Muon tomography with Trasgos: MuTT

Jose Cuenca (UZH)

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What is it?

Muon tomography is a technique that uses muons to produce 3D-images of volumes

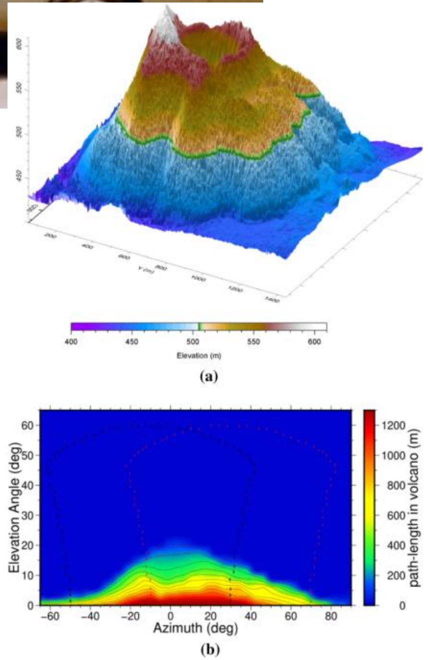
Obvious, right?
But wait…let's distinghish between:

1. Muon **radiography:** measurement of the muons that survive after crossing a material.

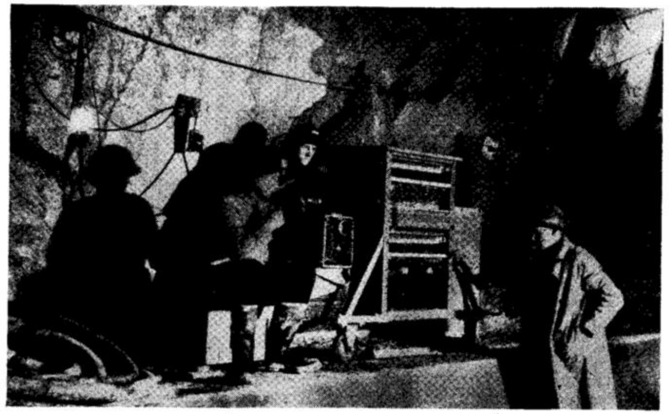
2. Muon **tomography:** measurement of the scattering of the muons in a material.

(This is not new)

L. Alvarez (1970)



Cheng, YP., Han, R., Li, ZW. *et al. NUCL SCI TECH* **33**, 88 (2022)



Commonwealth Engineer, July 1, 1955 455

Cosmic Rays Measure Overburden of Tunnel

● Fig. 1—Geiger counter "telescope" in operation in the Guthega-Munyang tunnel. From left are Dr. George and his assistants, Mr. Lehane and Mr. O'Neill.

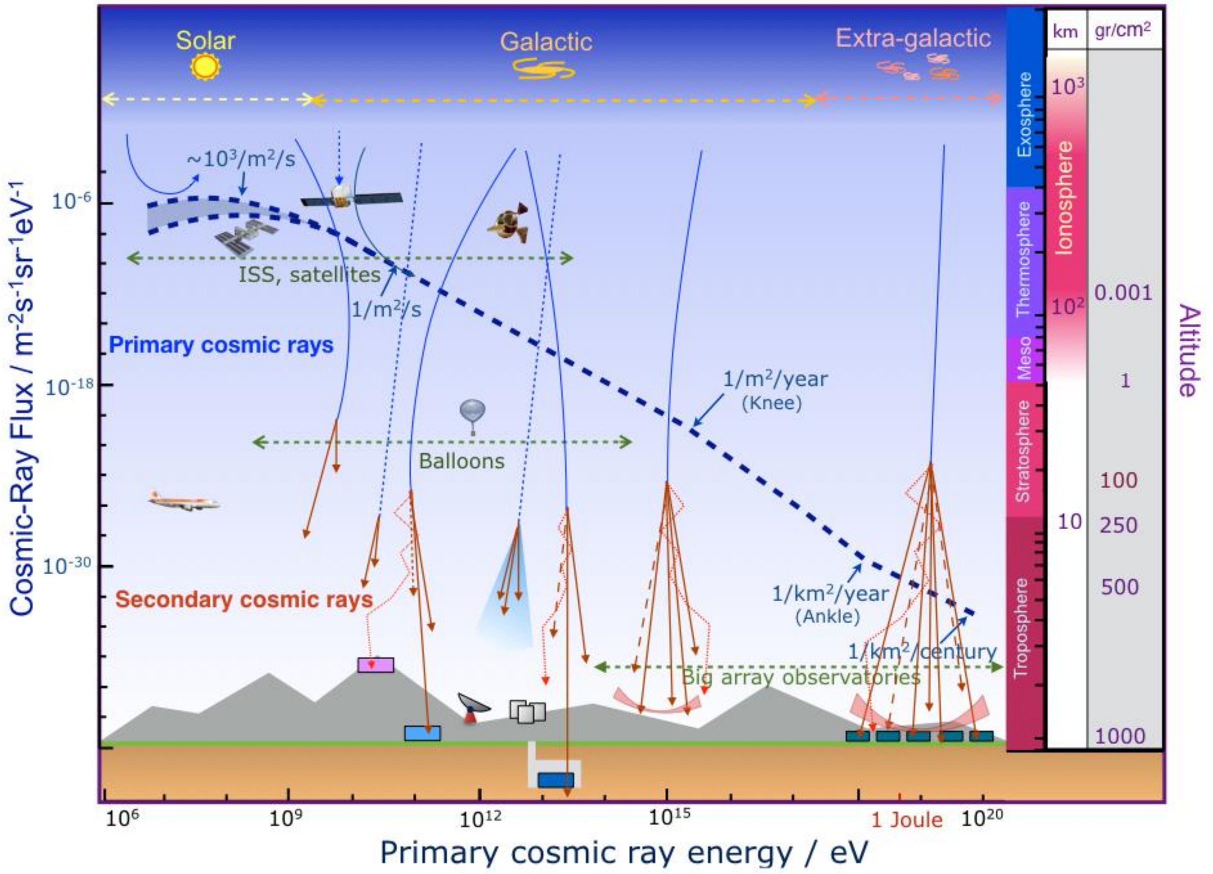
Geiger counter telescope used for mass determination at Guthega project of Snowy Scheme . . . Equipment described

By Dr. E. P. George*
University of Sydney, N.S.W.

