Muon tomography using a 4-layer strip detector

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What is Muon tomography

Muon tomography

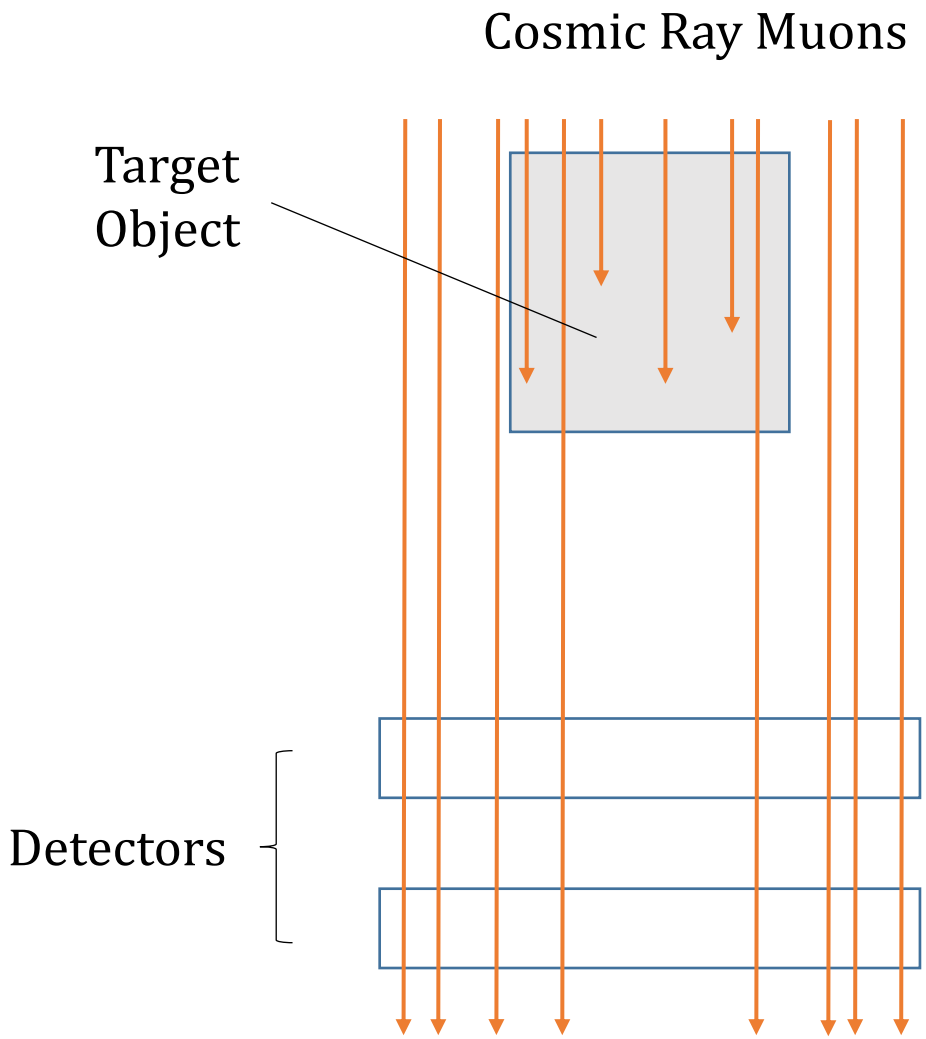
… a technique to get a 3D-image

using cosmic ray muons

With strip detectors,

→ reconstruct a truck of muon from two (x, y, z) positions

→ there should be some amount of attenuation of muon flux



My research topic

- Estimation of attenuation rate and angular resolution

- To know how many events are required

- To know how accurately we can indicate a position of a target object

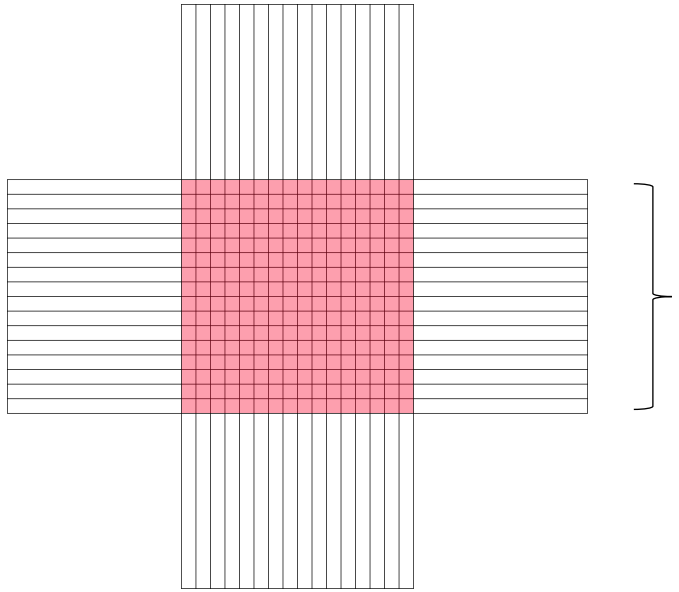
- Test measurement & Analysis

- To confirm if our detector works for muon tomography

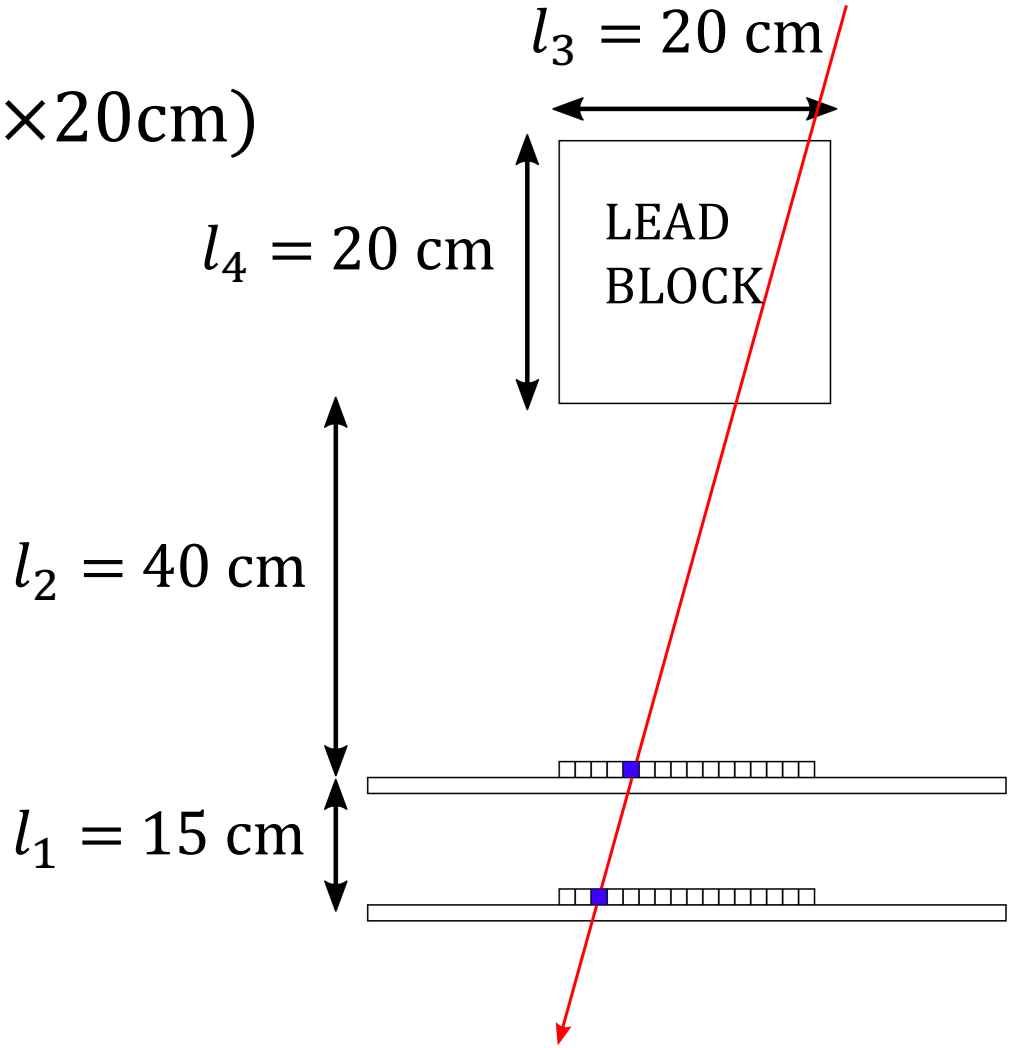
Setup

Target object : Lead block (20cm×20cm×20cm)

Detection area (19.2cm×19.2cm)



1.2cm × 16strips
= 19.2cm



Estimation of attenuation rate & angular resolution

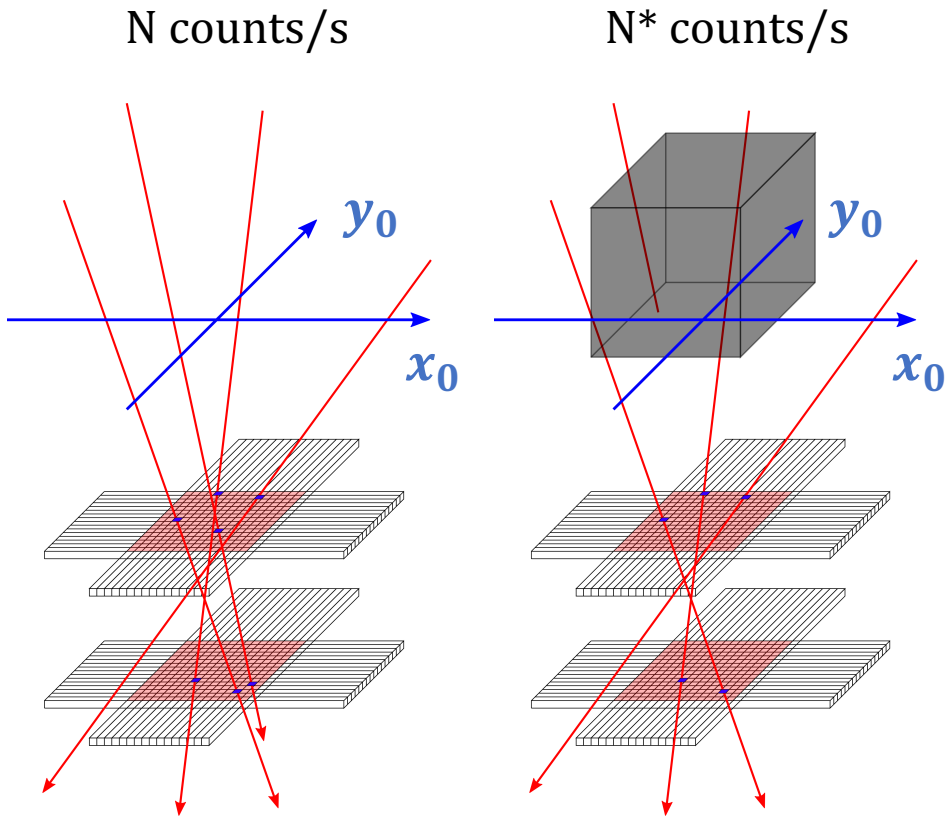
Attenuation rate : $R(x_{0,}\, y_0) \equiv 1 - N^*(x_{0,}\, y_0)/N\,(x_{0,}\, y_0)$

$N\,(x_{0,}\, y_0)$,$N^*\,(x_{0,}\, y_0)$:

Count rate at the level of the bottom surface of the lead block

Angular resolution : $\delta\theta$

→ determined by strip width, distance between both detectors, multiple scattering etc.

