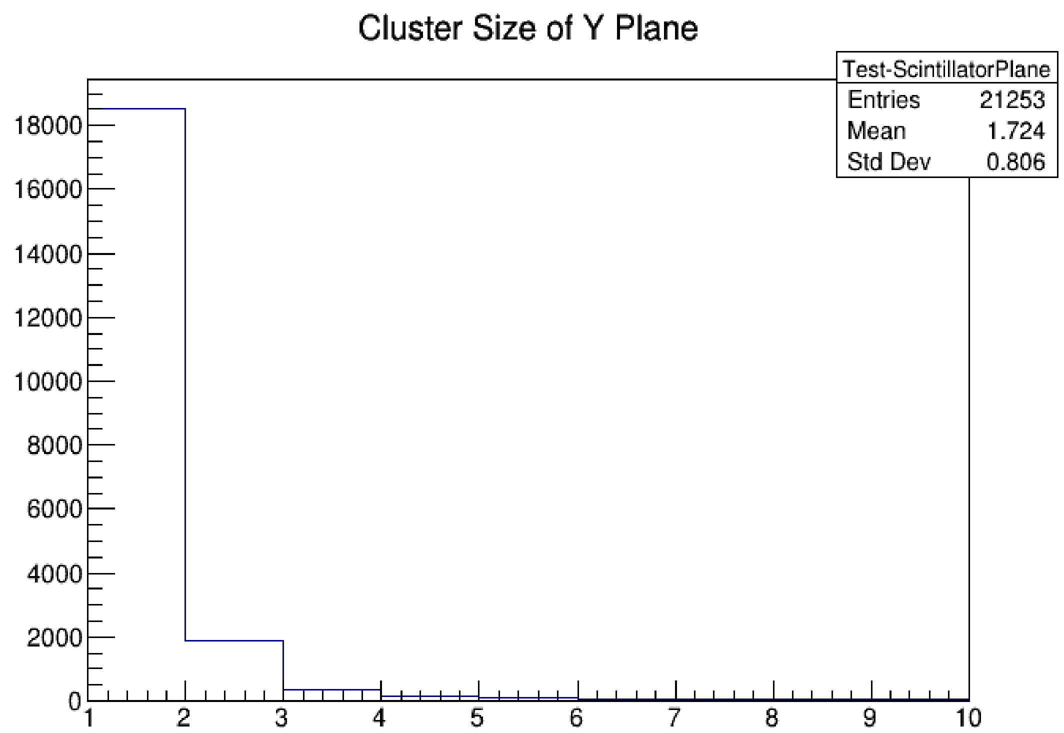


Strip Profile of Full Detector (X and Y plane)

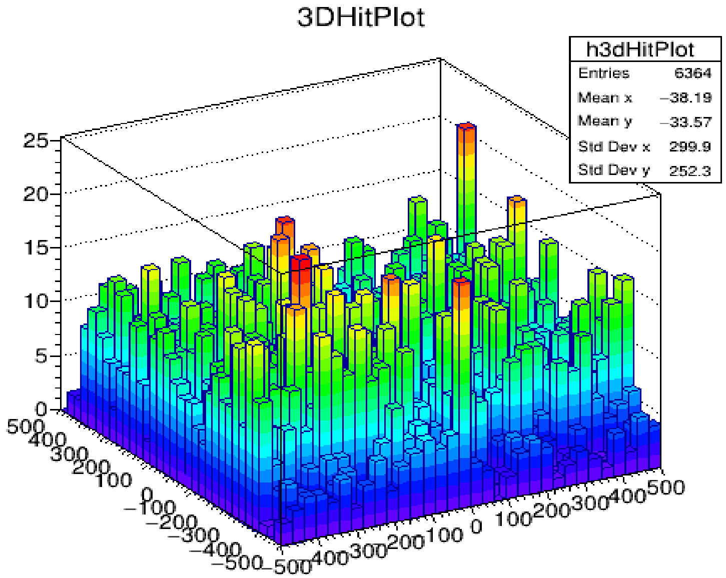


Cluster Size of X and Y Plane Strips

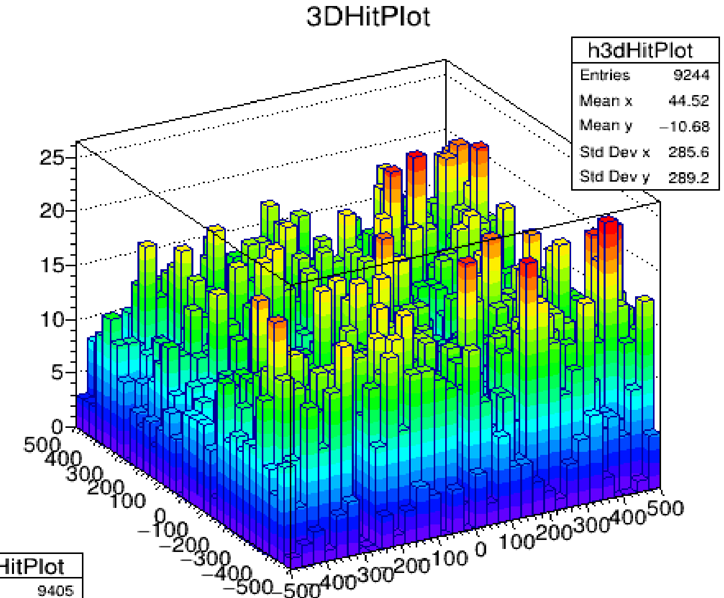




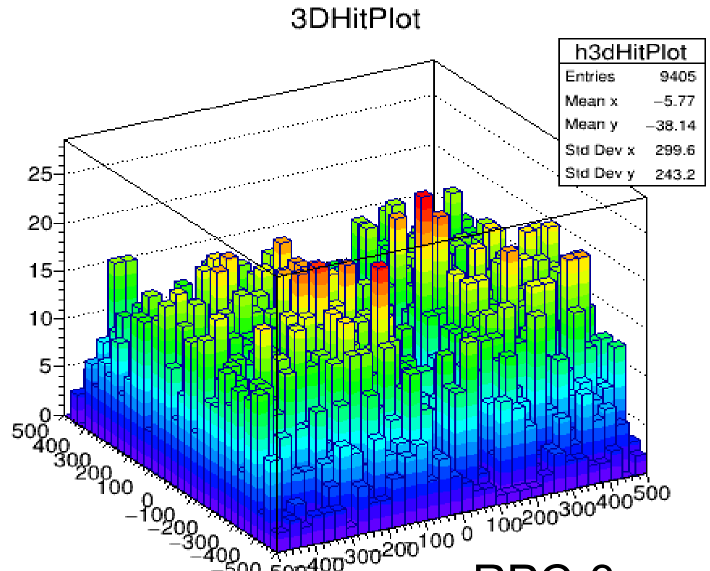
3D Hit plot of RPCs



RPC-1



RPC-2



RPC-3

Track Reconstruction Algorithm

Due to spatial resolution of RPC, we don't get the exact hit location.

What we got is, the strip number that got fired in X and Y Plane.

As a first step we have considered only those events where only one strip fired in X and Y.

Once we get the strip numbers, we try to map them to 3D coordinate system, with origin as the centre of hodoscope.

One strip in X and Y direction give us the area (Pixel) on the Detector from where the muon has pass through.

The area of this pixel is rough 2.8cm X 2.8cm

We took the center of the pixel as the muon hit position (which is not actually true), infact the hit position is distributed throughout the area of the pixel.

The true position can be obtained by fitting the straight line through the center of fired pixel for the stack of 'N' detector.

The more the number of detectors the better is the hit location estimation.

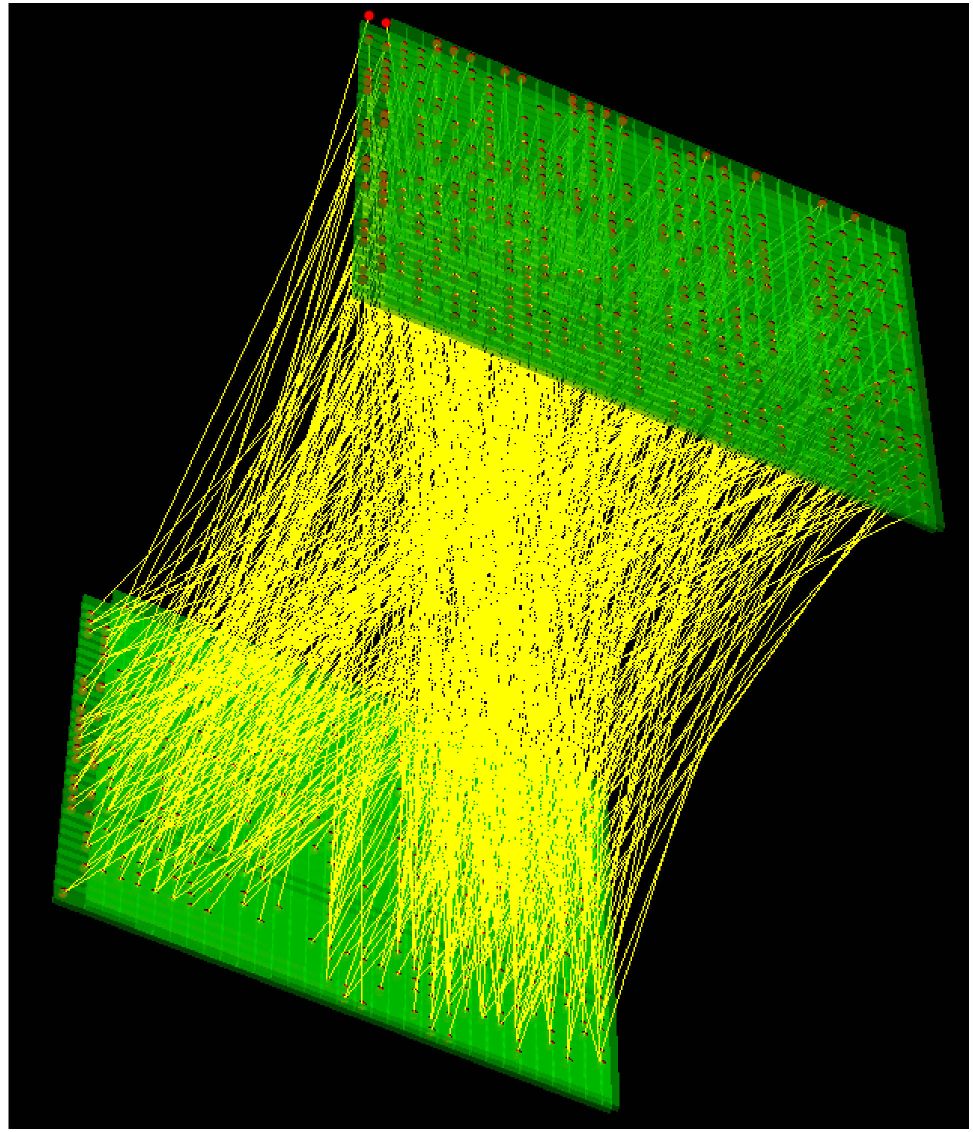
Muon Tracks from two RPCs (1m x 1m) with 32 read outs each in X and Y planes (From Experimental data)

Here we have tried to visualize the muon tracks from two RPC detectors.