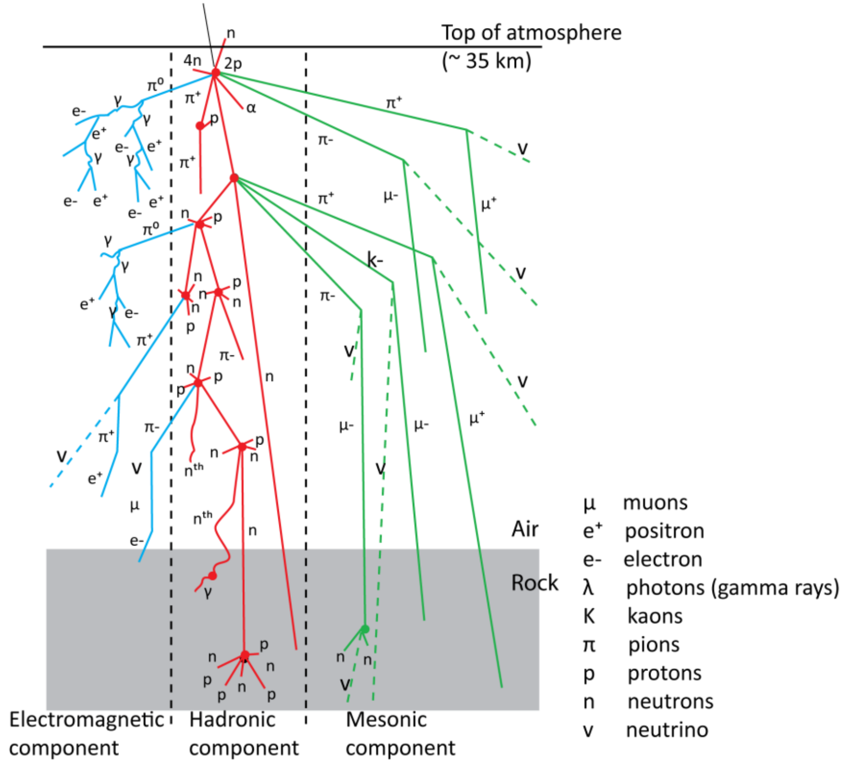
E.P. George (1955)

It works nice for big volumes

Cosmic rays



Secondary particle production in atmosphere and rock
After Gosse and Phillips, 2001