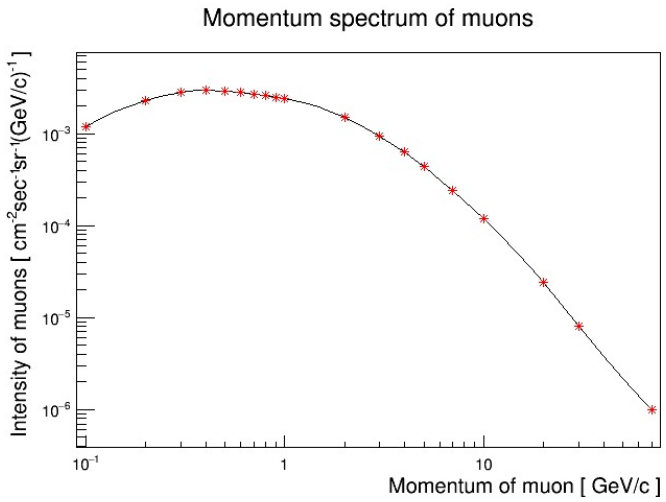


Parameters for Toy Monte Carlo simulation

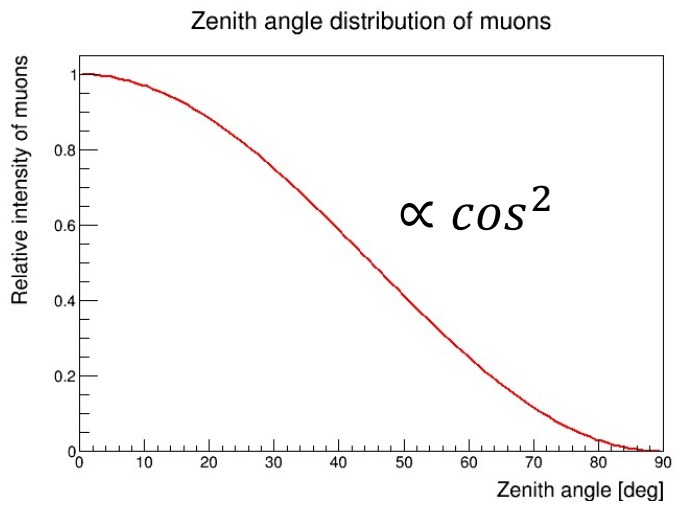
Generate muon with…

p:momentum, θ:zenith angle, φ:azimuthal angle

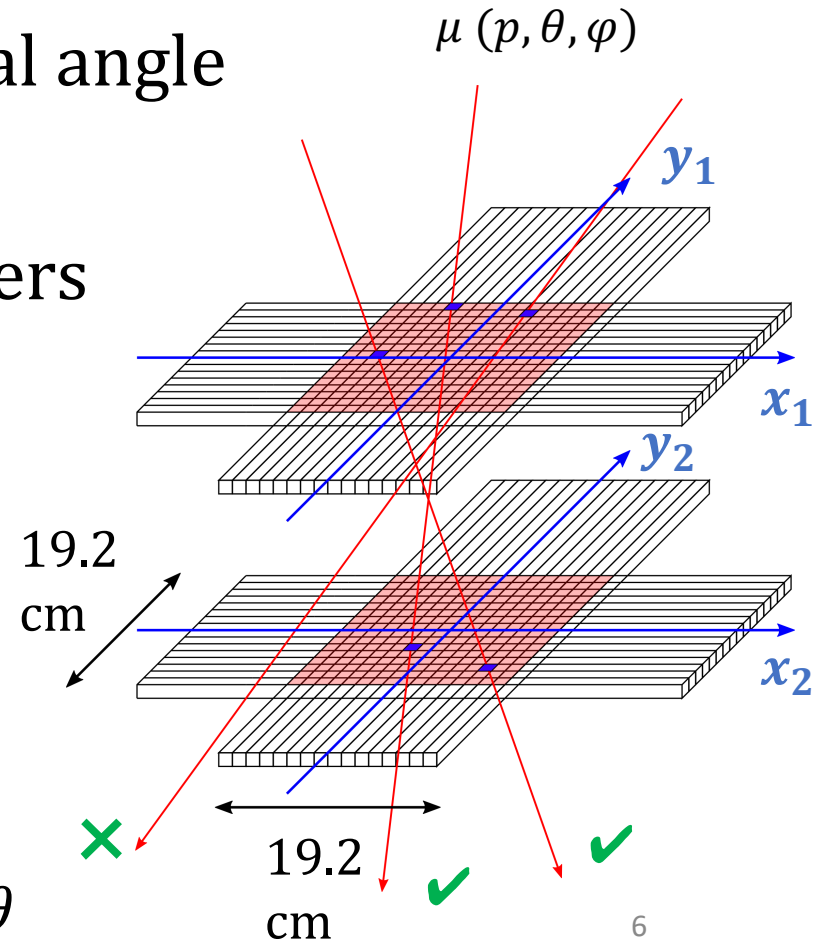
- Decide above parameters using random numbers
- Intensity of muon depends on p and θ



p



θ



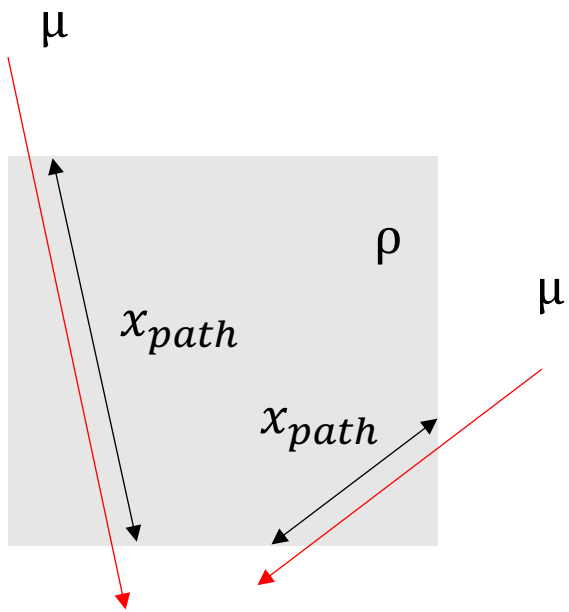
Energy loss

- Check if muons have enough energy to penetrate a lead block

$$\Delta E \approx (dE/dx)_{mip}\,[MeV \cdot cm^2/g] \cdot x_{path}\,[g/cm^2]$$

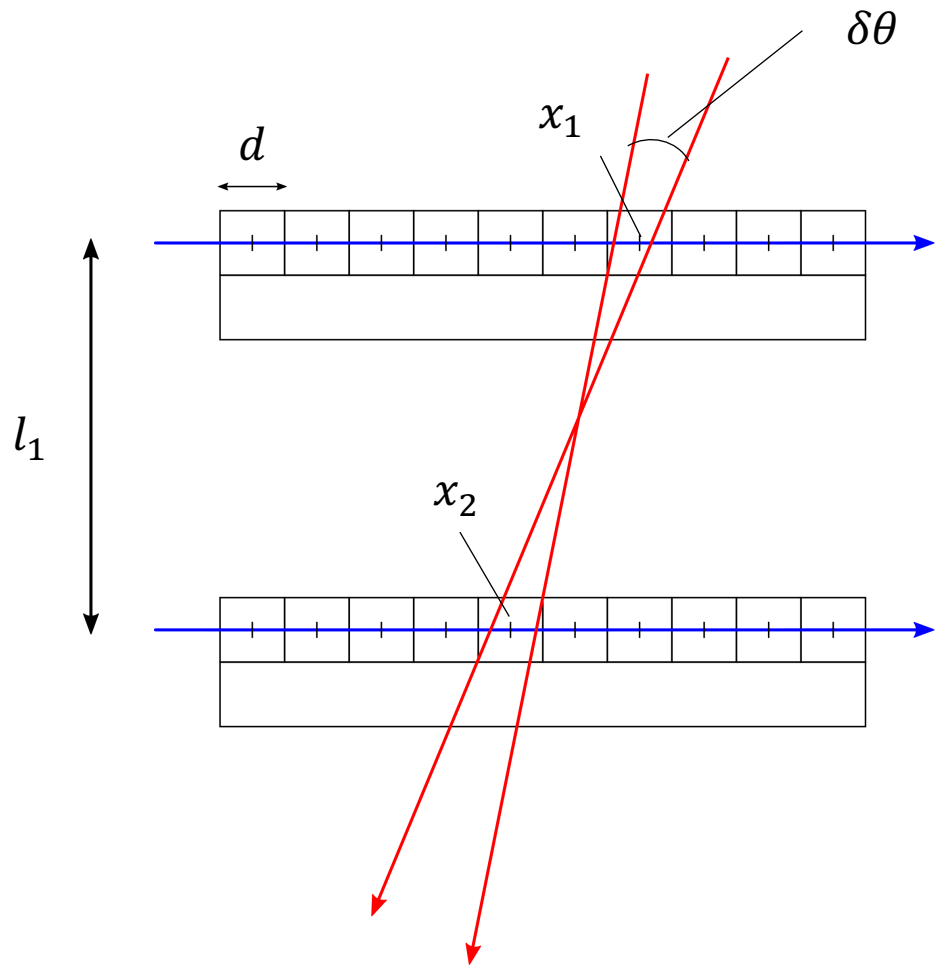
$$(dE/dx)_{mip} \approx 2\,[MeV \cdot cm^2/g]$$