These are separated vertically by 120 cm

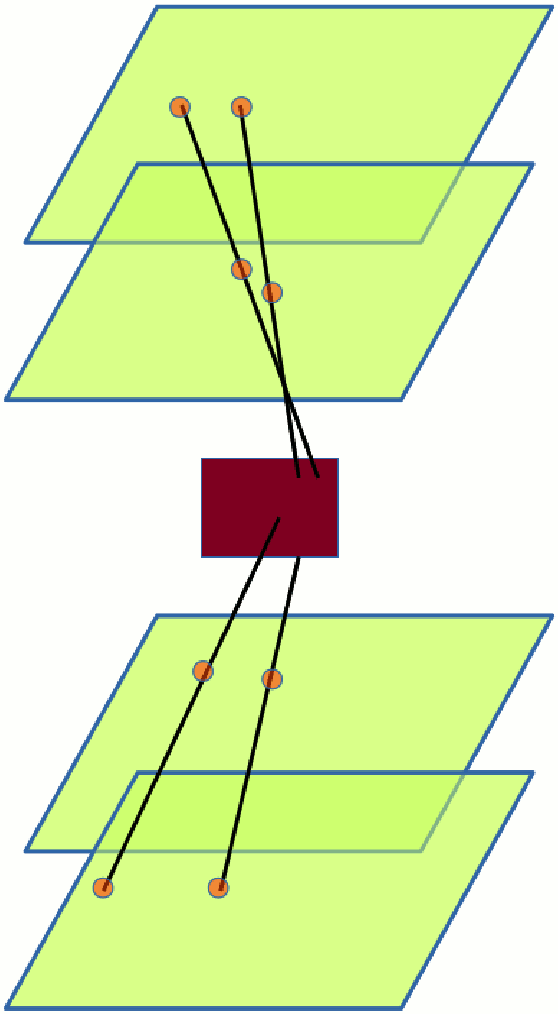
Only those events are considered where only one strip fired in X and Y.

The figure display 600 such tracks.

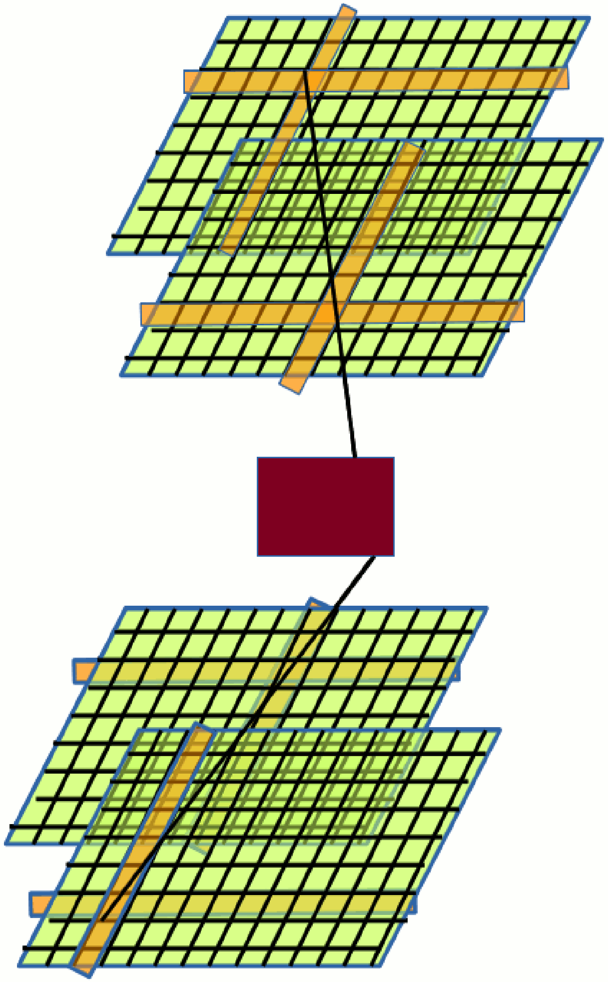


Schematics of various situations

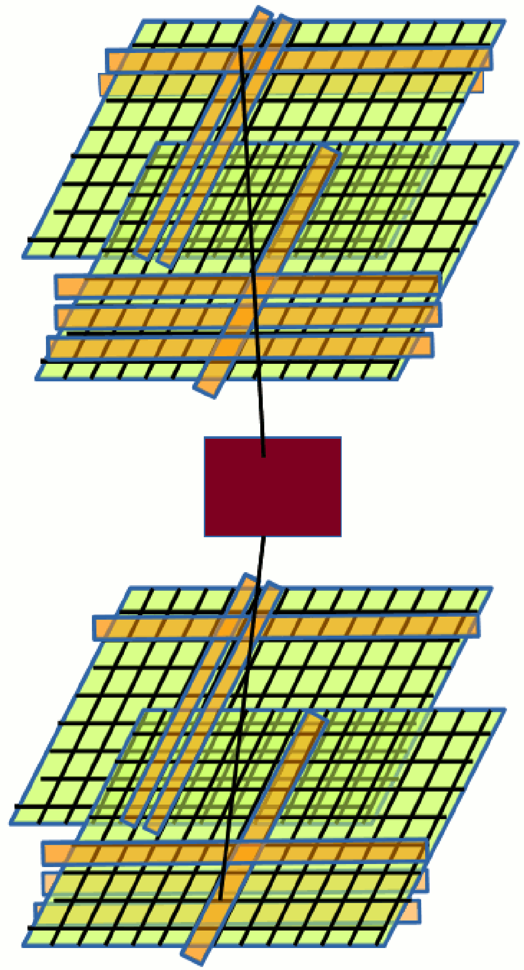
Ideal Situation (Simulations)



Currently what we are doing



In Reality what may be happening



Limitations

Currently the main limitation is the number of detectors.

In order to reconstruct the track, we are chosing only those events, where only one strip fired in X and Y plane.

This will result in reduced detector efficiency.

In addition to that, the event will be useful only if all the detectors fired with above mentioned criteria.

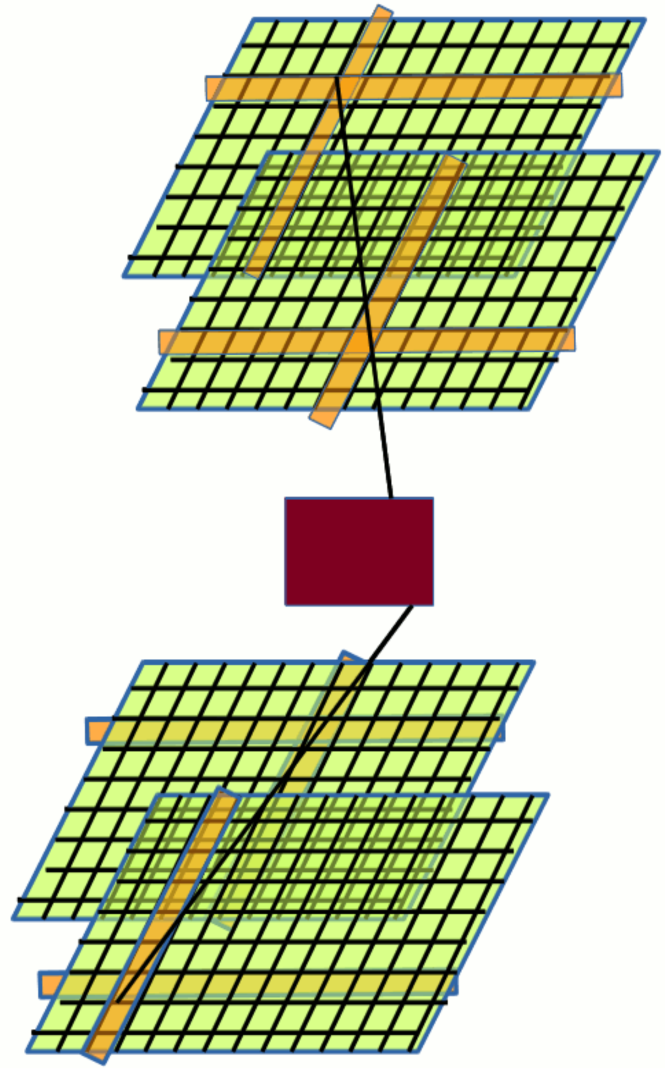
This will result in reduced overall tracking efficiency.

How to overcome these limitations.

Increase the number of detectors

So that we can also take those events where multiple strips fires in X and Y planes.
With this we get more detector efficiency.

Take the line of best fit as the muon track.



Next stage Simulation Plan

Start with setup consist of 4 Resistive Plate Chambers (RPC) placed in Z direction.

Each RPC of 1m x 1m surface area will be having two readout planes (X and Y) and will be placed orthogonally.