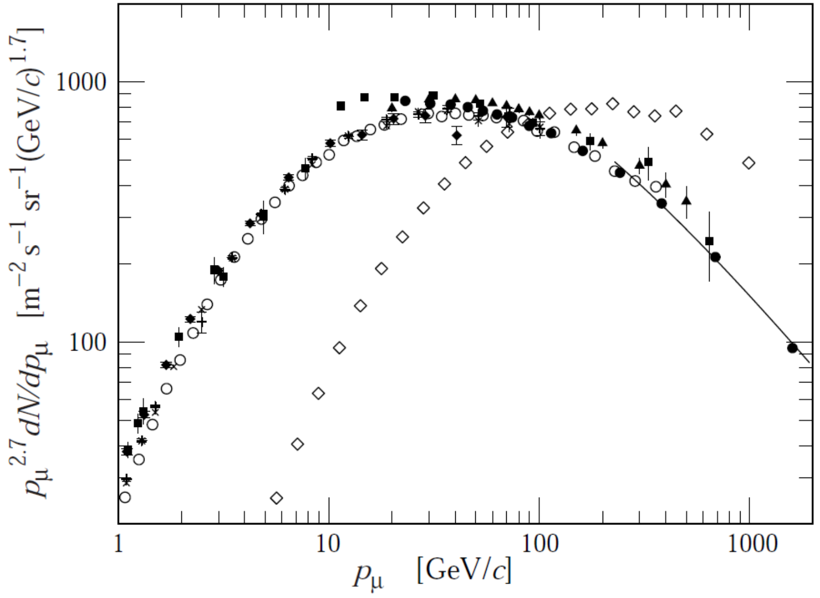


Cosmic muons

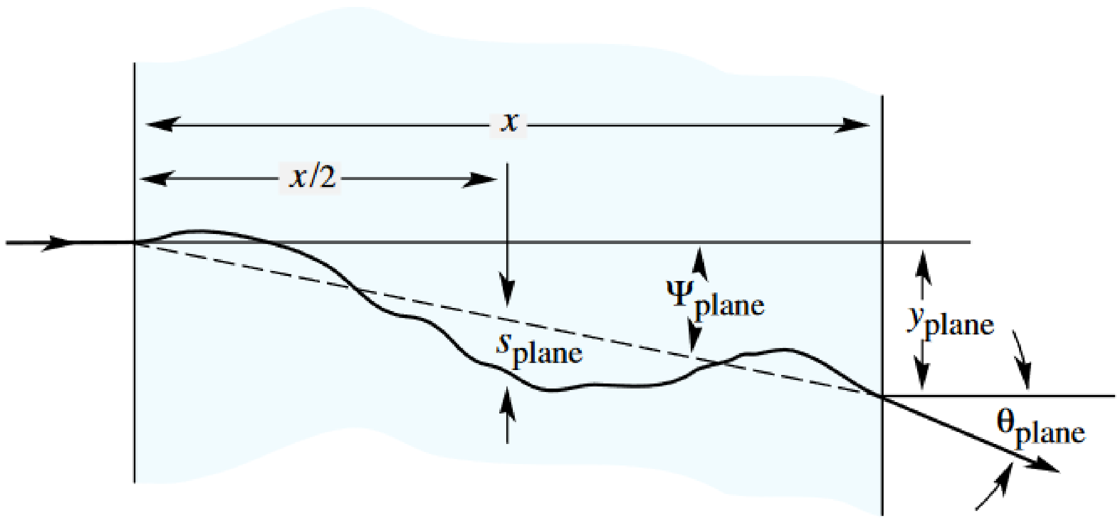
- At sea level, 1 muon/min/cm^2
- Energy of 3-4 GeV.
- Angular distribution follows the $\cos^2(\theta)$ law.

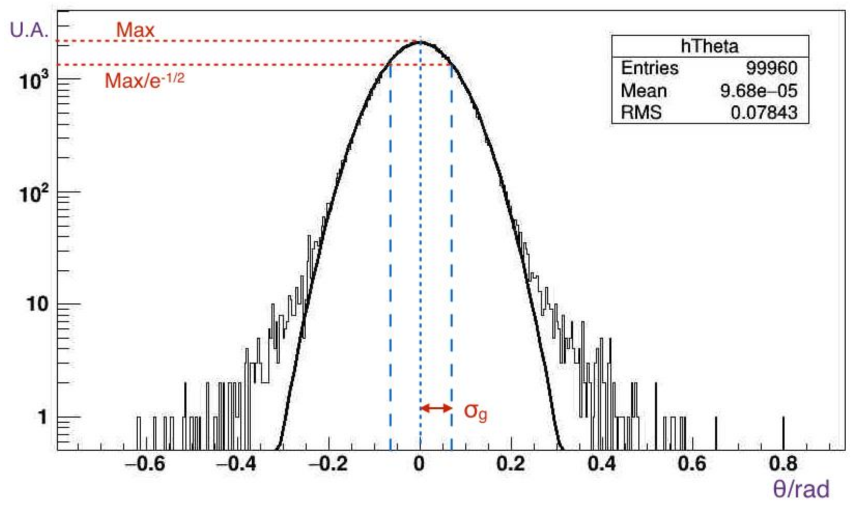
Mean Flux of Cosmic Rays at the Sea Level ($m^{-2}s^{-1}sr^{-1}$)
(Adapted from: Kaye&Laby. Tables of Physical and Chemical constants, www.kayelaby.npl.co.uk)

E(GeV)	Muons				Electrons	Photons	Protons	Neutrons
	Flux	IntFx./ %	DiffFx./%	Lead Range/cm				
0.1	99	1	1	4.8	6.0	8	1.9	10*
0.2	97	3	2	12	3.0	3.5	1.5	-
0.5	86	14	11	34	1.0	1.1	0.9	1.5
1	69	31	17	69	0.4	0.4	0.5	0.7
2	46	54	23	1.3E2	0.1	0.1	0.25	*) Estimated theoretical values
5	20	80	26	3.1E2			0.1	
10	9	91	11	5.8E2	0.02	0.02	0.03	
20	3	97	6	1.1E3				



How does it work?





Multiple Coulomb Scattering (MCS):

- The angular distribution is Gaussian just in the central part.

$$\frac{dN}{d\theta_x} = \frac{1}{\sqrt{2\pi}\theta_0} e^{-\theta_x^2/2\theta_0^2}$$