$$T_\mu = \sqrt{{p_\mu}^2 + {m_\mu}^2} - m_\mu > \Delta E$$



Angular resolution

- $\delta\theta = \sqrt{(\delta\theta_{det})^2 + (\delta\theta_{M.S})^2}$



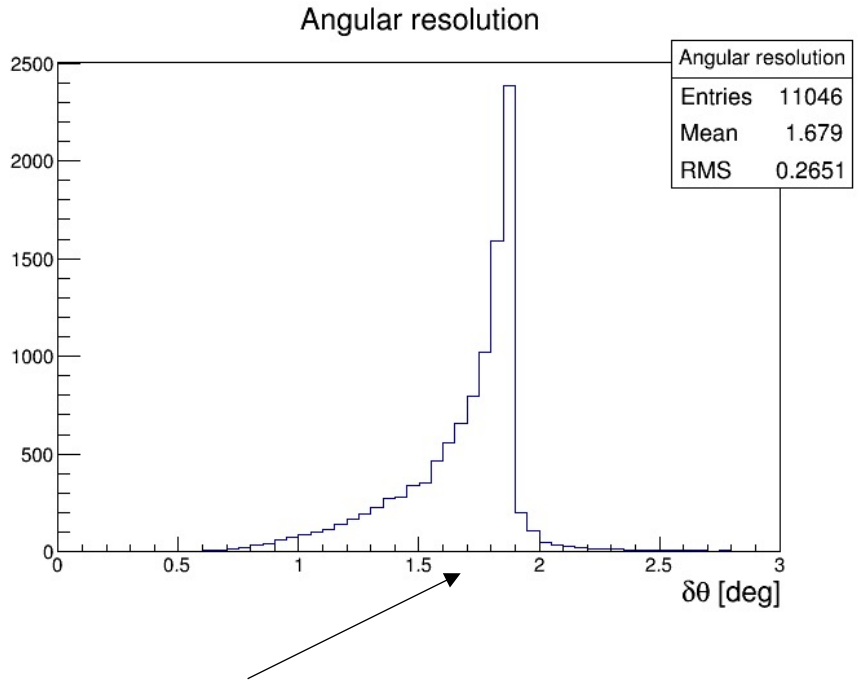
- Dimension of the detector

$$\delta\theta_{det} = \frac{d\cos^2\theta}{\sqrt{6}l_1}$$

- Multiple Scattering

$$\delta\theta_{M.S} = \frac{13.6MeV}{\beta cp} z\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$$

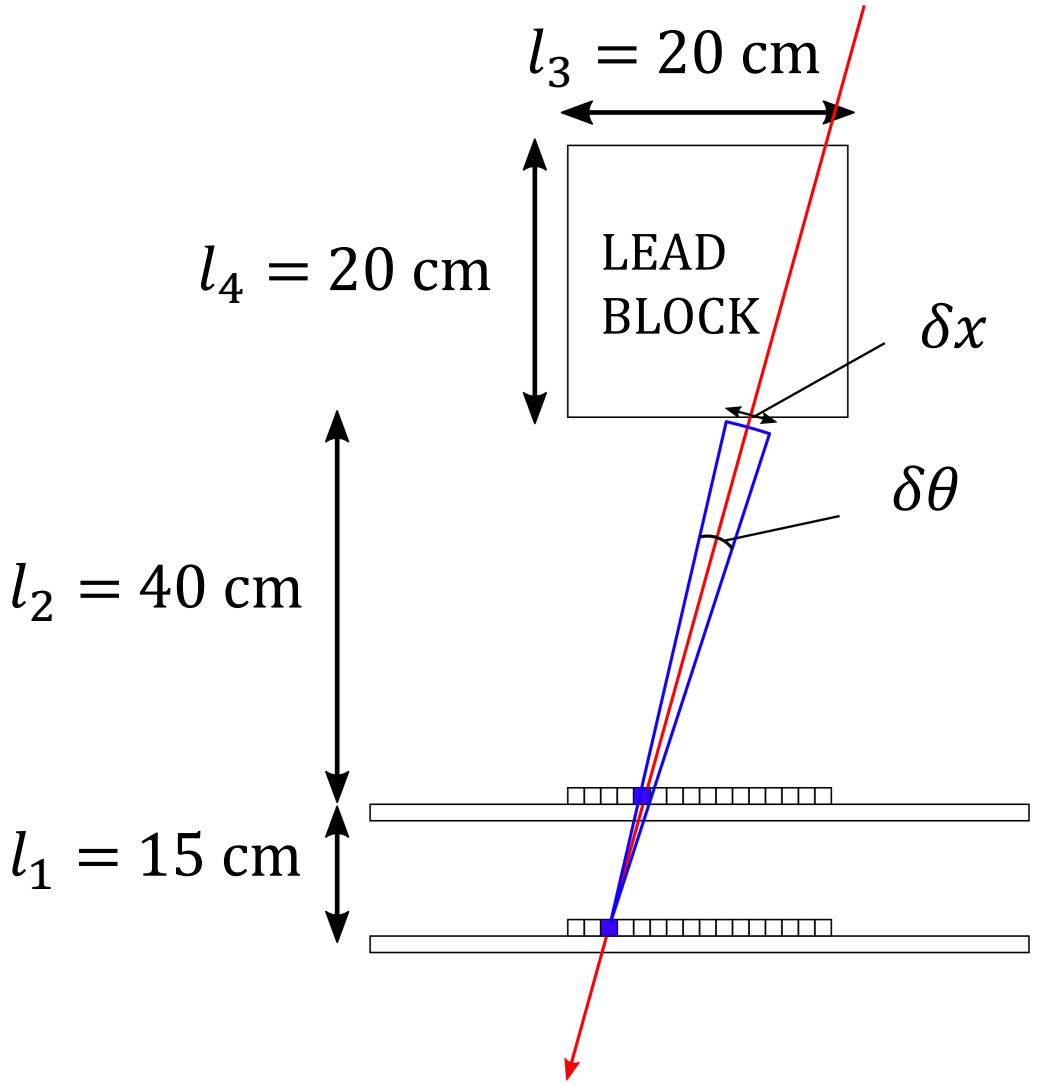
Angular resolution



$\delta\theta \approx 1.68$ [deg] $(= 0.029$ [rad]$)$

$\delta x \approx \delta\theta\ (l_1 + l_2) = 1.61$ [cm]

$\rightarrow \delta x\ /\ l_3\ \approx 8.1\ \%$



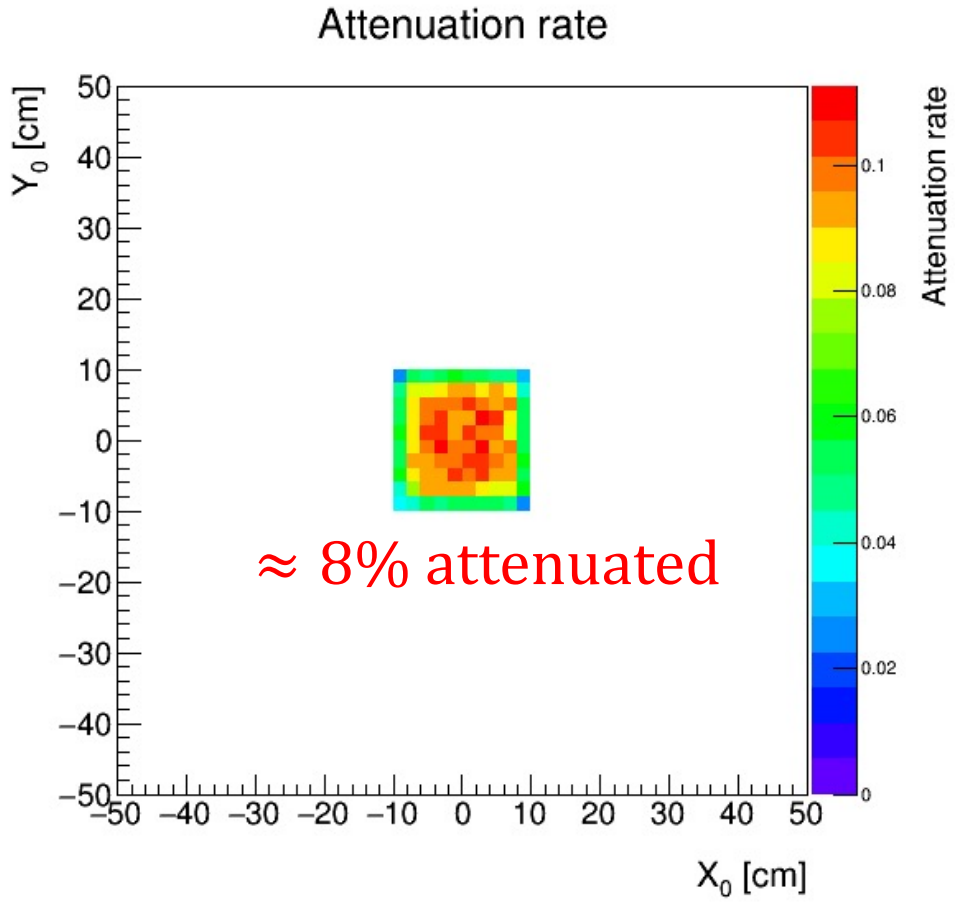
Attenuation rate

How many events do we need to observe the lead block ?

If we require CL 95% $\rightarrow 1.6\sigma$

$$\begin{cases} R = 1 - N*/N \\ N* = N - 1.6\sigma \end{cases}$$

$$\rightarrow N = (1.6/R)^2$$



N ≈ 400 events are necessary at the target object

Test measurement & Analysis

Data taking

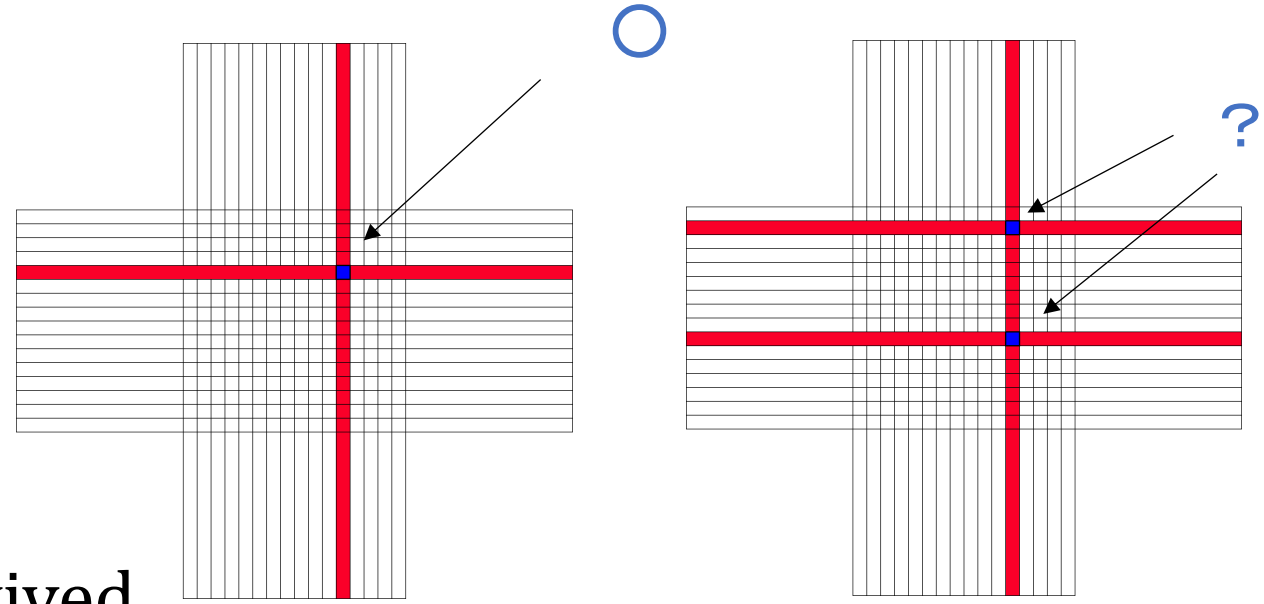
The number of events detected by two detectors