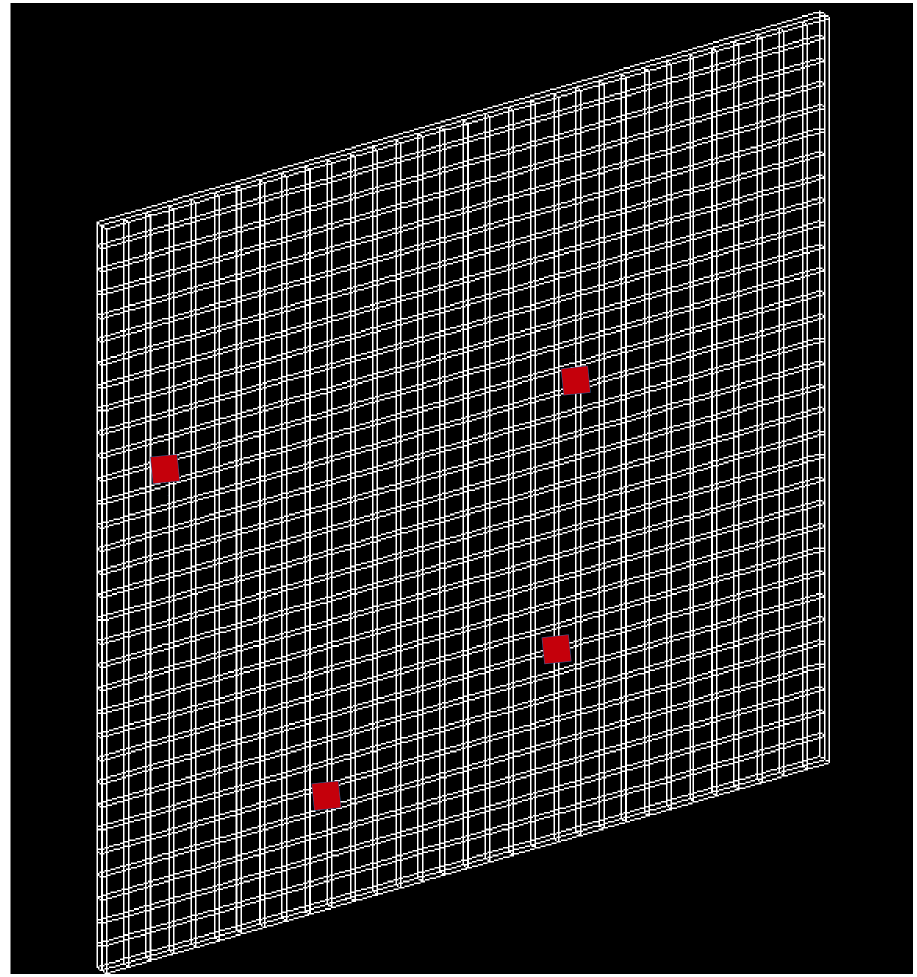
Each of these planes will be having 32 readout strips.

The strips will be separated by 2mm dead area.

Instead of storing the exact hit point, we will store the hitted strip number in X and Y plane.

This will exactly mimic the geometry of real RPC.

Then we will run these simulation with different numbers of detector each time, and get the line of best for incoming and outgoing trajectory



This will give the idea of minimal number of detectors required to get the hit position closer to exact hit point

Image Reconstruction Algorithms

Point of Closest Approach (POCA)

- ***Purely geometry based***
- ***Estimates where each muon is scattered***

Maximum Likelihood Expectation Maximization for Muon Tomography

- ***Introduced by Schultz et al. (at LANL)***
- ***More physics based-model than POCA***
- ***Based on the concept of Voxelization***
- ***Estimates Scattering density (λ) per voxel***

Image Reconstruction using Point of Closest Approach (POCA) : A purely geometric algorithm

Consider two lines L1 and L2 : Analogous to Muon tracks in our case

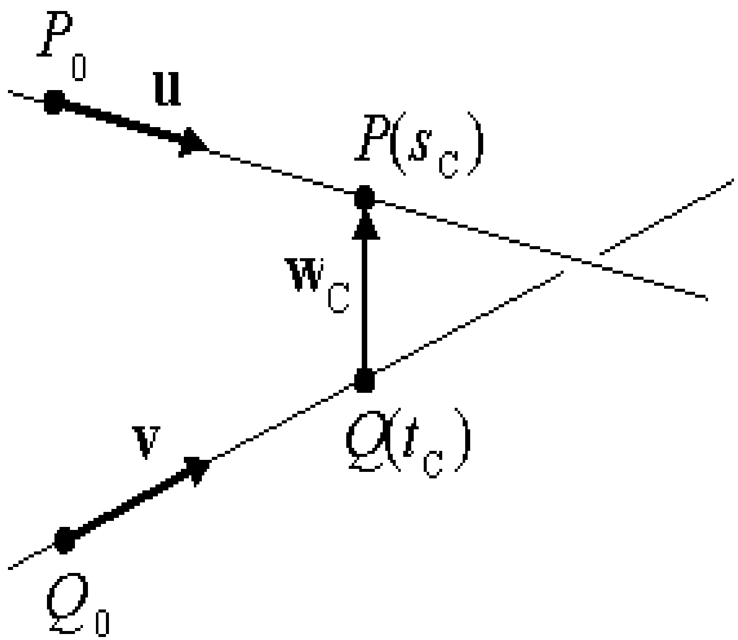
Let W be a vector between points on the two lines. We want to find the d(s,t) that has a minimum length for all s and t.

The distance 'd' is know as distance of closest approach.

The mid point of P and Q is said to be the Point of Closest Approach (POCA)

In muon tomography we assumed this POCA point to be the one where scattering has happened

This algorithm assumed single point scattering but completely ignores multiple scattering which is really happened.

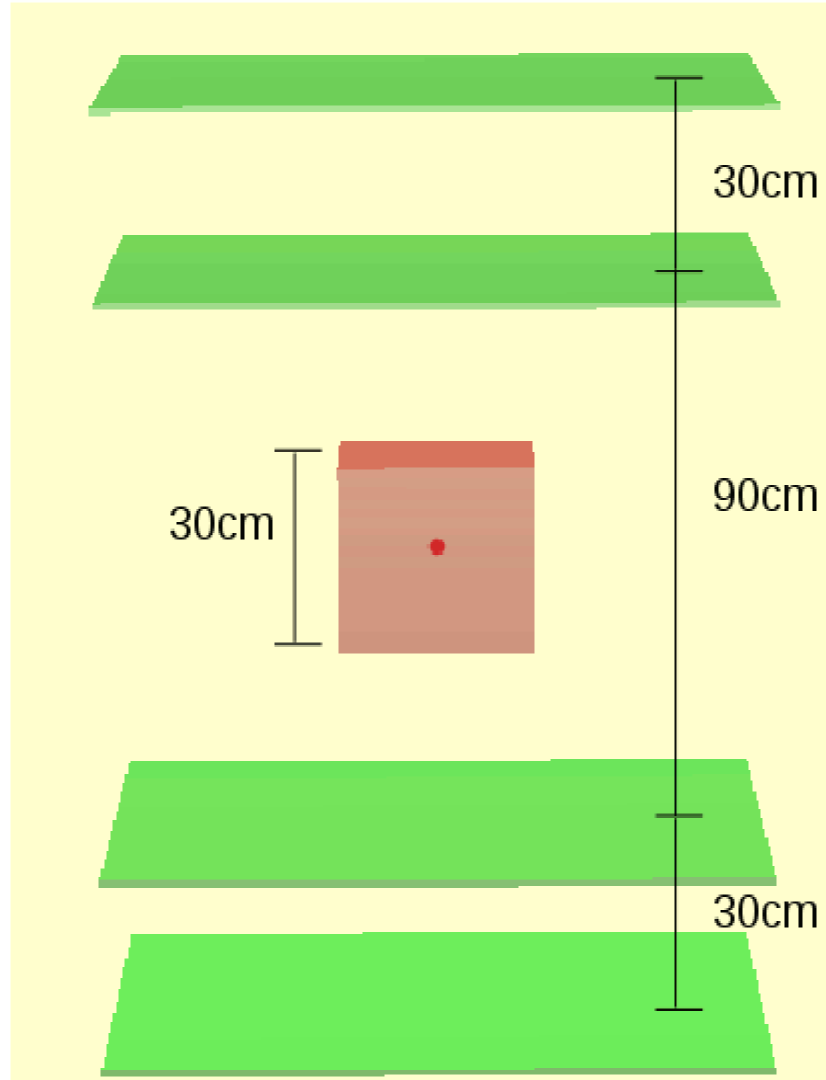


Simulation Setup to test Point of Closest Approach (PoCA) algorithm, With a Lead Cube of 30 cm as scatterer

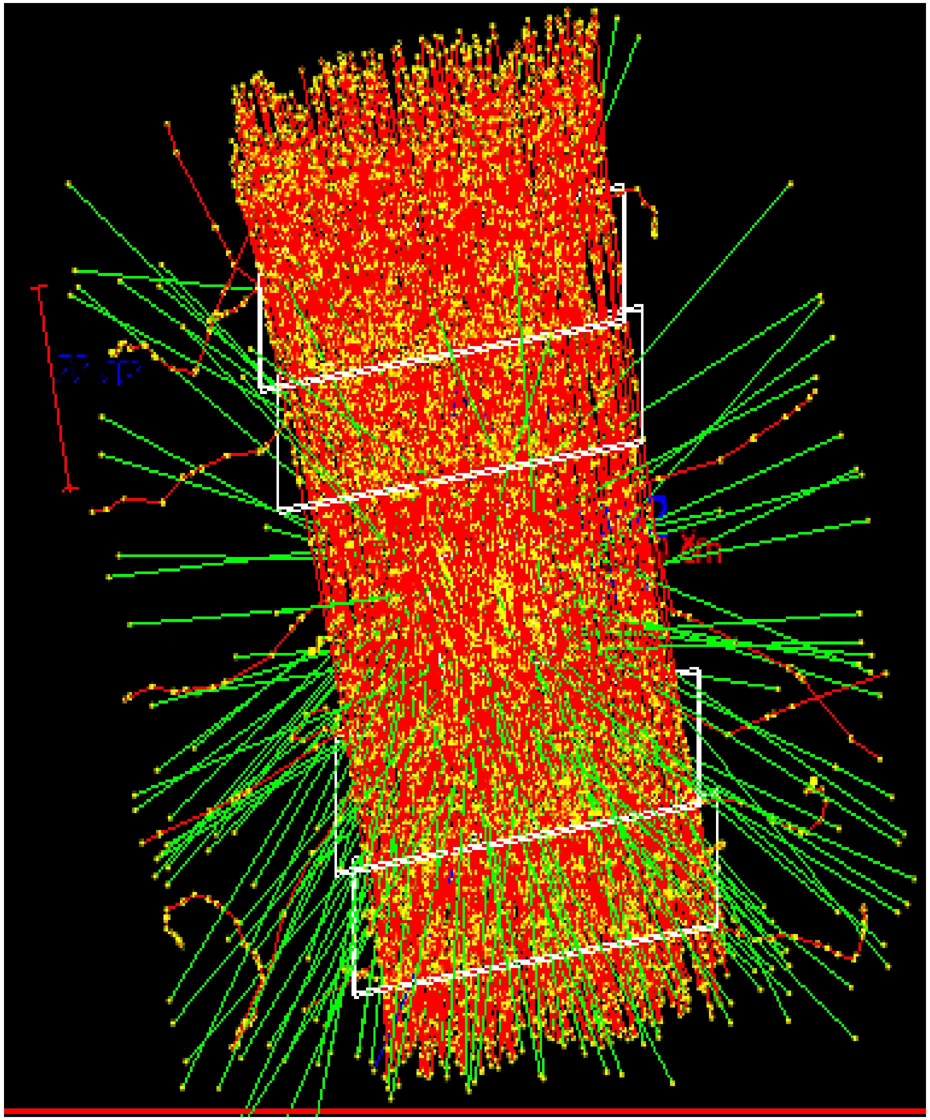
Number of Events acquired in Simulation : 20,000