$$\theta_0 = \frac{13.6MeV/c}{p\beta}\sqrt{\frac{x}{X_0}}$$

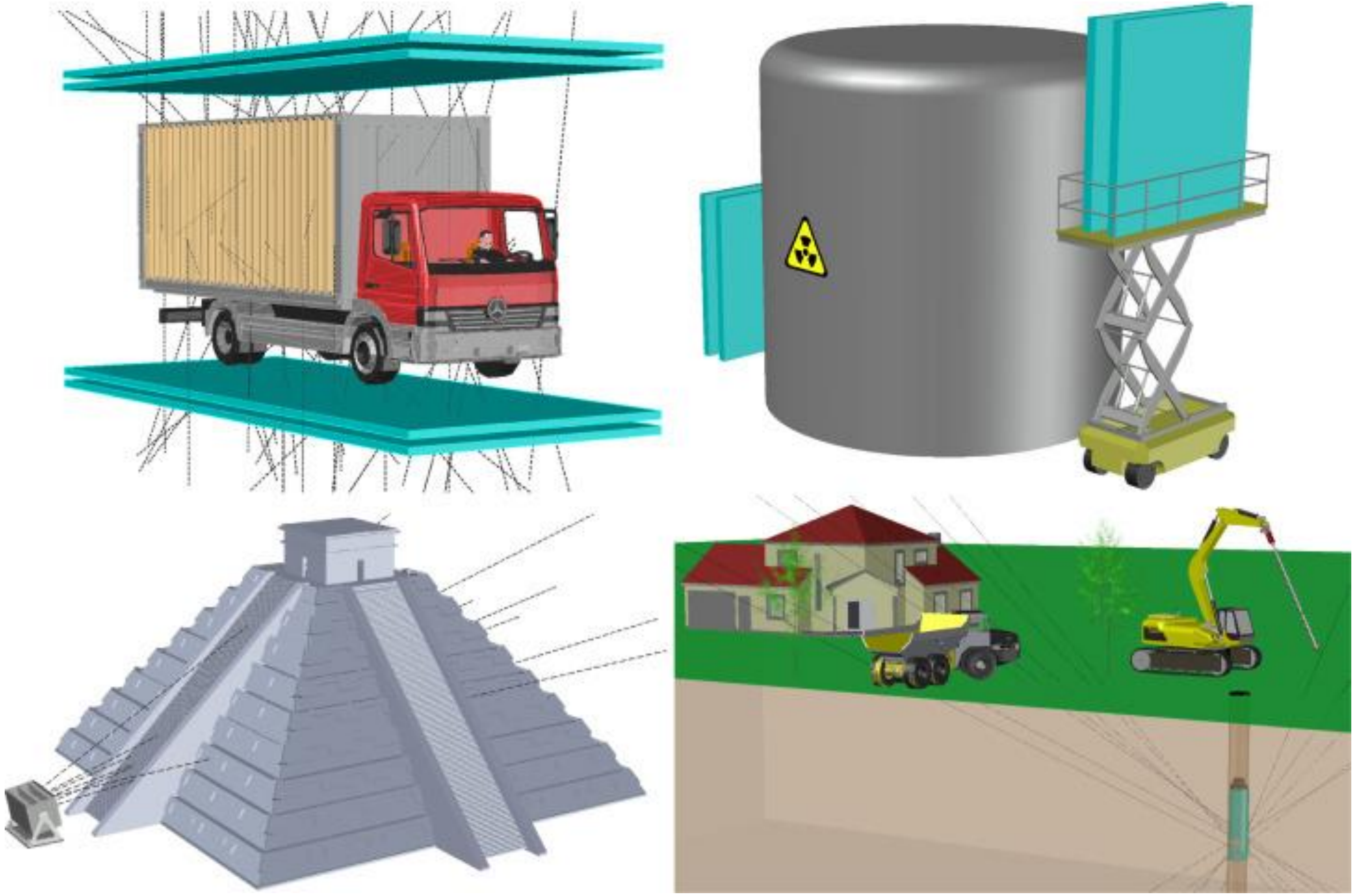
The radiation lenght:

$$X_0 = \frac{716.4\ g/cm^2 A}{\rho Z(Z+1)\ln(\frac{287}{\sqrt{Z}})}$$

A: mass number
Z: atomic number
ρ: material density

What is the usefulness of this?

- Geological studies.
- Nuclear waste imaging.
- Imaging of the core of nuclear reactor (for example, after the Fukushima accident)
- Homeland security: scan of cargo containers against illegal transport of radioactive materials.



The strategy

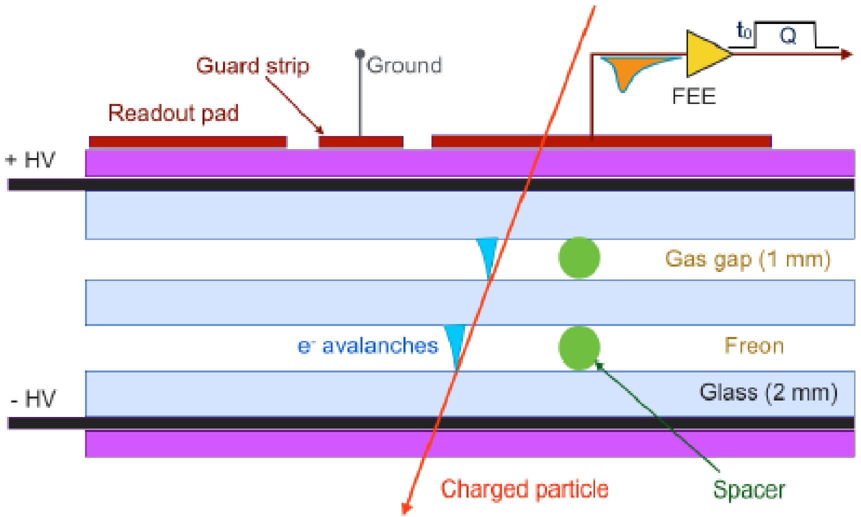
- Design a prototype to be used in ports.
- Easy to operate.
- Fast scanning capability.
- Good reconstruction of the tracks.

For our prototype, we used:

- Resistive Plate Chambers (RPCs)
- Two detectors on top, two on the bottom.
- TimTrack algorithm.