	Time	Number of events	Rate
Without lead block	15[h]31[m]25[s]	25779	0.46[/s]
With lead block	9[h]47[m]34[s]	16229	0.46[/s]

*Scintillator strip efficiency : 60~ 70%

Event selection

- Only one hit or cluster at each detector



→ About 47% of events survived

	Time	Number of events	Rate
Without lead block	15[h]31[m]25[s]	25779→12155	0.22[/s]
With lead block	9[h]47[m]34[s]	16229→7716	0.22[/s]

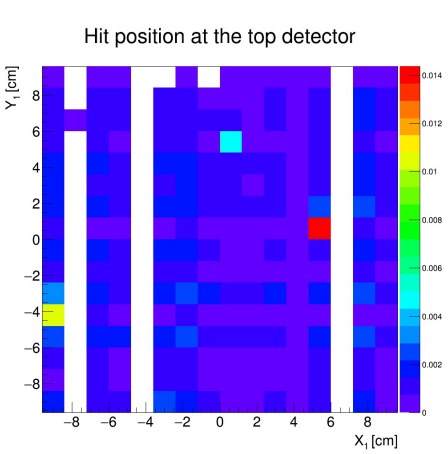
Hit position at the two detectors

Top Detector

Bottom Detector

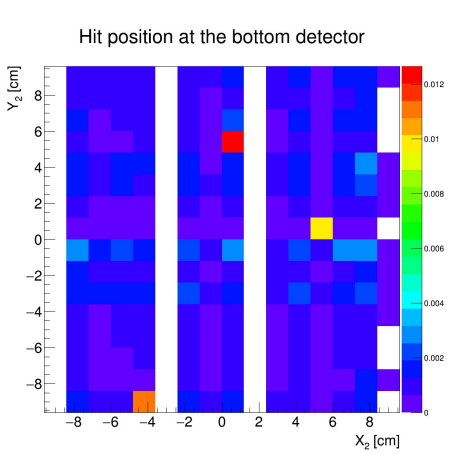
Without Lead Block

y_1



x_1

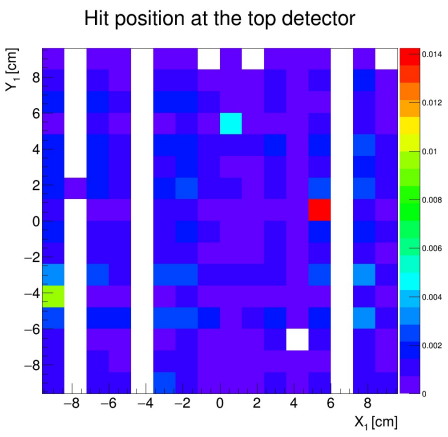
y_2



x_2

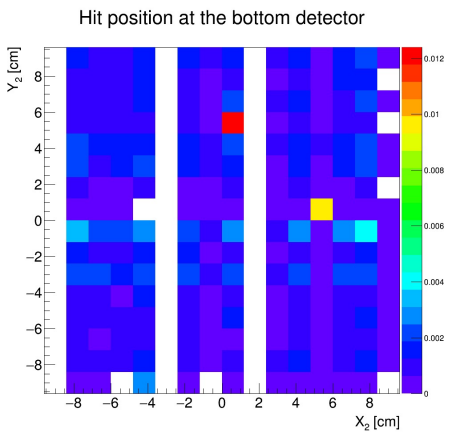
With Lead Block

y_1



x_1

y_2



x_2

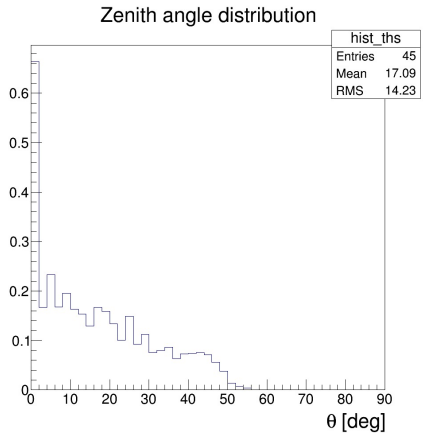
6 channels are not working well

Angular distribution

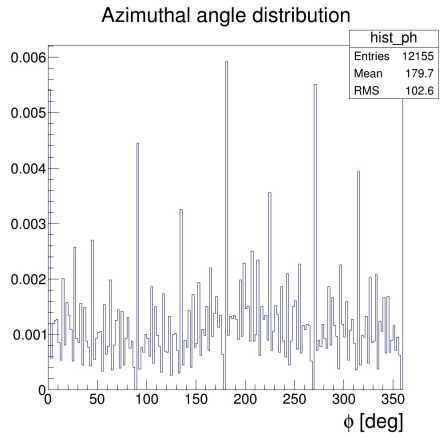
Zenith angle

Azimuthal angle

Without Lead Block

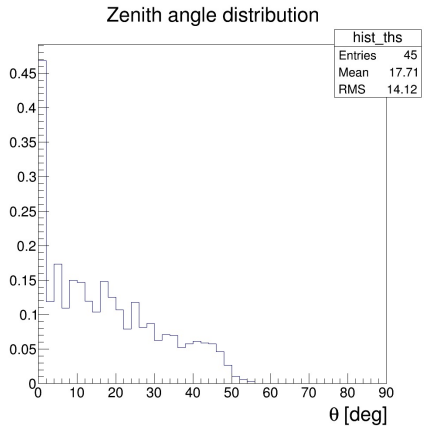


θ

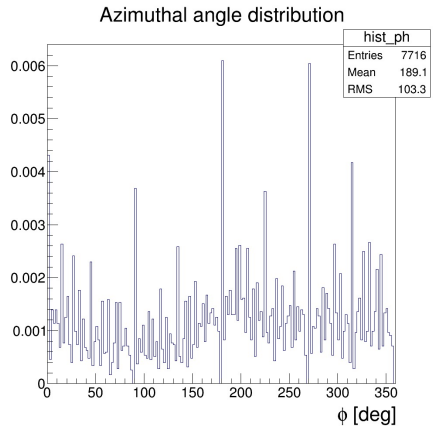


φ

With Lead Block



θ



φ

Zenith angle

↓

Detected up to $\theta \sim 60°$

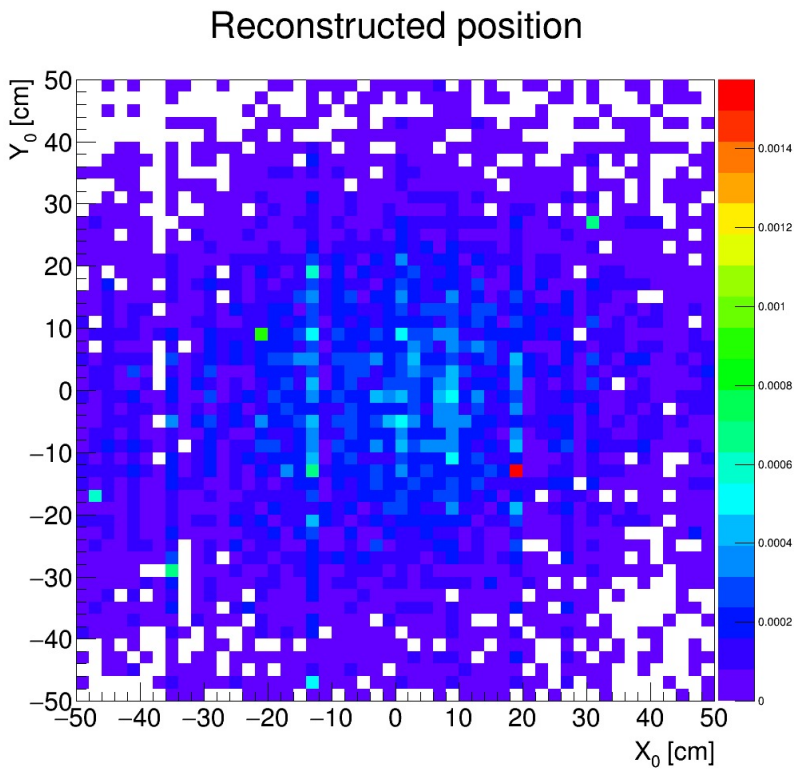
Azimuthal angle

↓

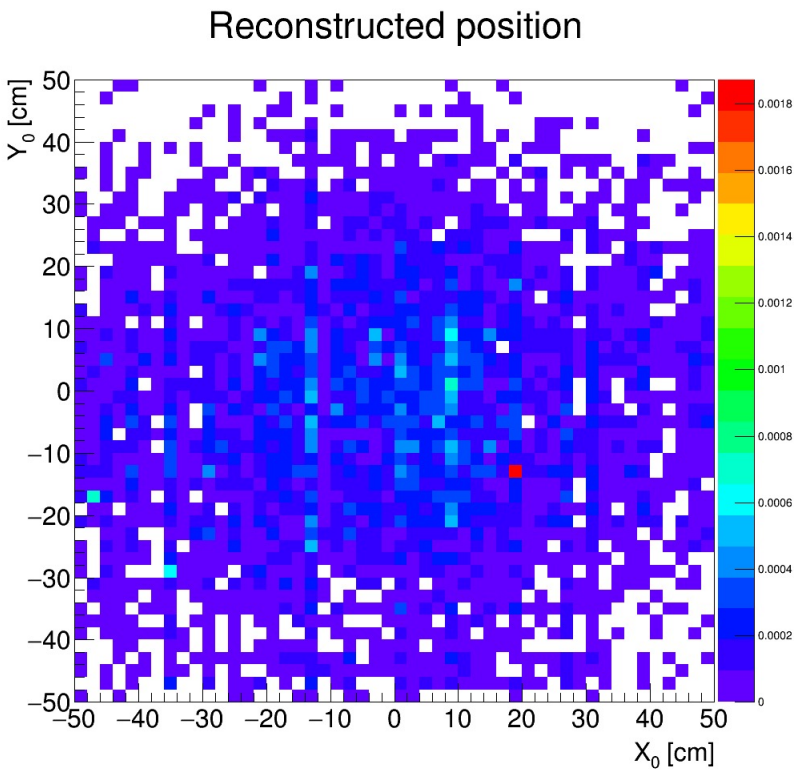