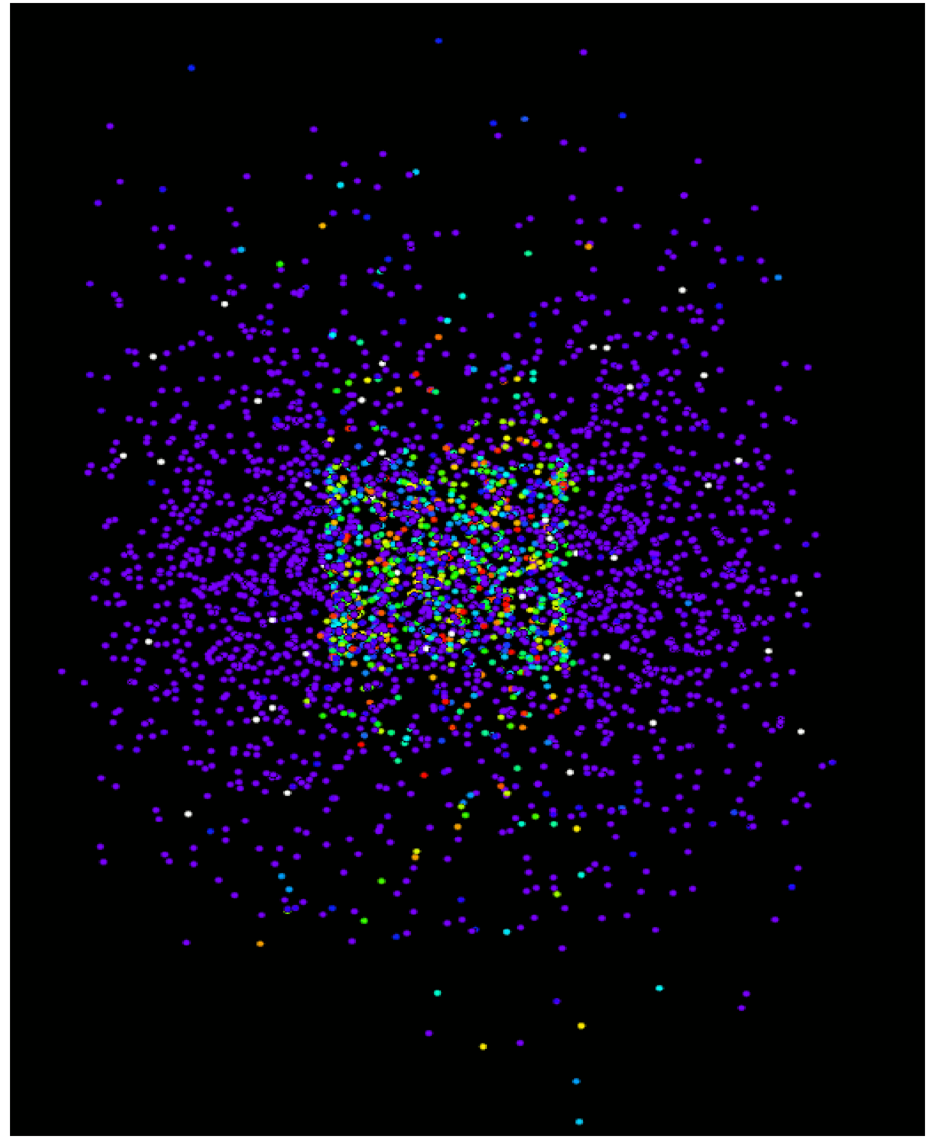
Scatterer : Cube of Lead of 30 cm side

Energy of injected muons : 2GeV

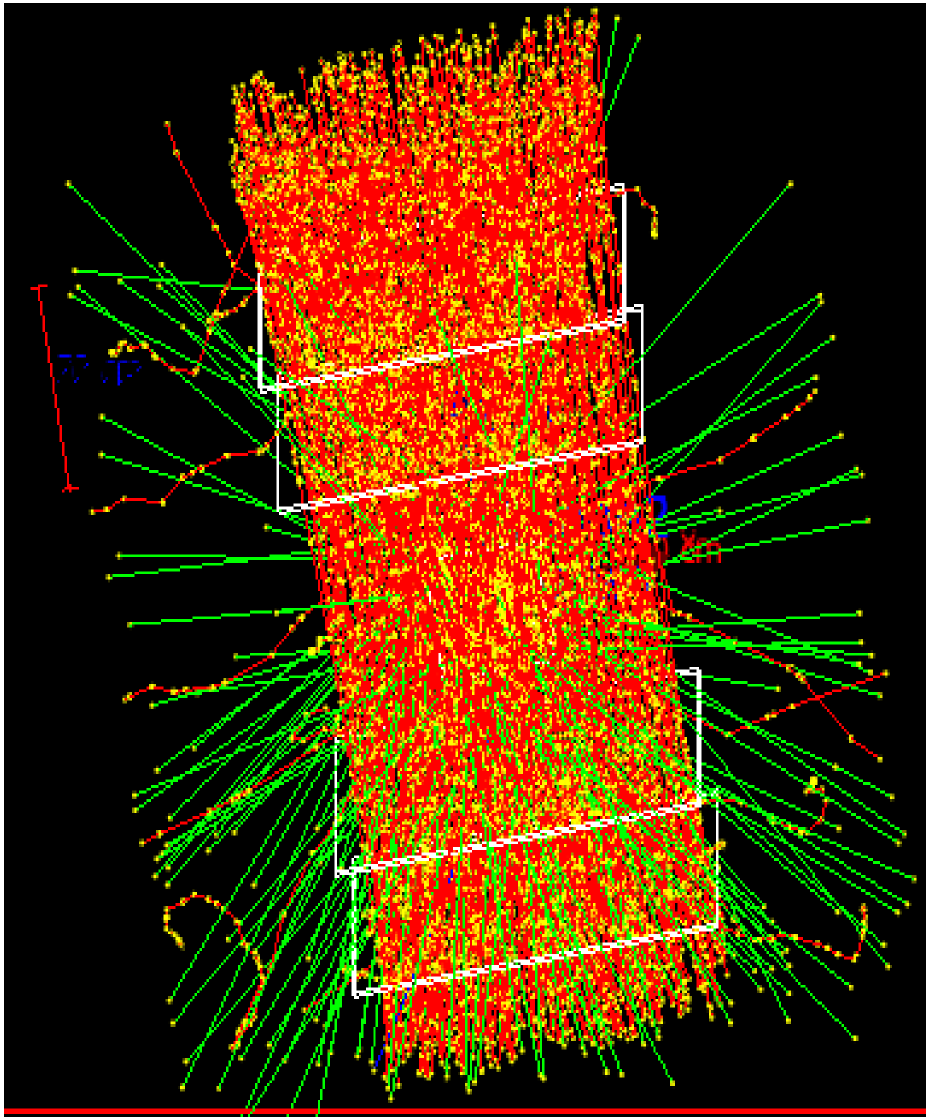


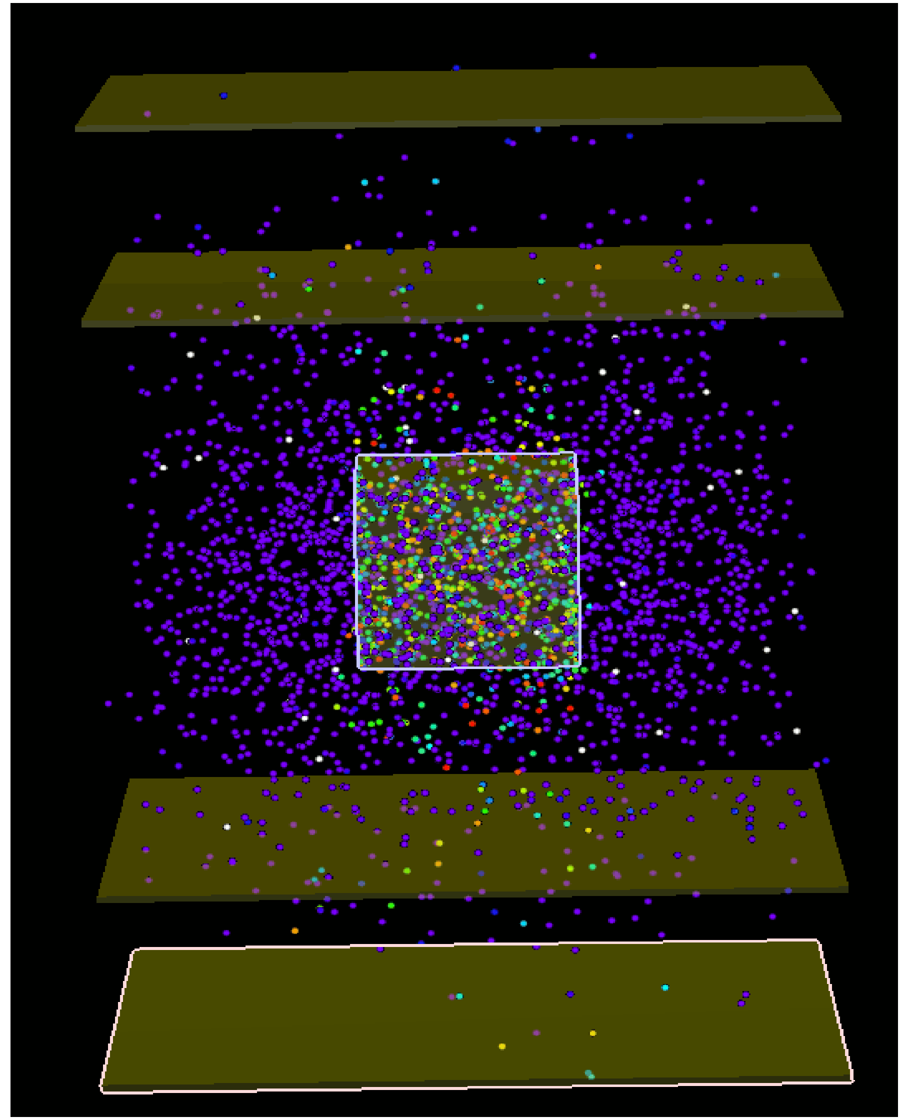
Reconstruction using PoCA point cloud from simulation data