Resistive Plate Chambers

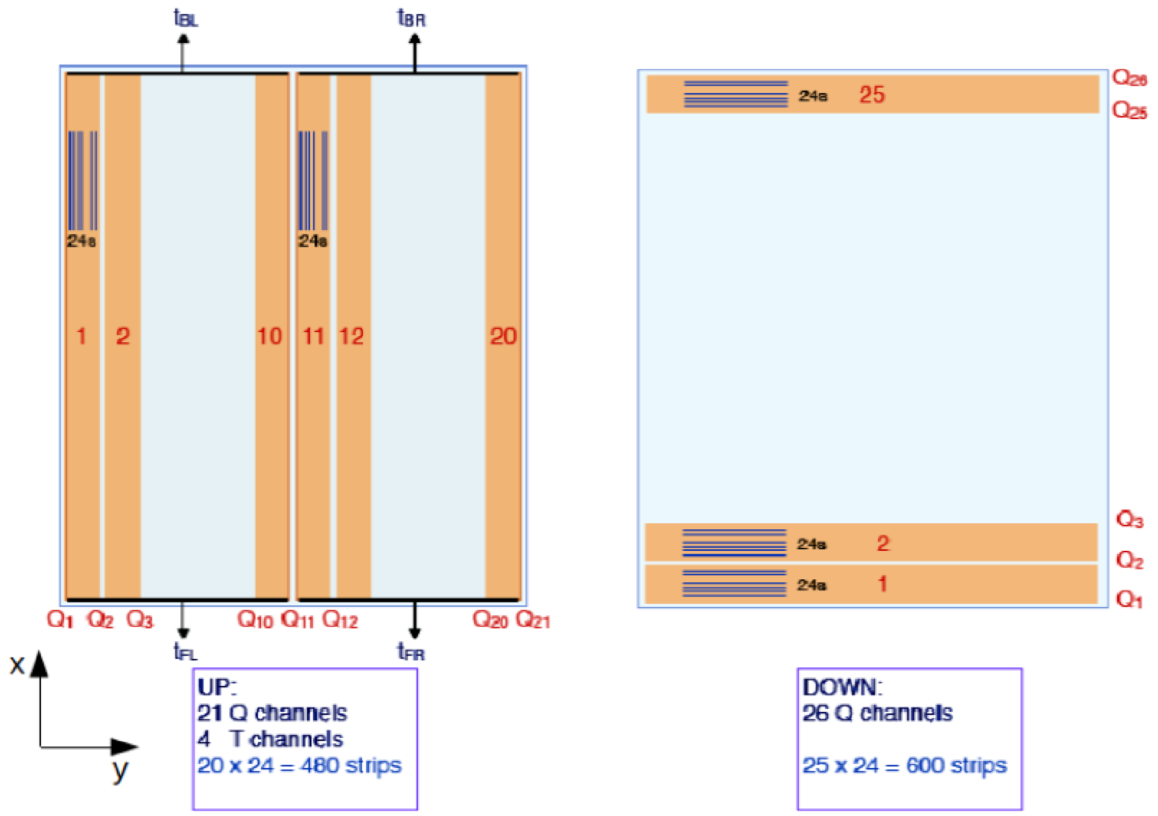
- Gaseous detectors developed in the 80s.
- Traditionally, they have been used as counter trigger detectors (for example at ATLAS)
- They can cover large detection areas with a relative low cost per channel.
- BUT: nowadays RPCs reach nanosecond resolution and can be used as tracking detectors.



This is the working principle…but there are more options:

- Pads
- Strips
- More gaps
- Other materials

The muTT detector



Medium	Z-thickness (mm)
Aluminium box top side	3,000
Polyethylene Foam	3,100
FR4 layer	1,500
Copper	0,030
Polycarbonate box top side	1,000
Acrylic electrode layer	0,010
Glass	1,000
R-134a gap	0,300
Glass	1,000
R-134a gap	0,300
Glass	1,000
R-134a gap	0,300
Glass	1,000
R-134a gap	0,300
Glass	1,000
R-134a gap	0,300
Glass	1,000
R-134a gap	0,300
Glass	1,000
Acrylic electrode layer	0,010
Polycarbonate box bottom side	1,000
Copper	0,030
FR4 layer	1,500
Copper	0,030
Aluminium box bottom side	3,000
Aluminium base	3,000
Sum	**26,010**

They were designed and produced by LIP-Coimbra

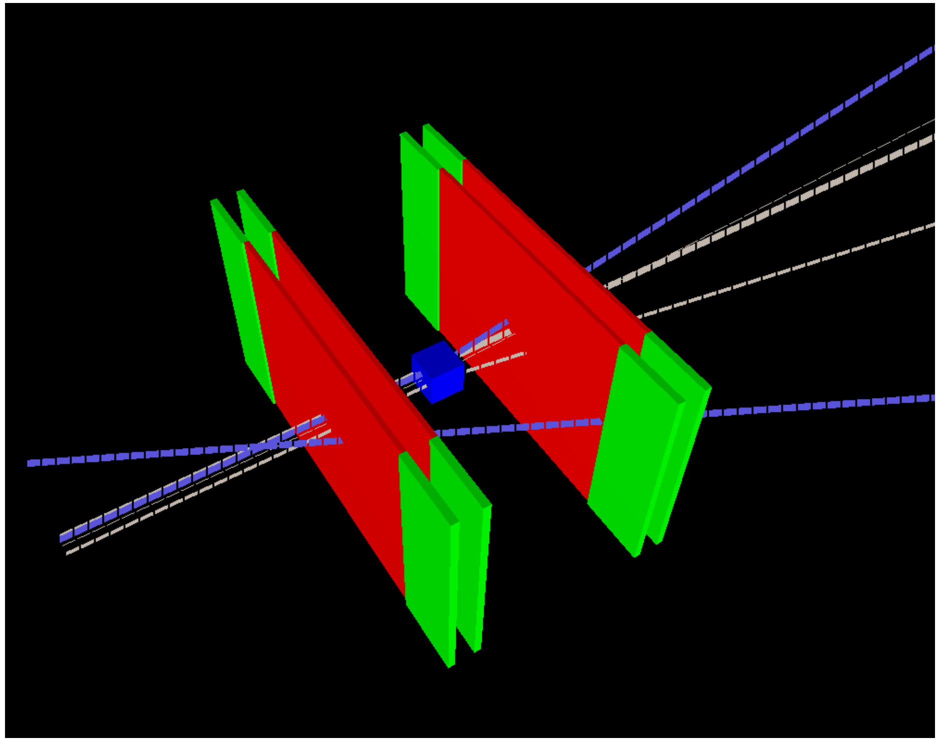
Time resolution: 90 ns
x,y resolution: 1.2 mm

Simulations

- Geometry (detectors, targets)
- Tracking.
- Cosmic rays: CRY library.

This was done in the EnsarRoot framework.