$0° < \varphi < 360°$ roughly uniform

Count rate distribution at the level of the target object

Without Lead Block



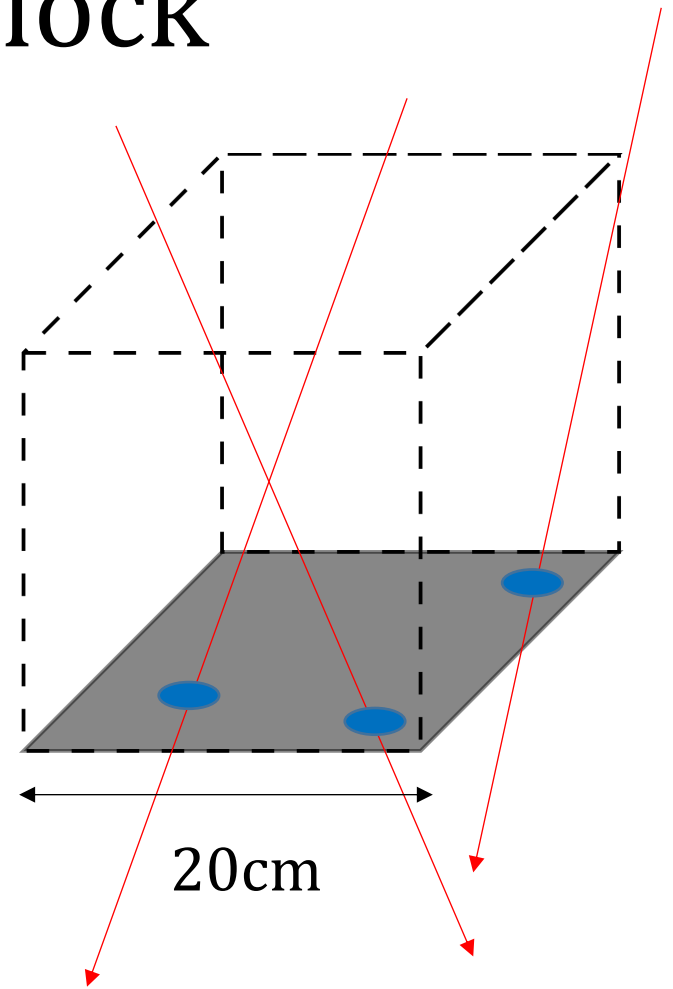
With Lead Block



Number of events at the lead block

Without the lead block → 1505 events
With the lead block → 912 events
→ Statistical error ~ 4.2%
→ difficult to observe attenuation of ~ 8%

We need to …
- take several times number of data
- improve efficiency
- reduce the number of cross-talk events



Conclusion

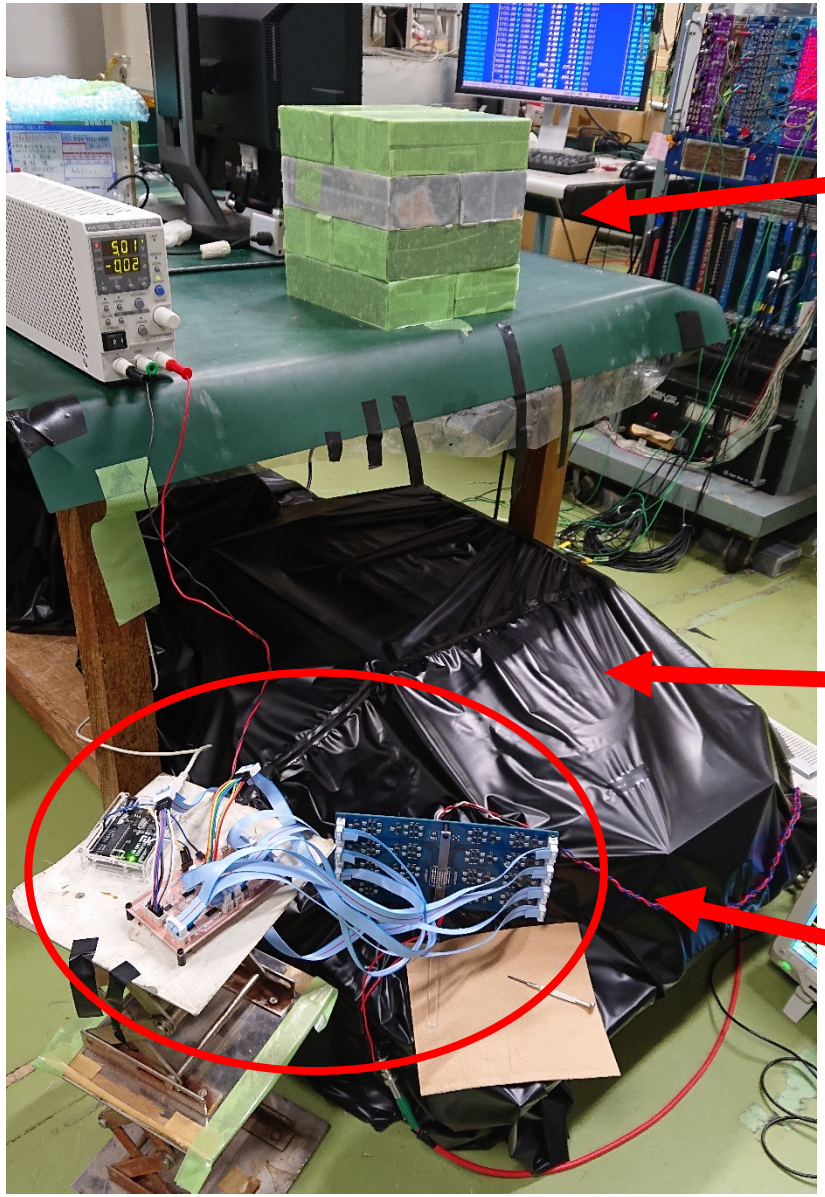
- Estimated attenuation rate and angular resolution by Toy Monte Carlo simulation for required number of events and expected pointing precision

- Have yet to get an image of the lead block

END

Back-up

Setup



Lead Block
20cm×20cm×20cm

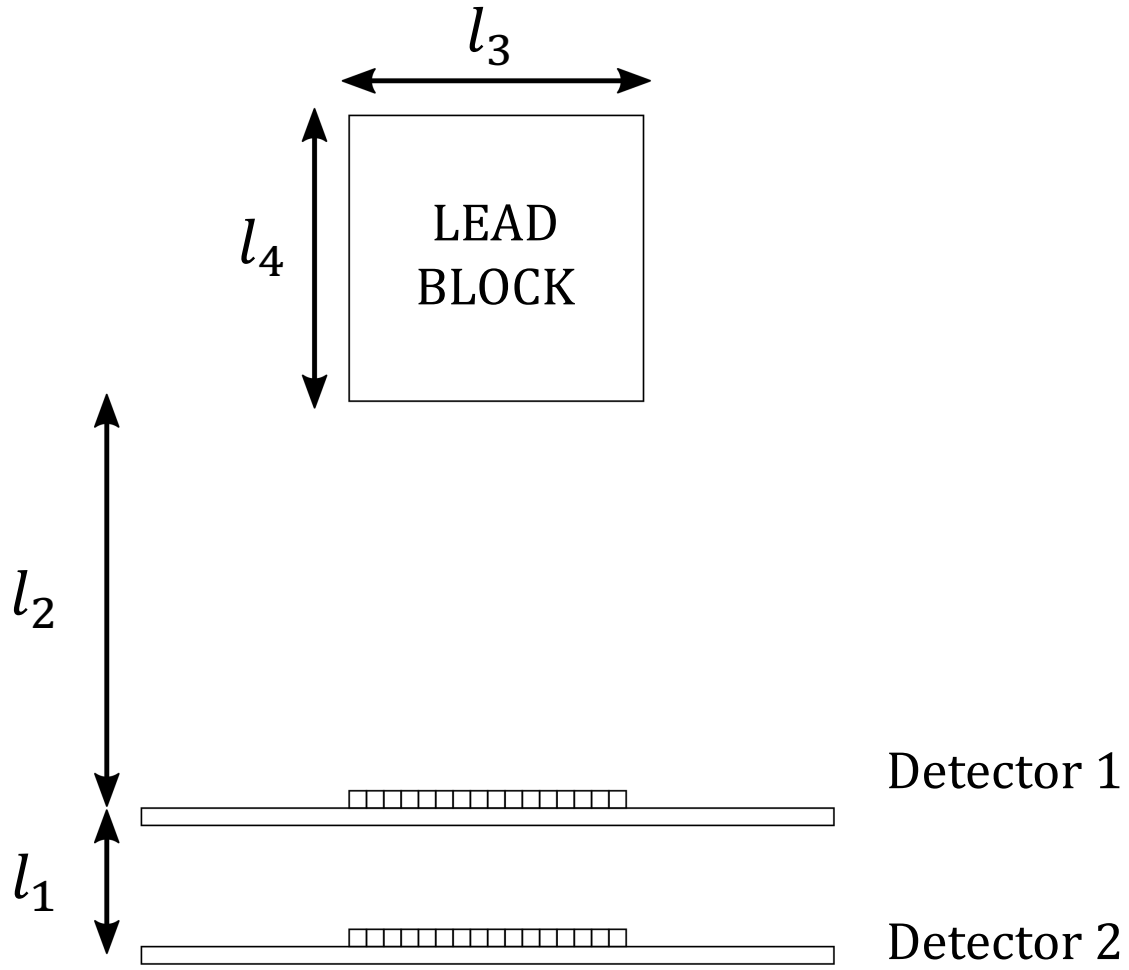
Detector wrapped in
black sheet

DAQ circuit

Geometrical parameters

- $l_1 = 15$ cm
- $l_2 = 40$ cm

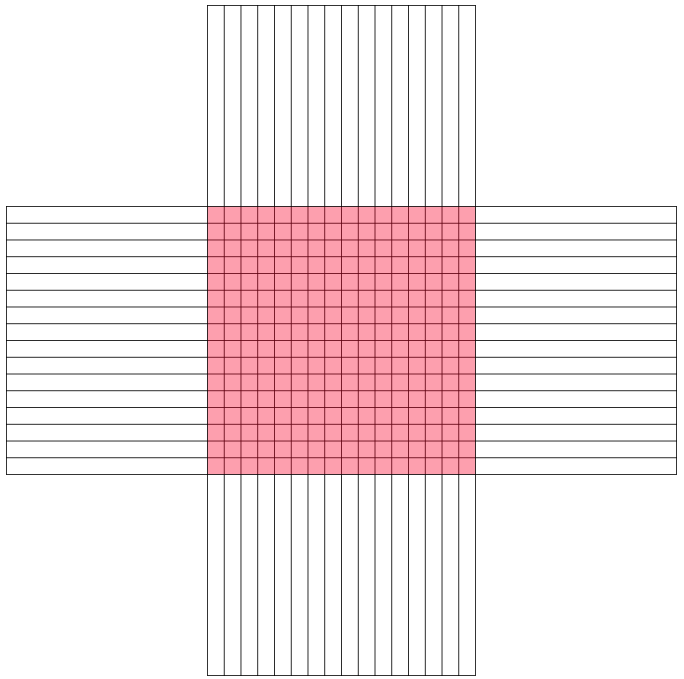
- $l_3 = 20$ cm
- $l_4 = 20$ cm



Detection area

Wrapping a scintillator strip in aluminized mylar film & black sheet

Strip width : 1cm → 1.2cm (0.2cm : Insensitive width in each strip)