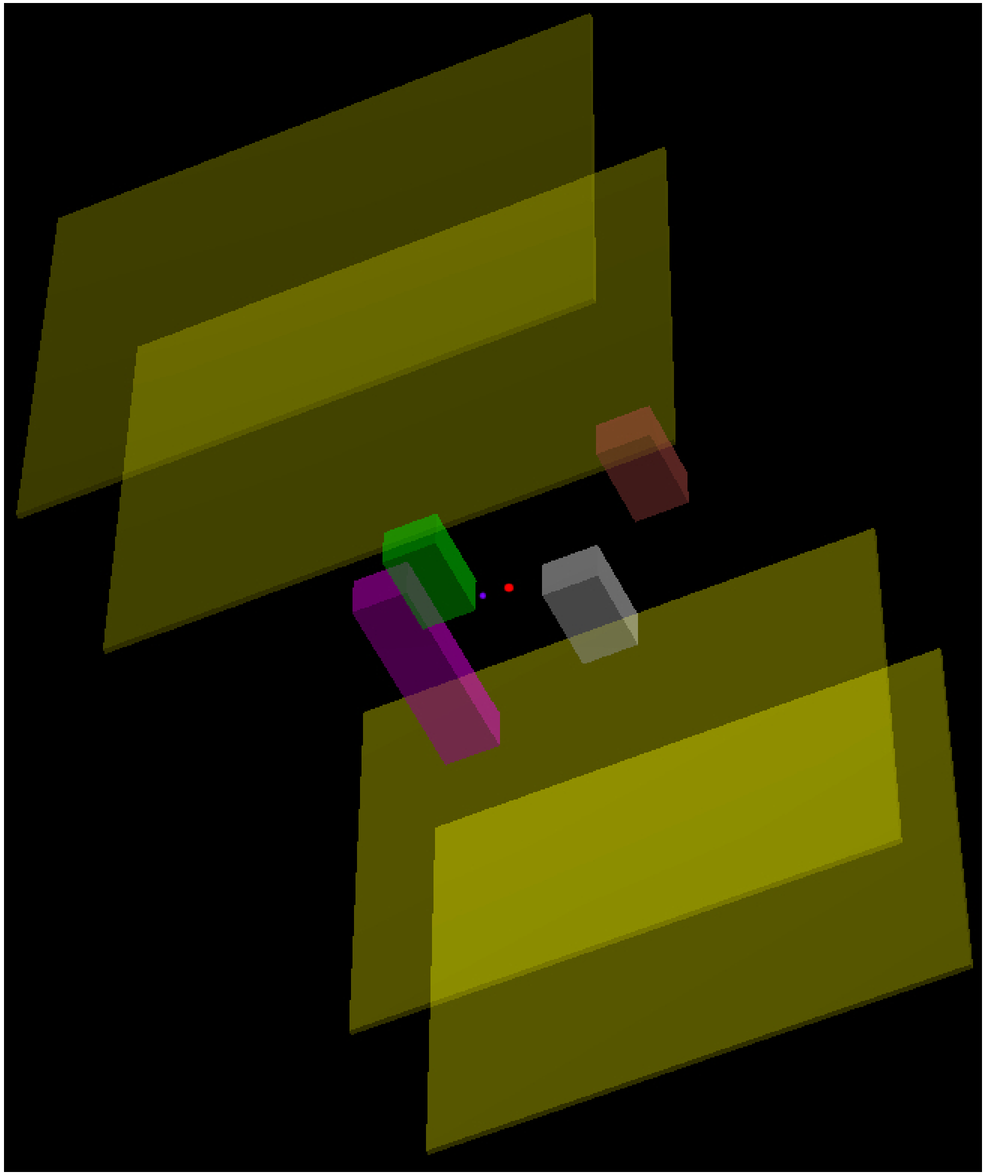


PoCA point cloud superimposed with Simulation Geometry

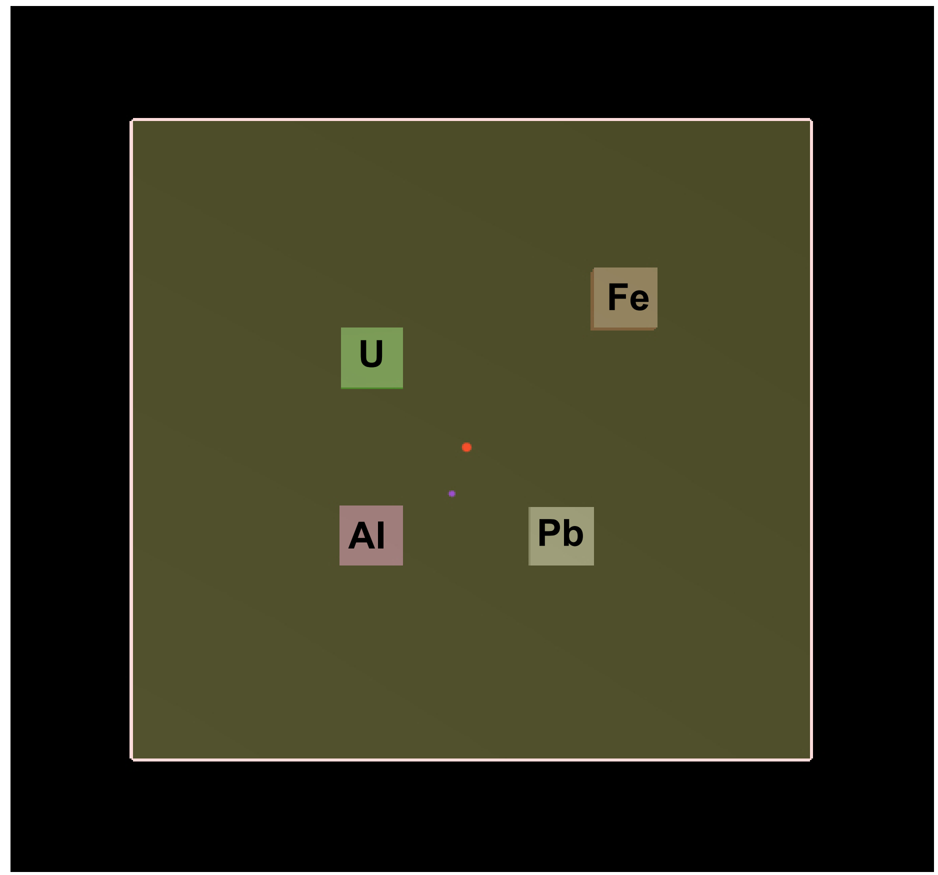




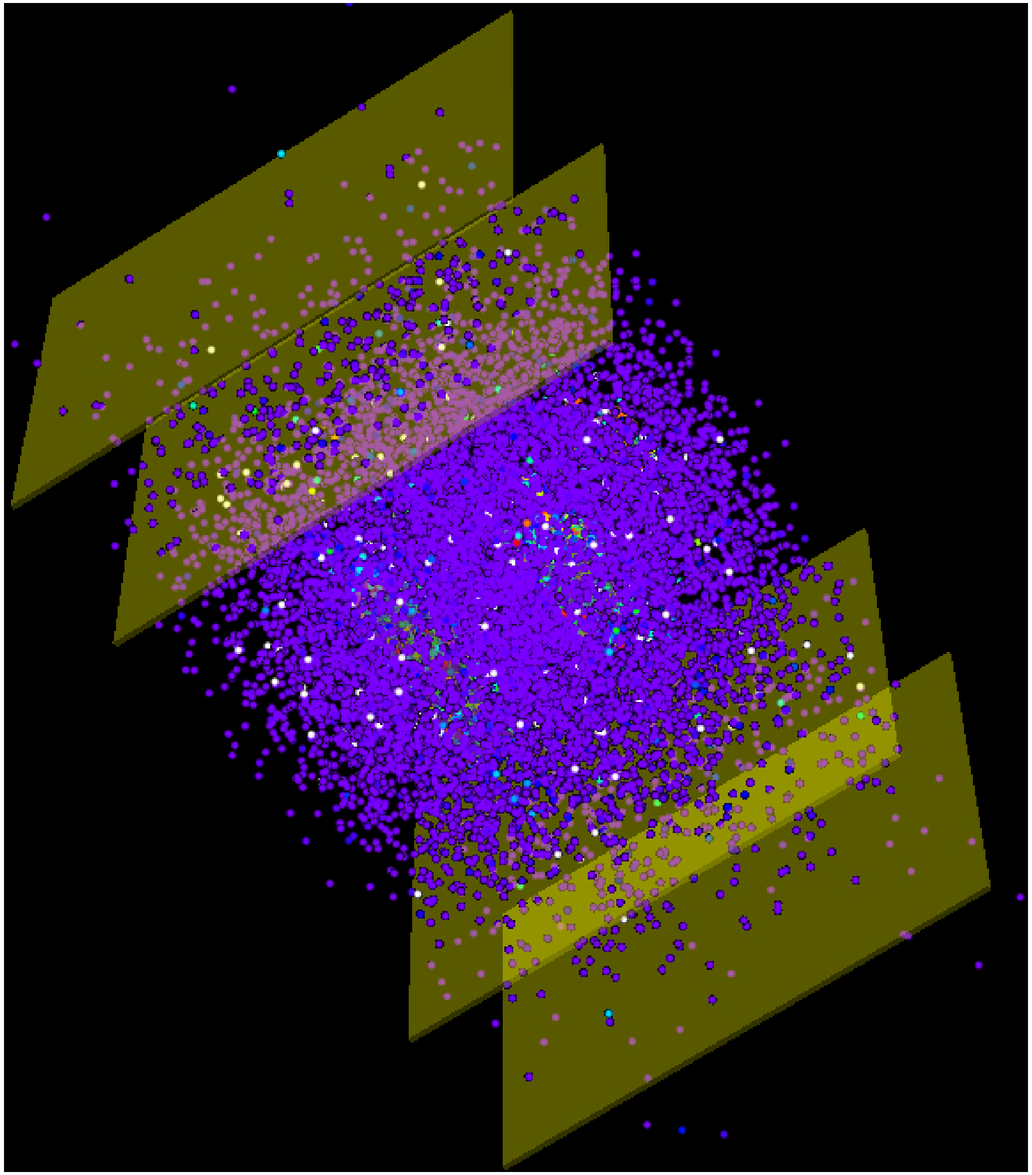
Simulation Setup with four different material