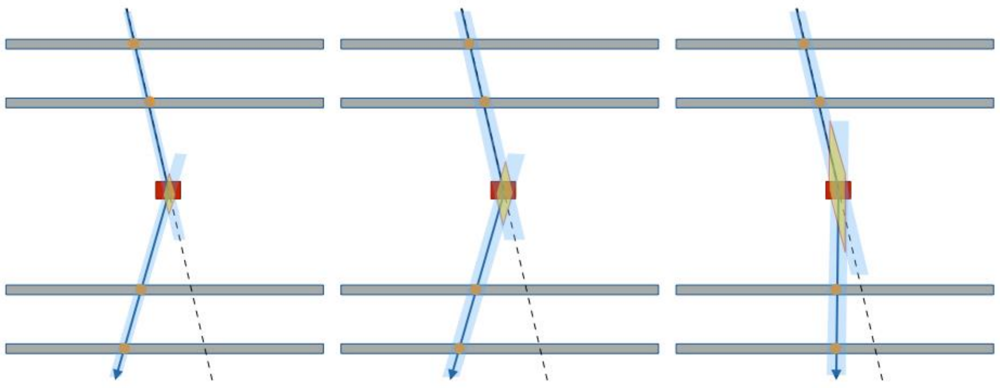
(Code here)



The tracking

There are several algorithms in the market. We compared two of them:

1. POCA (Point Of Closest Approach): it is easy to implement but it has high uncertainty.



2. TimTrack: it is basically the least squares method but with a fancy name.

A couple of words about TimTrack

The method needs several ingredients:

1. Experimental data. They are stored in a vector called *data* (d)
2. A set of parameters. They are in a vector named *saeta* (s)
3. A model connecting both spaces: d=m(s)

$$S = \sum_{i}^{n_d} \left(\frac{d_i - m_i(\mathbf{s})}{\sigma_i} \right)^2$$

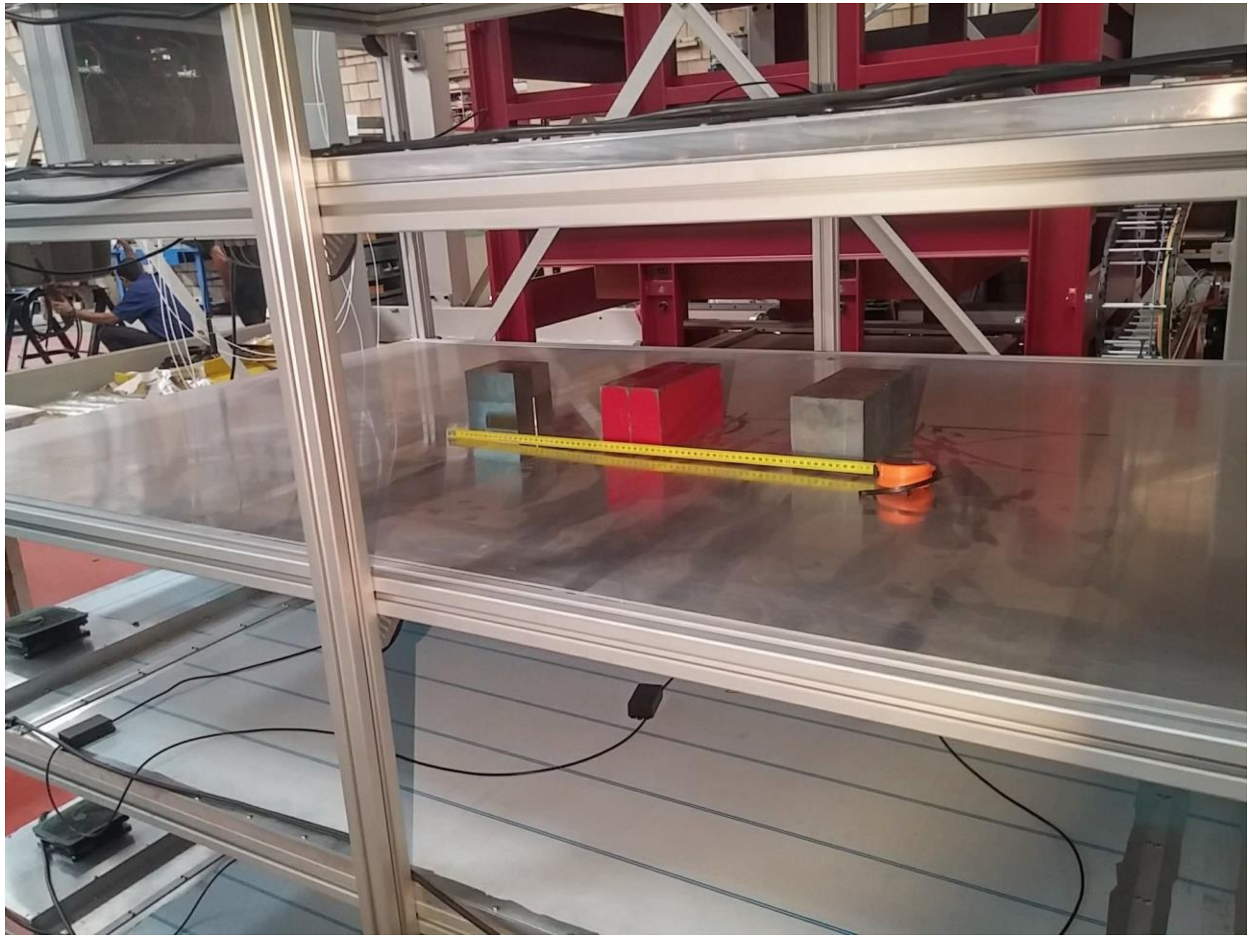
$$S = (\mathbf{d} - \mathbf{m}(\mathbf{s}))' \cdot W \cdot (\mathbf{d} - \mathbf{m}(\mathbf{s}))$$