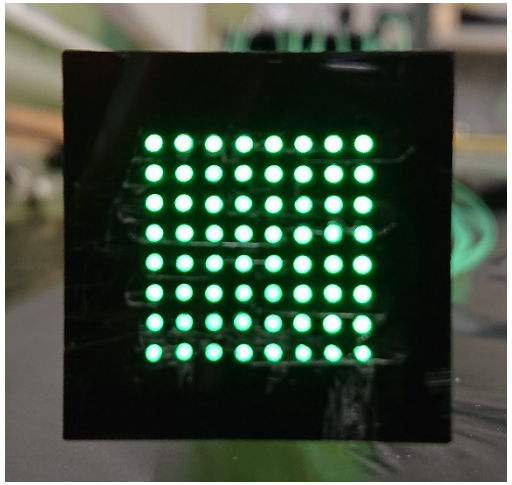


$1.2\text{cm} \times 16\text{strips} = 19.2\text{cm}$

Event selection

- Filtering
  - Cross-talk
  - Passing through two adjacent strips
  - Multiple muons detected at the same time

    ↓
- Number of events…***[events]



Resolution

- Angular resolution
  - Multiple scattering : $\delta\theta_{M.S}$
  - Detector : $\delta\theta_{det}$

- $\delta\theta = \sqrt{(\delta\theta_{M.S})^2 + (\delta\theta_{det})^2}$

- Position resolution
- $\delta x \approx (l_1 + l_2)\delta\theta$

Multiple scattering

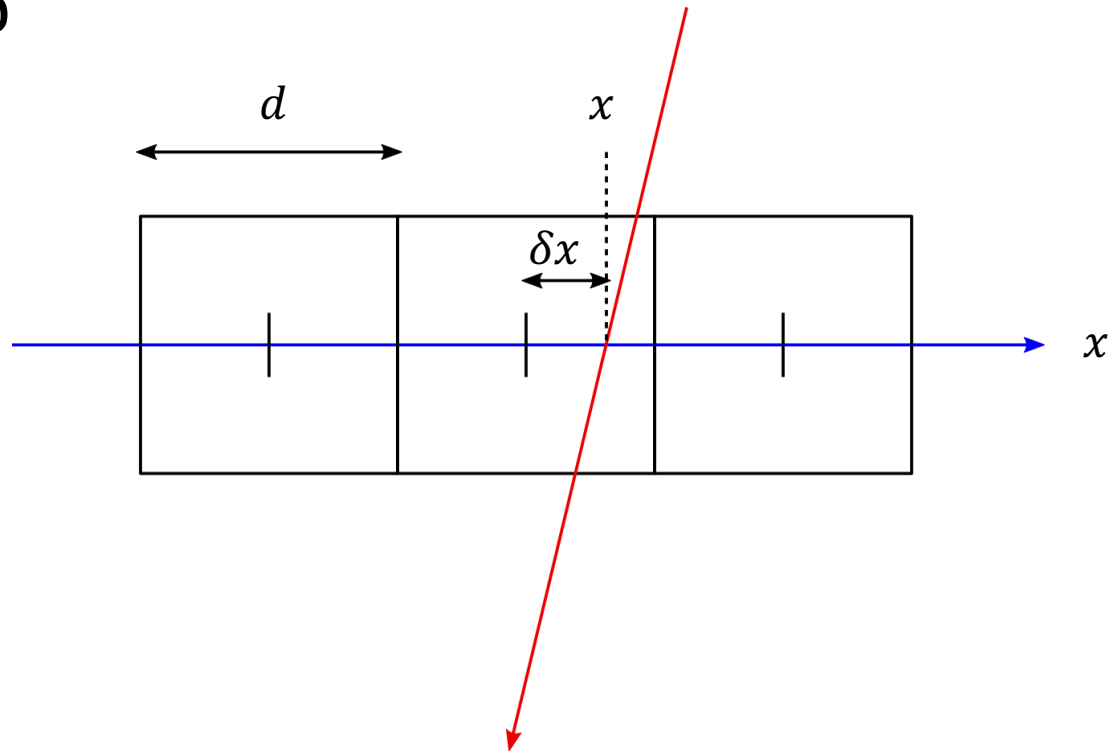
- $\delta\theta_{M.S} = \frac{13.6MeV}{\beta cp} z\sqrt{x/X_0}\,[1 + 0.038\ln(x/X_0)]$

- βc : velocity
- p : momentum
- z : charge
- x/X_0 : thickness of the scattering medium in radiation lengths

Detector

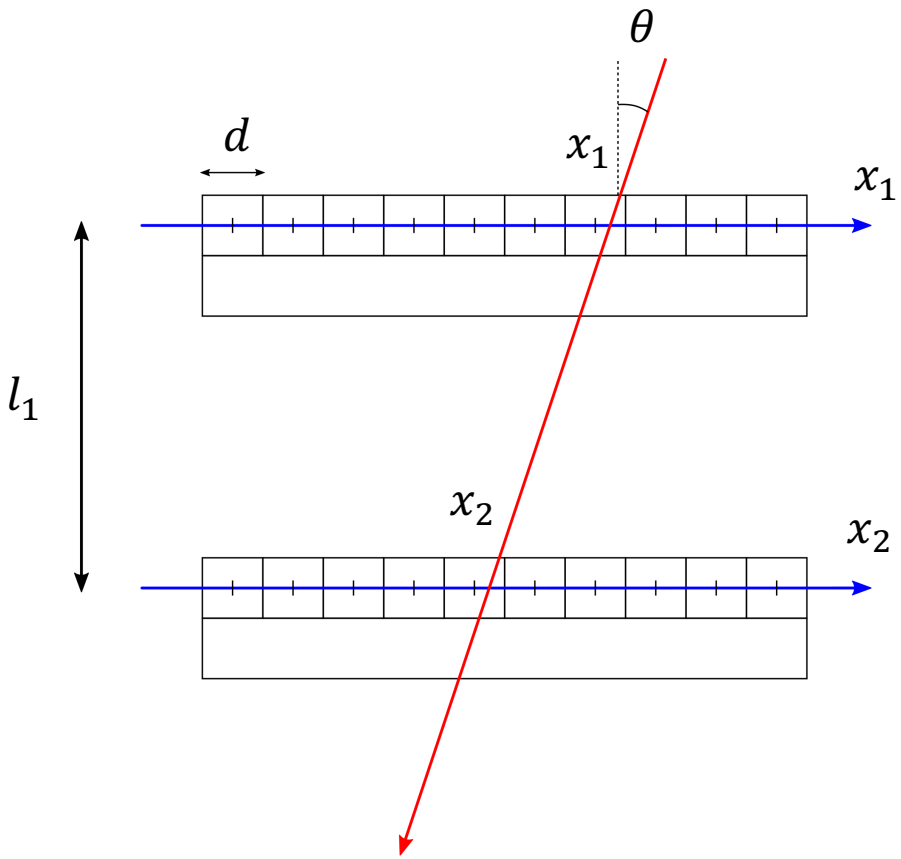
- Position resolution at each strip

- $(\delta x)^2 = \dfrac{\int_{-d/2}^{d/2} x^2 dx}{\int_{-d/2}^{d/2} dx} = \dfrac{d^2}{12}$
- $\delta x = \dfrac{d}{\sqrt{12}}$