Four material of different dimension of box shape are kept at four different location between a pair of top detectors and a pair of bottom detectors



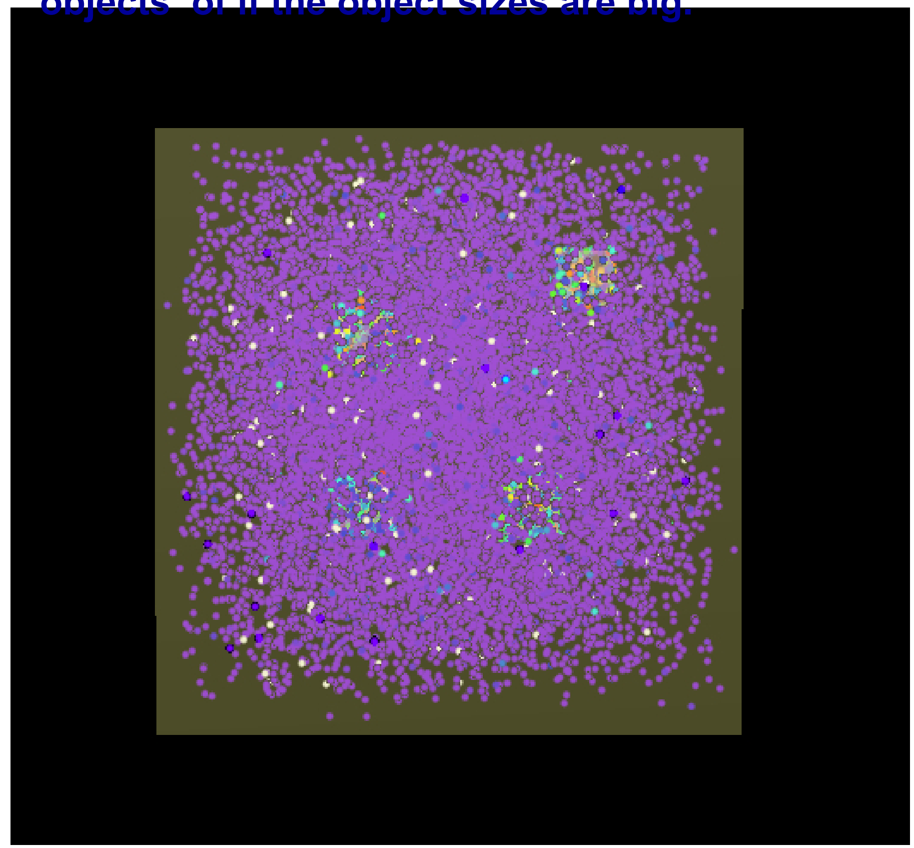
Results from Point of Closest Approach (POCA)



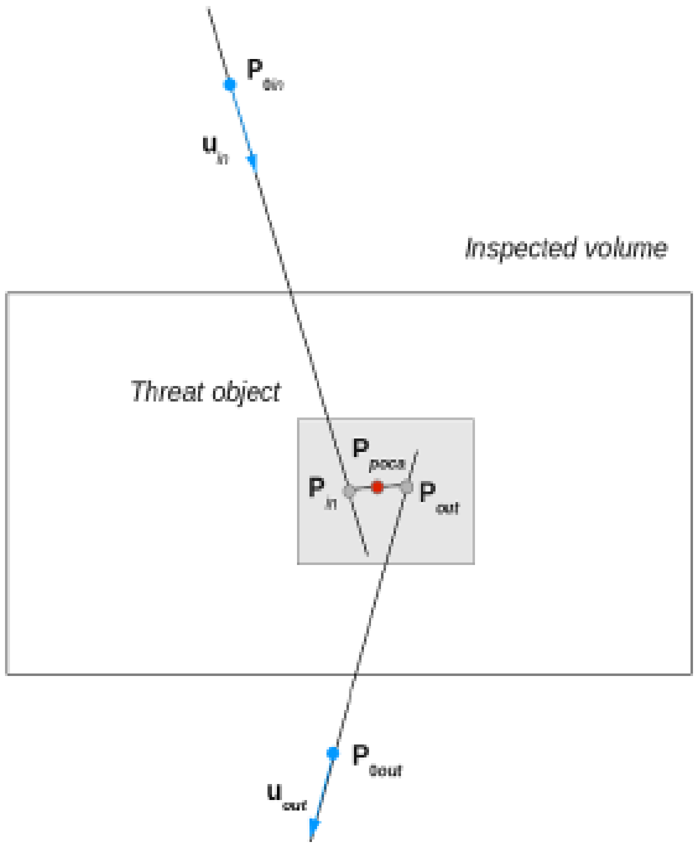
- Plotting all the Poca point for which the
- calculated scattering angle is less than 0.3 milliradian

- A lot of false positive signal

- Not suitable for scenario where there are multiple
- objects, of if the object sizes are big.



Conclusion from POCA Algorithm



Simplest approach, fast and easy to implement
Geometrical point of closest approach between incoming and outcoming tracks

$$\mathbf{P}_{poca} = \frac{1}{2}(\mathbf{P}_{in} + \mathbf{P}_{out})$$

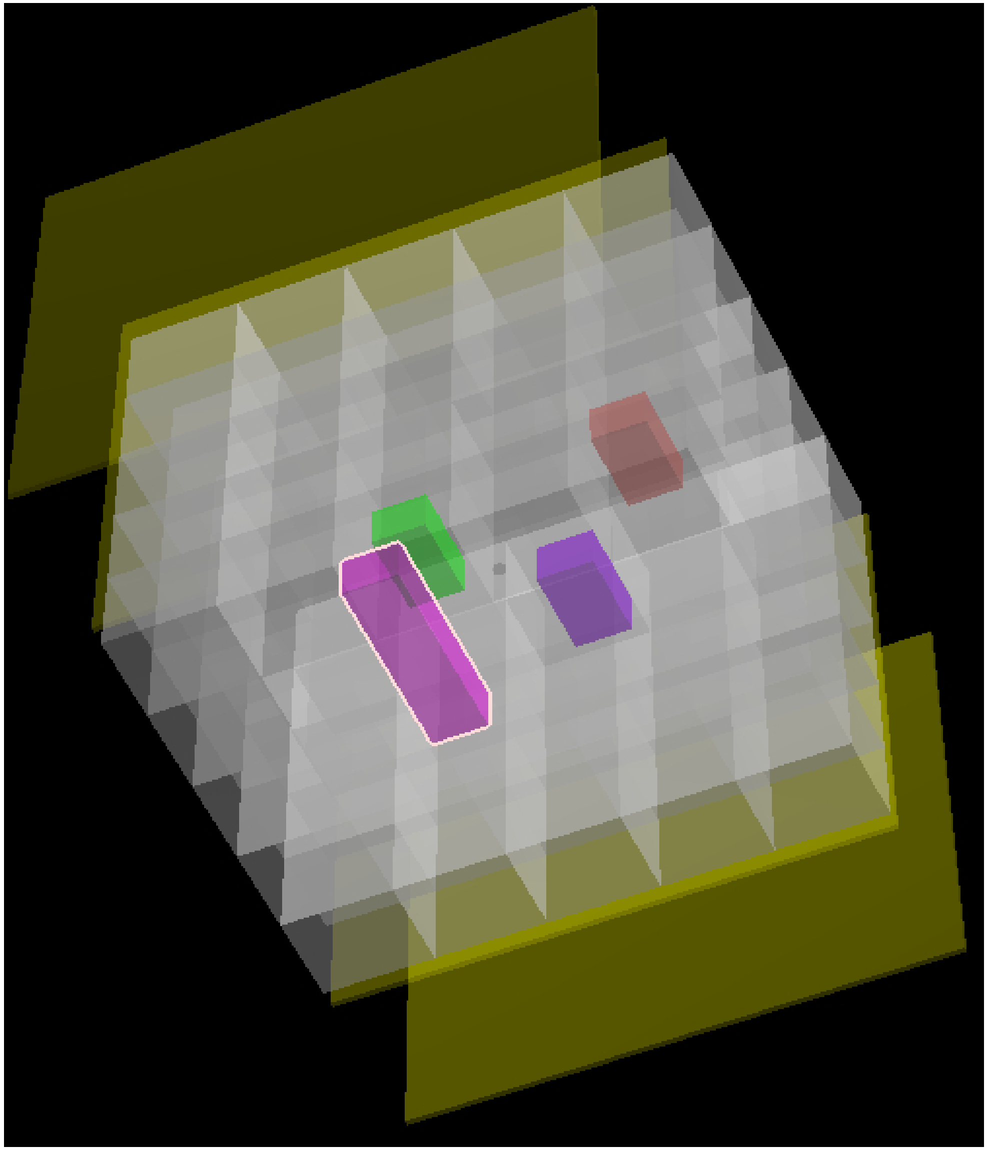
However:

- Neglects multiple scattering within the material
- Poor resolution images
- Critical behaviour for material located close to volume borders

Several improvements may be implemented:

- Filteration using Voxelization
- Density based clustering algorithms

Voxelization of Volume of Interest



- Dividing the volume of interest into small boxes
- called Voxels

- These Voxels can be very much helpful in
- removing the false positive POCA points.