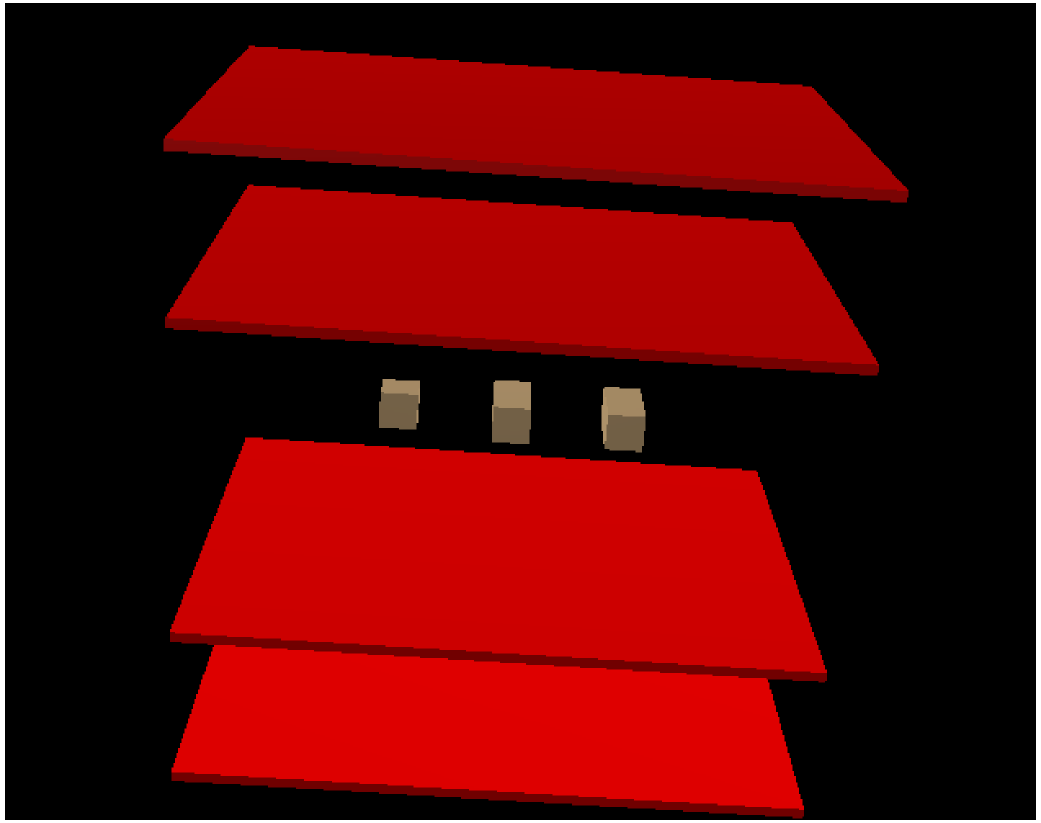
$$\mathbf{m}(\mathbf{s}) = G \cdot \mathbf{s} + \mathbf{g}_0(s)$$

$$G = \frac{\partial \mathbf{m}(\mathbf{s})}{\partial \mathbf{s}} = \begin{pmatrix} \frac{\partial m_1(s)}{\partial s_1} & \frac{\partial m_1(s)}{\partial s_2} & \cdots & \frac{\partial m_1(s)}{\partial s_{n_s}} \\ \frac{\partial m_2(s)}{\partial s_1} & \frac{\partial m_2(s)}{\partial s_2} & \cdots & \frac{\partial m_2(s)}{\partial s_{n_s}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial m_{n_d}(s)}{\partial s_1} & \frac{\partial m_{n_d}(s)}{\partial s_2} & \cdots & \frac{\partial m_{n_d}(s)}{\partial s_{n_s}} \end{pmatrix}$$