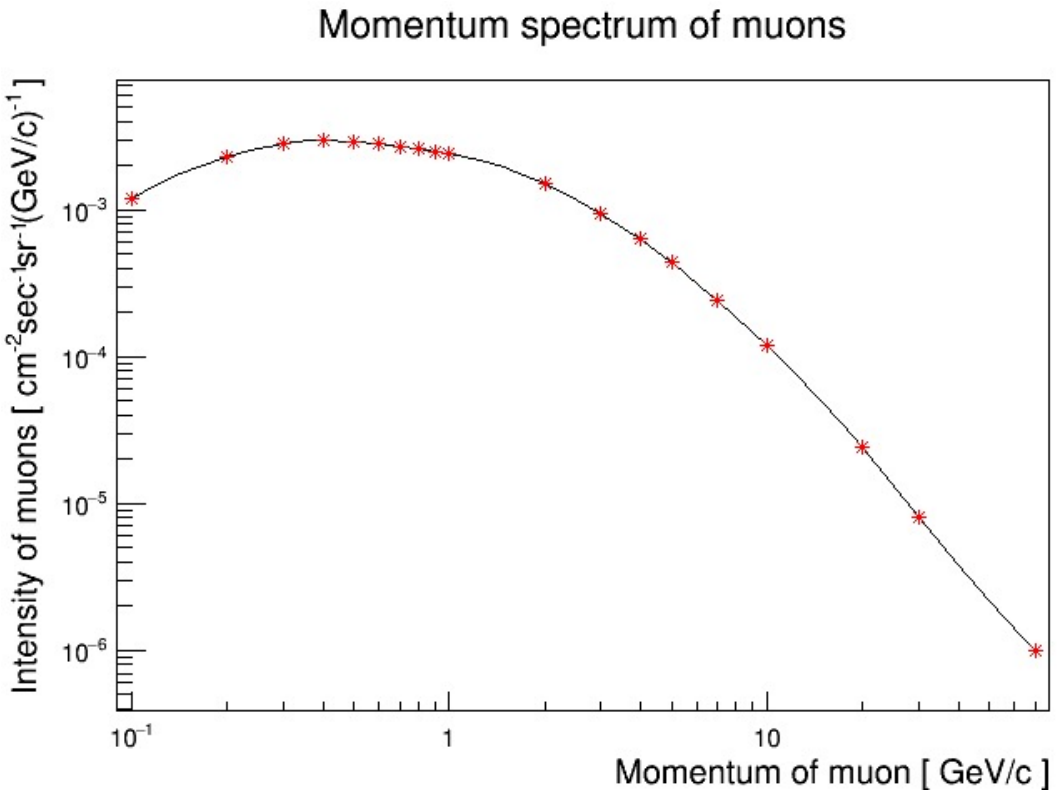


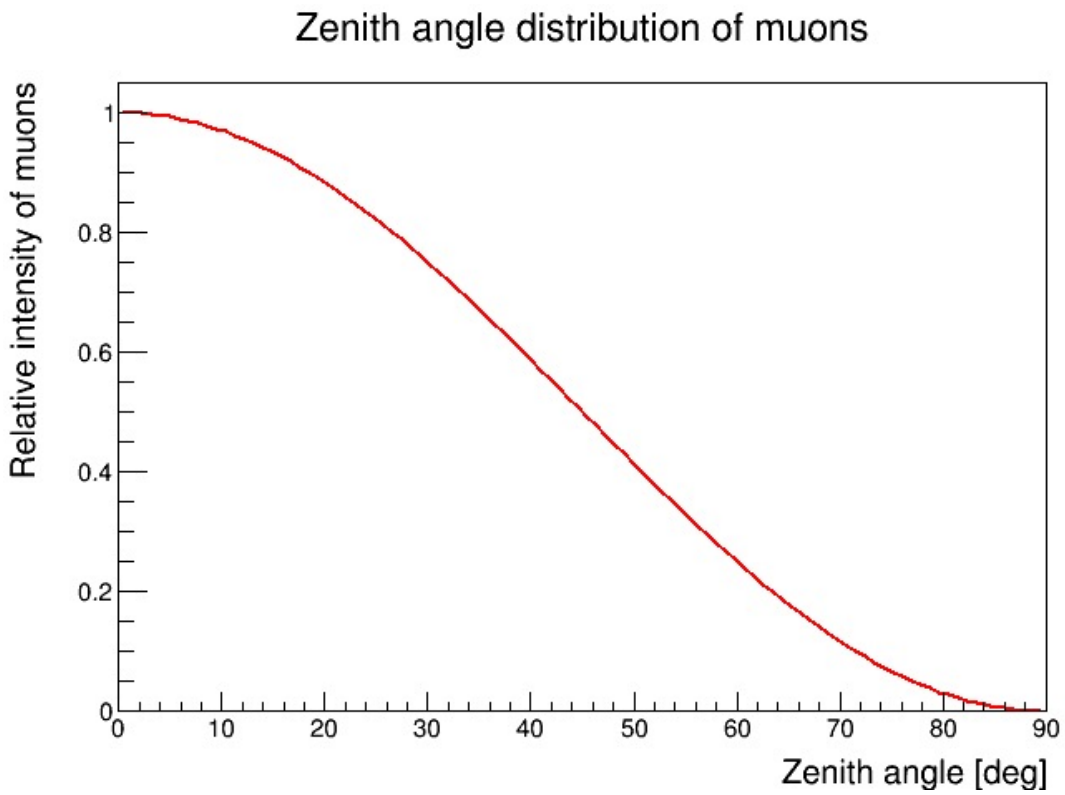
Detector

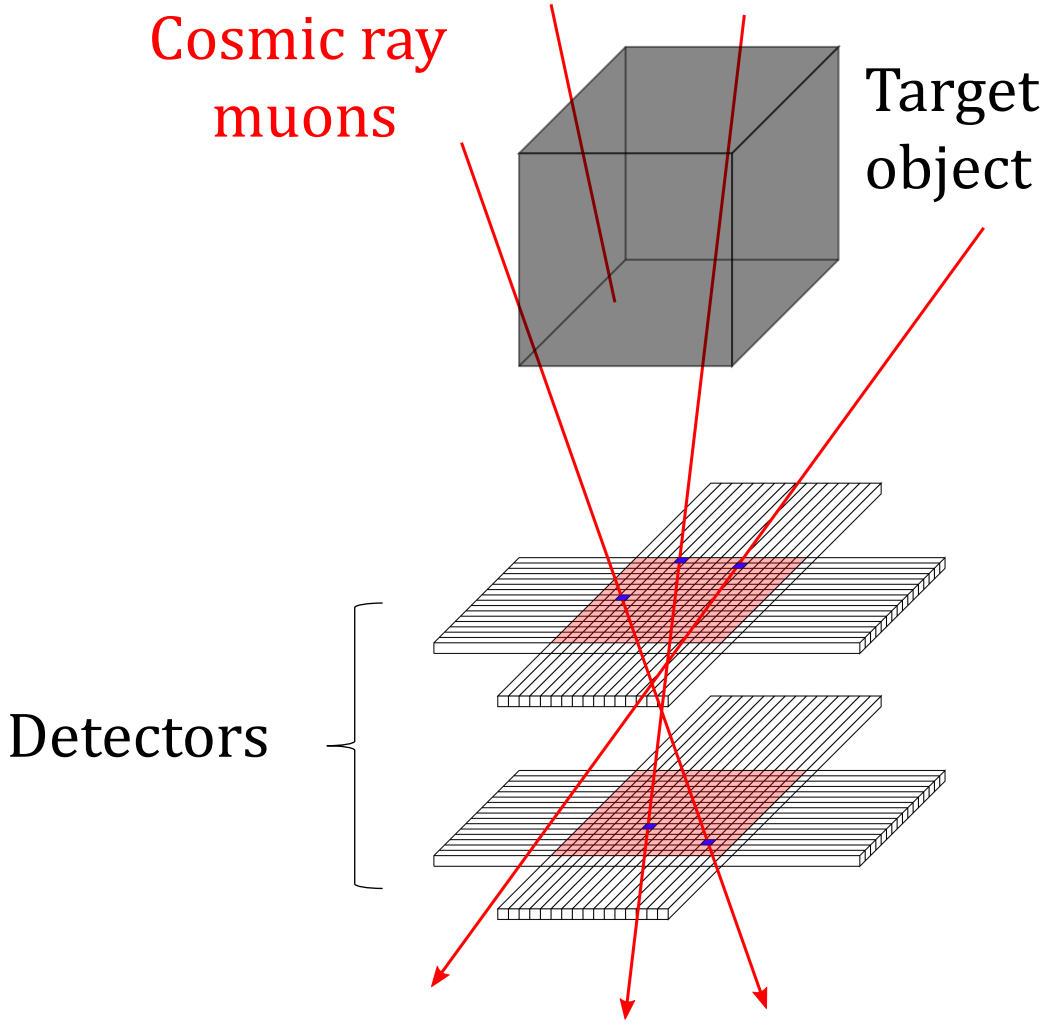
- $tan\theta = \frac{|x_1 - x_2|}{l_1}$
- $\delta\theta_{det} = cos^2\theta\ \delta(tan\theta) = cos^2\theta \frac{\delta|x_1 - x_2|}{l_1}$
- $\delta|x_1 - x_2| = \sqrt{(\delta x_1)^2 + (\delta x_2)^2} = \frac{d}{\sqrt{6}}$
- $\delta\theta_{det} = \frac{dcos^2\theta}{\sqrt{6}l_1}$