- If a Voxel belong to some material then the
- scattering of Poca points that Voxel contains are
- correlated.

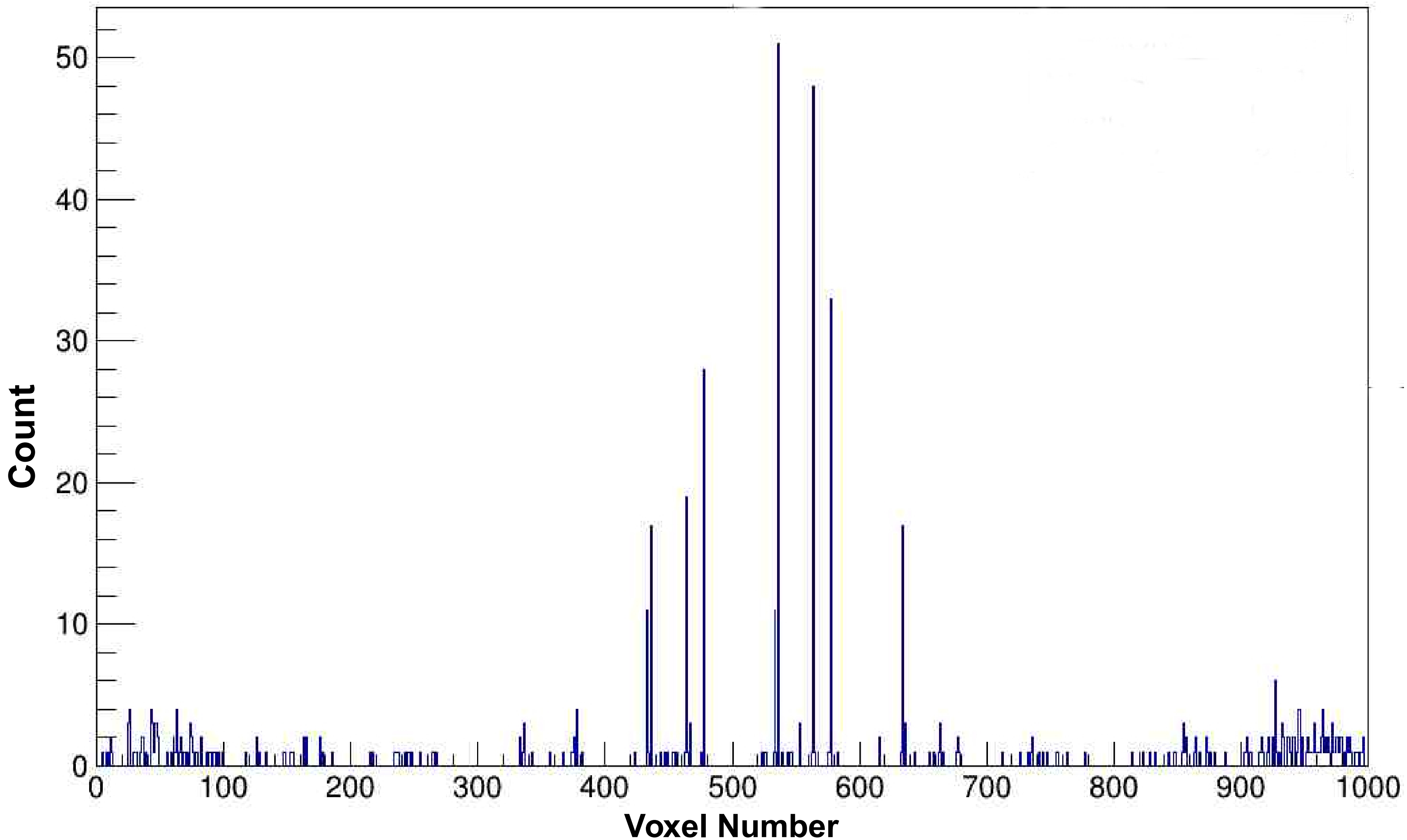
- If a Voxel contains false Poca Point then those
- Poca Points are uncorrelated.

- Another simple criteria to detect if the Poca
- points that Voxel contains are genuine or not is
- the Threshold on the number of Poca Points (N)
- that a voxel cantains.

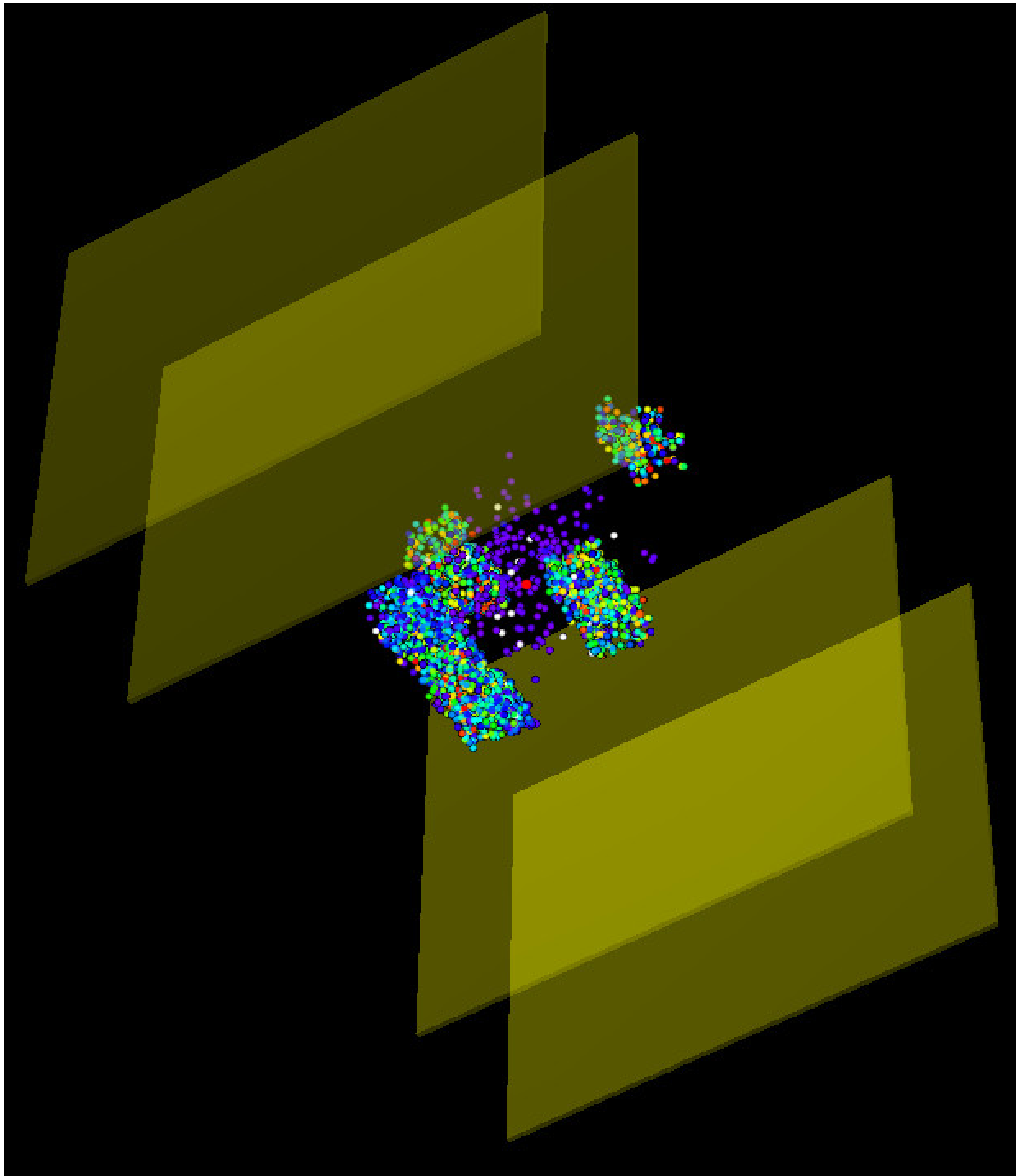
- If N < threshold value then the Poca Points are
- not genuine and may be rejected

- Big Question : How to select the threshold
- value ??