And then solve: $\frac{\partial S}{\partial \mathbf{s}} = 0$

A (simulated) real case

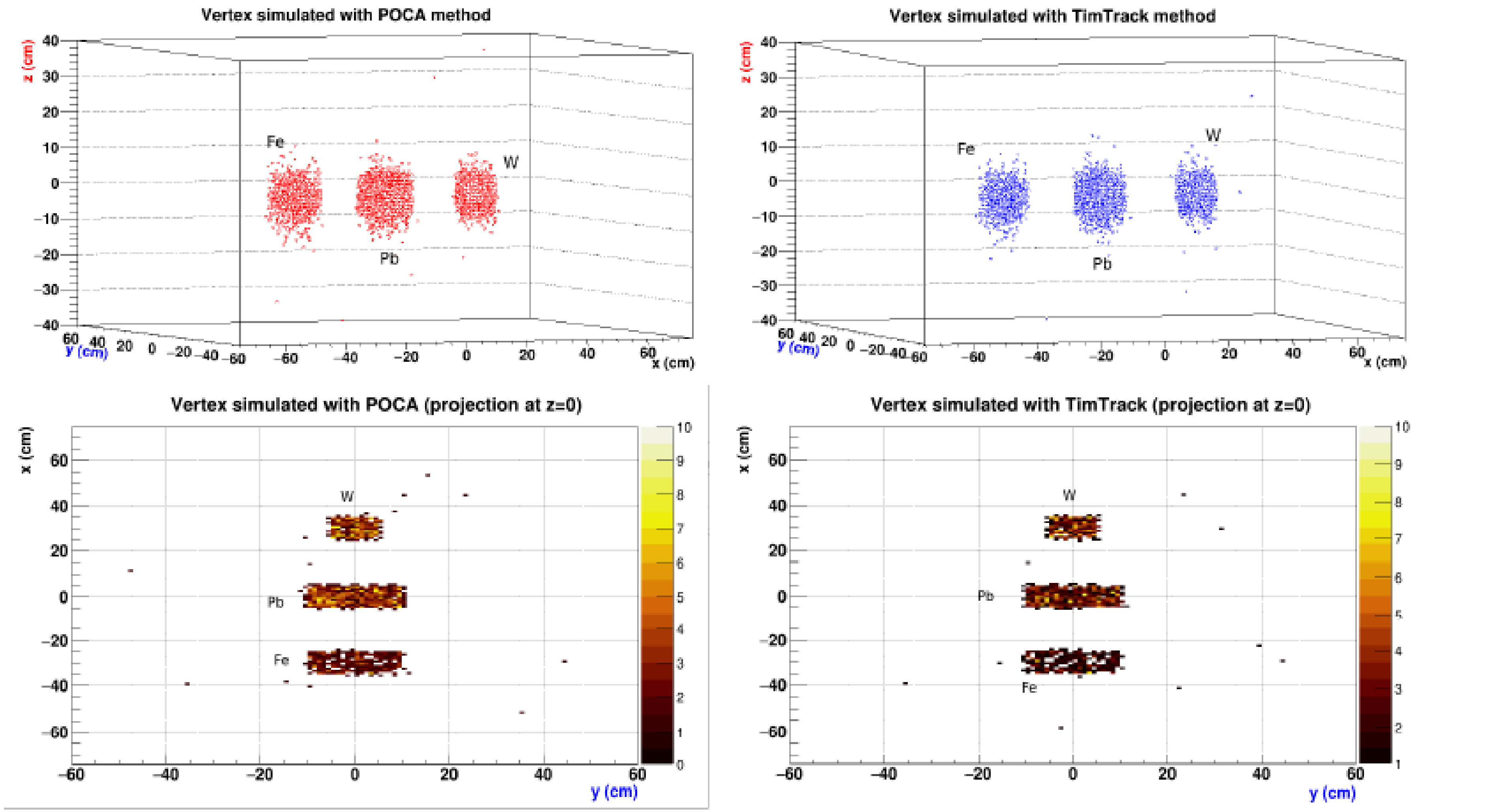




(1L tungsten, 2L lead and 2L iron)

DIGAFER (Porriño, Pontevedra)

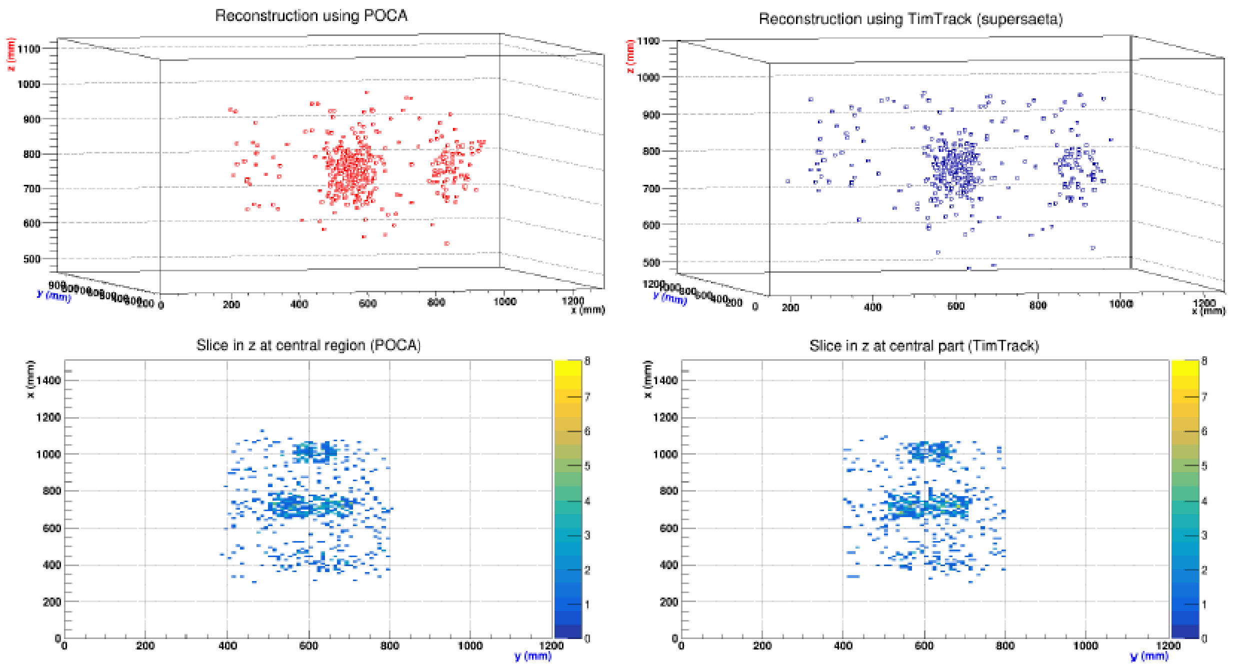
Reconstruction of vertices



Well, it seems it will work

The real thing

- We run the experiment with the 3 bricks:
- Start: September, 8th 2017.
- Number of events: 193k.
- Trigger: one and only one hit at the four planes.
- Rate of registered events: 5 Hz.



After some cuts it is possible to make a guess about the material.

The prototype

Summary

- It is possible to use muon tomography for homeland security purposes.
- New models of Resistive Plate Chambers are very efficient in tracking muons.
- Reconstruction algorithms improve the features of the detectors.
- It is possible to produce an image of the object and also investigate the type of material.
- This method can be applied in other fields.