One Dimensional Histogram of counts of POCA points in Voxels



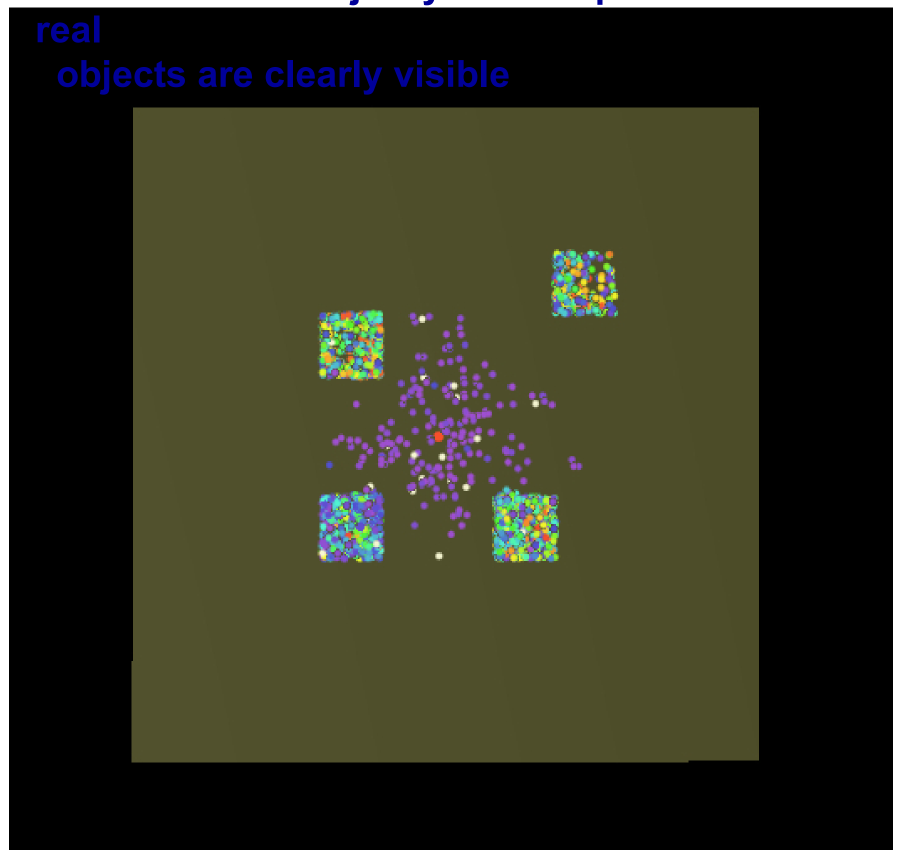
Filteration of POCA output using Voxelization



- Output of filteration algorithm applied on POCA
- points

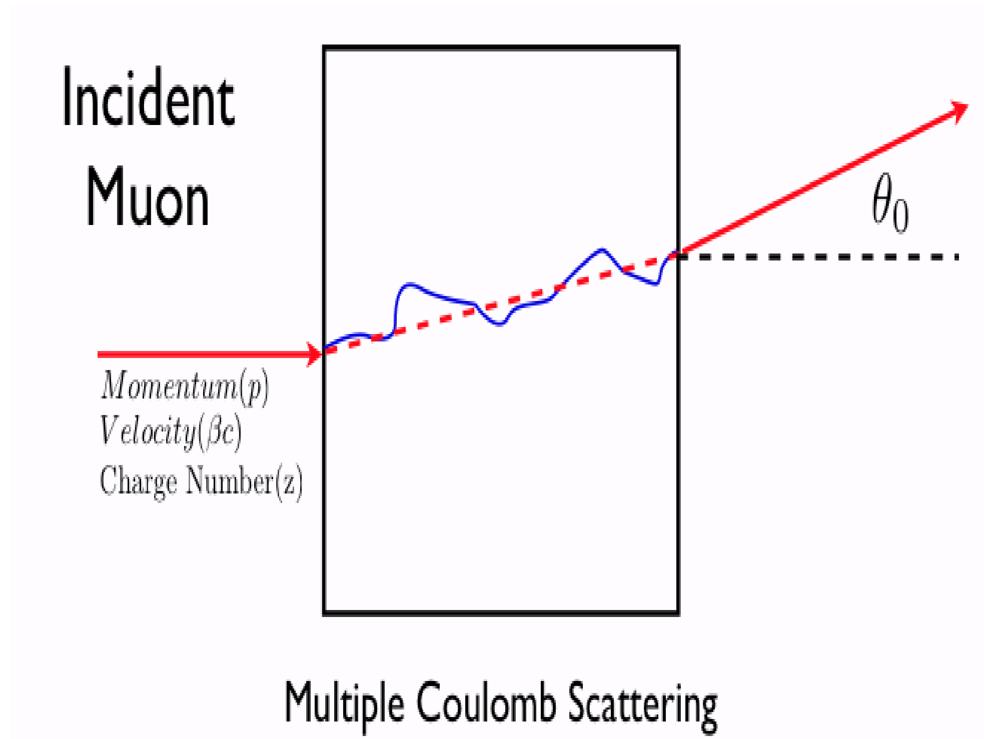
- Filteration is done by voxelizing the volume
- between 2nd and 3rd detector where objects under
- test are placed

- This removes majority of false positive and the real
- objects are clearly visible



POCA Pro's and Con's

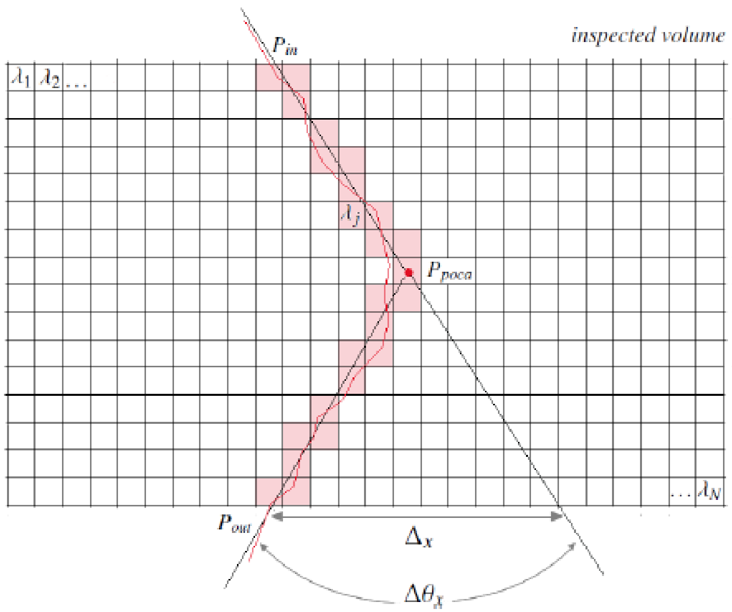
- *Pro's*
  - *Fast and efficient*
  - *Accurate for simple scenario's*
- *Con's*
  - *No Physics: multiple-scattering ignored*
  - *Deterministic*
  - *Unscattered tracks are not used*



What we achieved !!

- Till now we have seen what is POCA
- How it works.
- What are the drawbacks
- The main drawback : Its NOT using the underlying physics, purely geometrical.
- But when accompanied with Voxelization and Filteration, it works nicely and give us a
- very course reconstructed image.
- With this we can only reconstruct very approximate shape, and can only pin point the
- location of object under test.
- We cannot differentiate between object materials.
- But the target of Muon Tomography is to reconstruct the image as well to give some
- information about object material.
- That is possible when we include underlying physics in the algorithm.
- In this case the underlying physics is the Multiple Scattering.

Maximum Likelihood Expectation Maximization (MLEM)



Better statistical treatment of scattering processes by a log-likelihood method
Volume to be inspected divided into voxels
Scattering density defined for each voxel

Iterative est

$$\lambda(X_0) = \left(\frac{15\ \mathrm{MeV}}{p_0}\right)^2 \frac{1}{X_0}$$

g criterion

ML-EM Algorithm

(adapted from Schultz et al., TNS 2007, & Tech Reports LANL)

(1) gather data: (ΔΘ, Δ, p): scattering angles, displacements

(2) estimate track-parameters (L, T) for all m

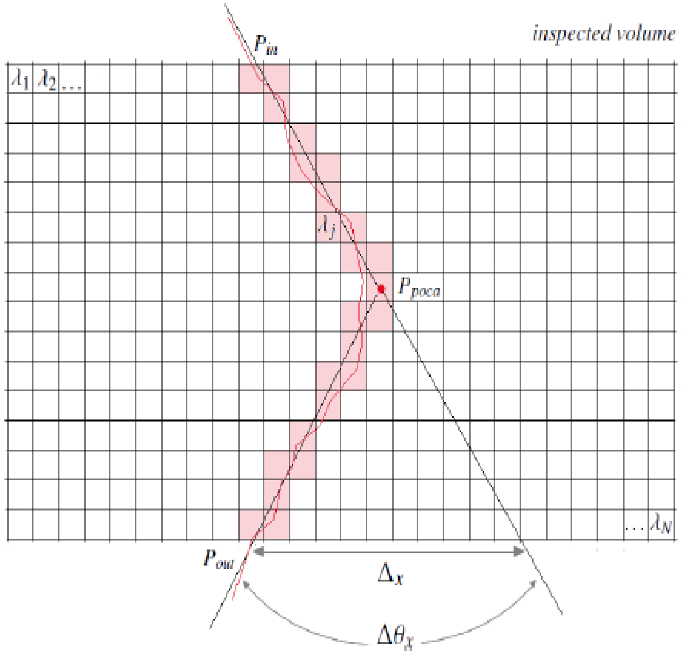
(3) initialize λ (arbitrary small non-zero numl

(4) for each iteration k=1 to I (or, until λ stabilize

(i) for each muon-track i=1 to M

Compute C_{ij}

(ii)for each voxel j=1 to N



(5) return λ

MLEM Pro's and Con's

Pro's:

- **Uses underlying physics of process involved**
- **Can give more accurate information about the composition**
- **of object under test.**

Con's

- **Very slow for complex scenarios**

Challenges

Reconstruction using MLEM need smart data structures for speed up and better memory usage

Possible options:

- **Usage of Vector Architecture of CPUs**
- **Using GPUs to do the processing**

Overall Status of Project

- **Hardware**
  - **Four Resistive Plate Chamber (RPCs) are already assembled.**
  - **Data taking from these RPCs are going on.**
  - **Once all the four RPC are tested then minimum hardware setup is ready to give us the incoming and outgoing muon track, and these tracks will be consumed by image reconstruction algorithm.**
- **Software**
  - **Completely written in C++.**
  - **Depending on ROOT for data analysis.**
  - **Visualizer depends on EVE package of ROOT.**
  - **Visualization is done using OpenGL.**
  - **Track reconstruction from data is done, tested with both simulated and real data**
  - **Preliminary PoCA implementation is done.**

Conclusion

- Muon tomography is very promising technique for the detection of high Z materials.
- Simulations are done (using Geant4) to understand the scattering pattern for different material.
- Simulated data is used to discriminate the material and to test reconstruction algorithm.
- First basic version of PoCA is already implemented, and results are encouraging.

Outlook

- Simulation program will be modified to generate the data much closer to real data.
- PoCA output contains a lot of false positive, so we have to work on removal of these false positive.
- We will try PoCA reconstruction on the scatterers of different shapes and sizes.
- There is a need of some good clustering and filteration algorithm, that can improve PoCA results.
- Parallely we had also started the study of MLEM algorithm to reconstruct better image.
- We will assemble the fourth RPC very soon.
- Then we will try to compare the experimental results with simulated results from simulation setup of 4 RPCs