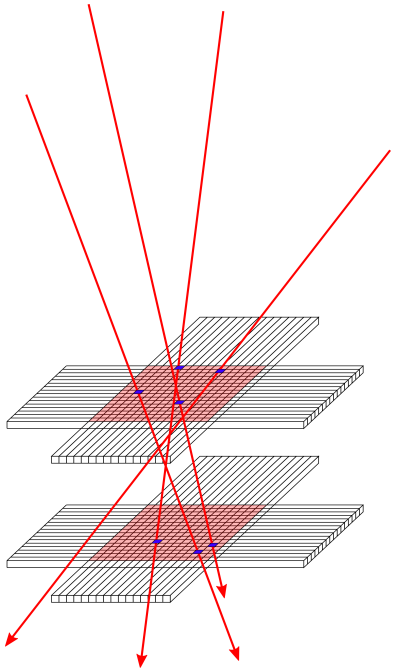


Intensity distribution

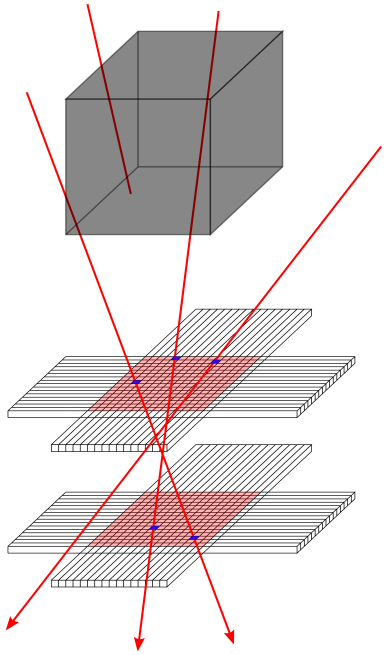








N counts/s

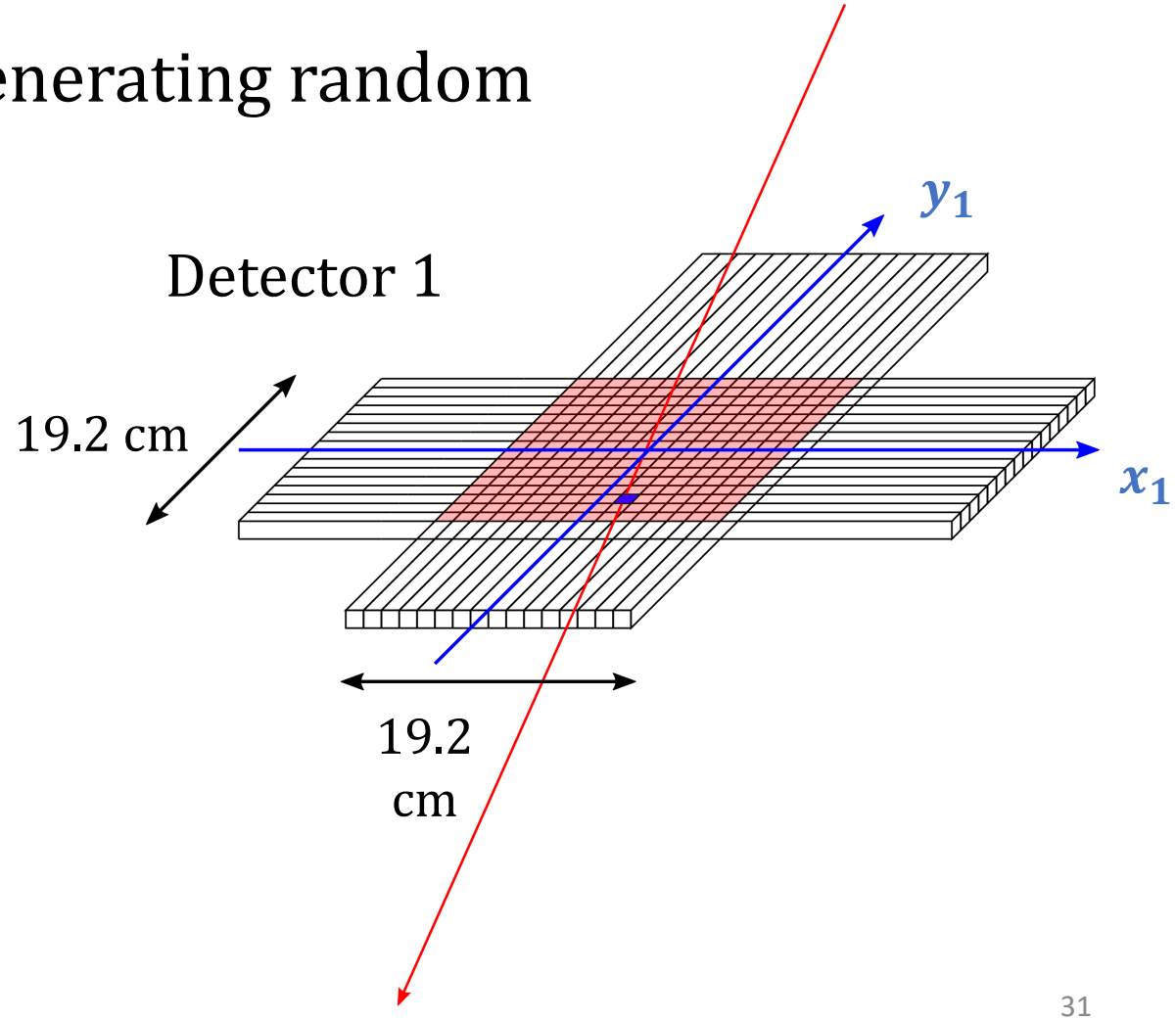


N* counts/s

Parameters for Toy Monte Carlo simulation

Set horizontal position (x_1, y_1) generating random numbers on the detector 1

$$\begin{cases} -9.6 < x_1 < 9.6 \\ -9.6 < y_1 < 9.6 \end{cases}$$



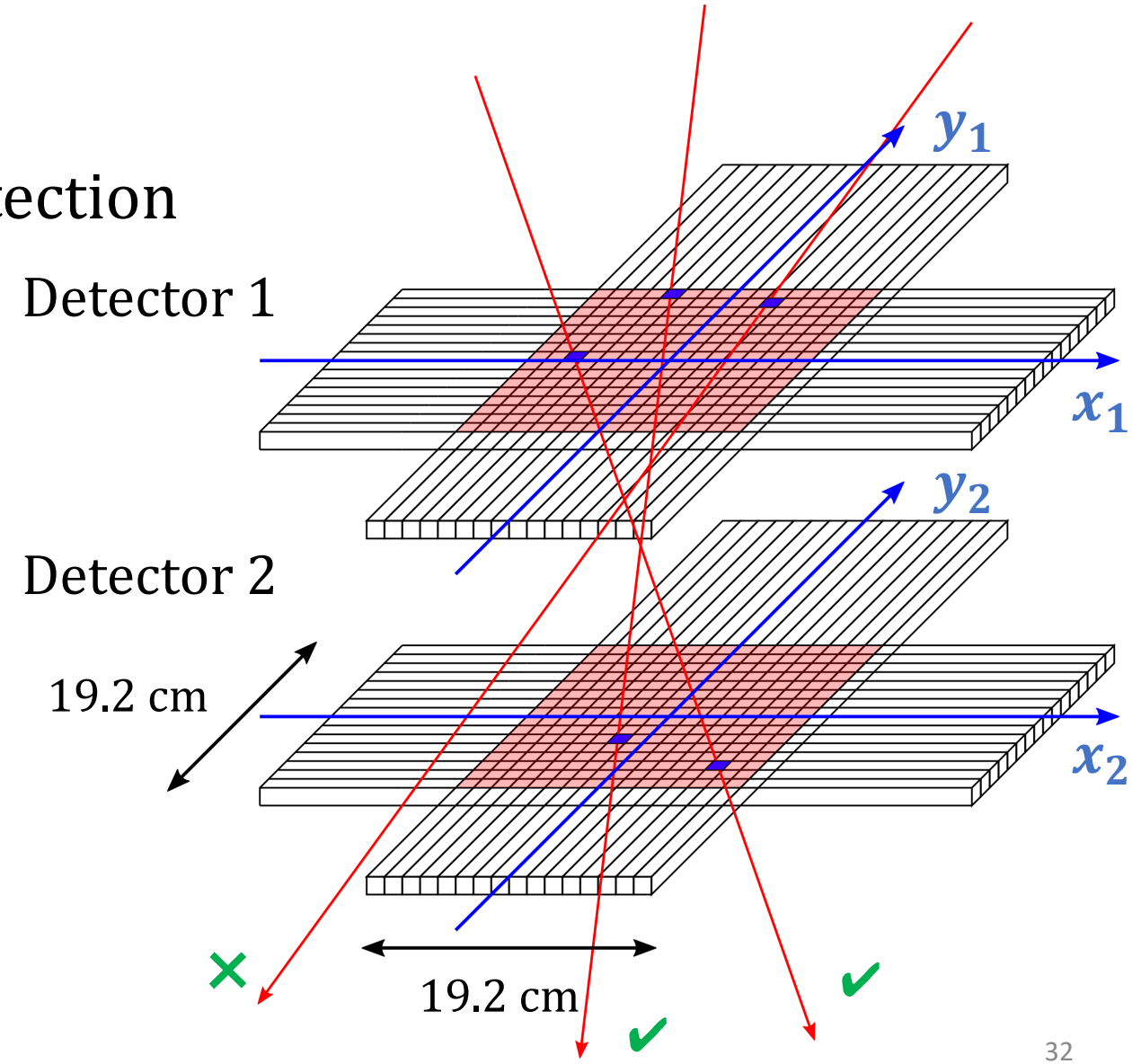
Condition 1

- Muons pass through each detection area of both detectors

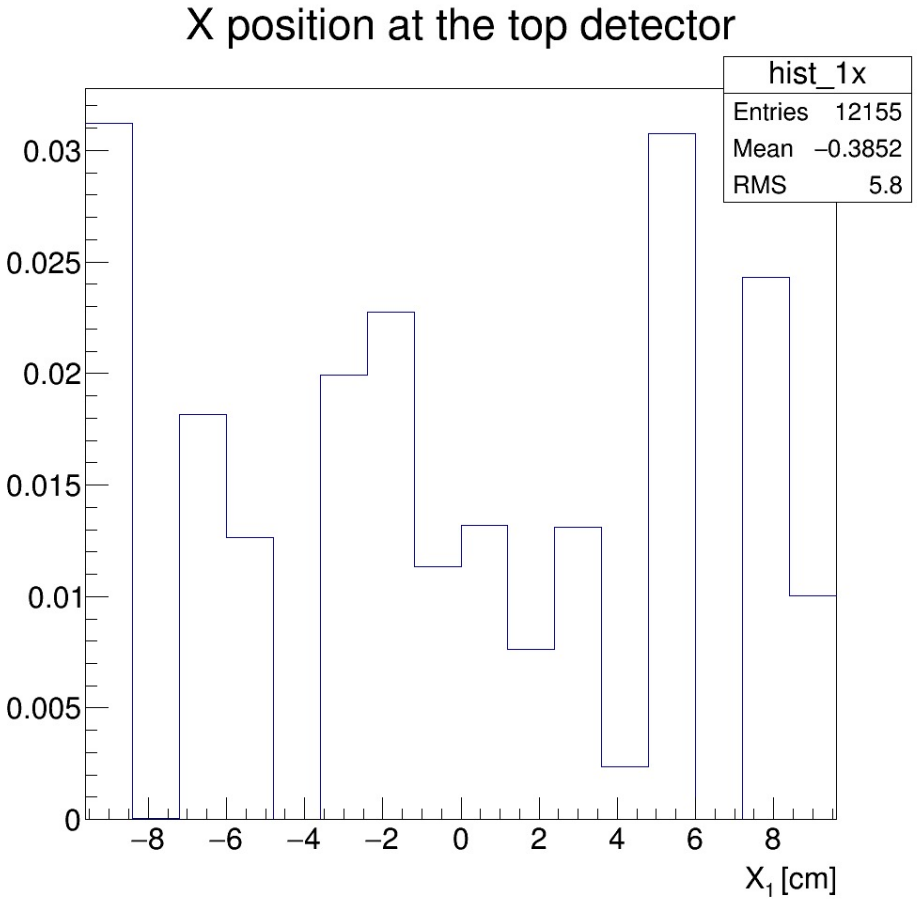
$(x_1, y_1, \theta, \varphi) \rightarrow (x_2, y_2)$

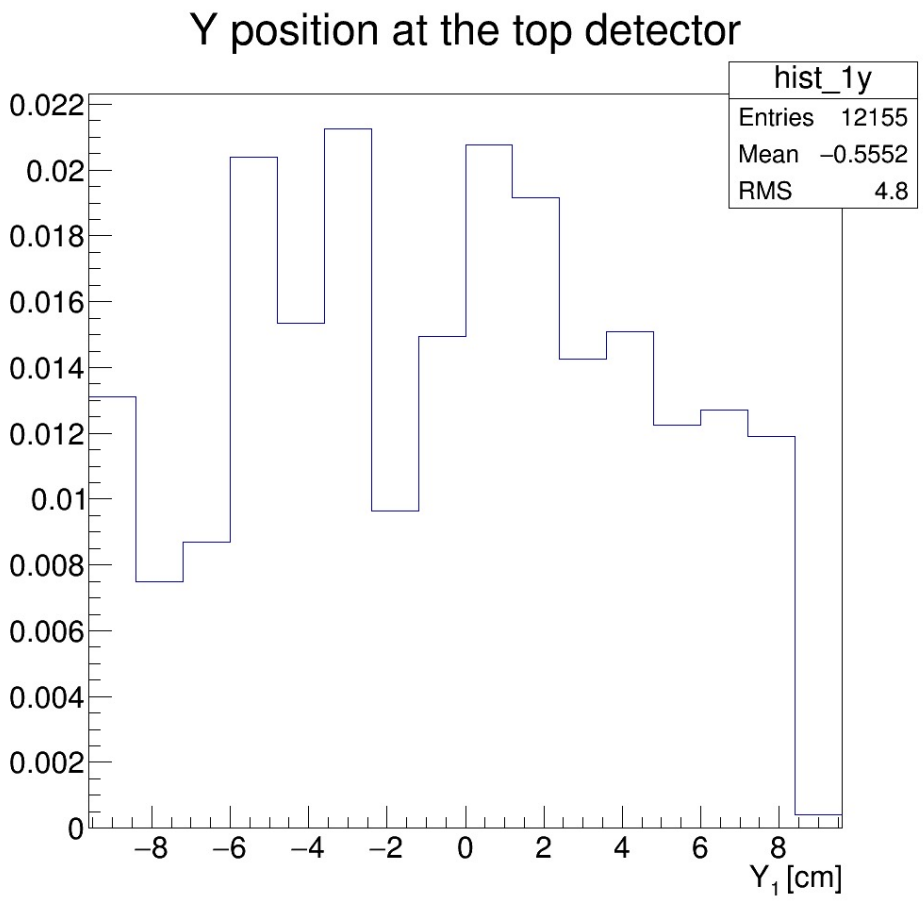
$$\begin{cases} -9.6 < x_1 < 9.6 \\ -9.6 < y_1 < 9.6 \end{cases}$$

$$\begin{cases} -9.6 < x_2 < 9.6 \\ -9.6 < y_2 < 9.6 \end{cases}$$

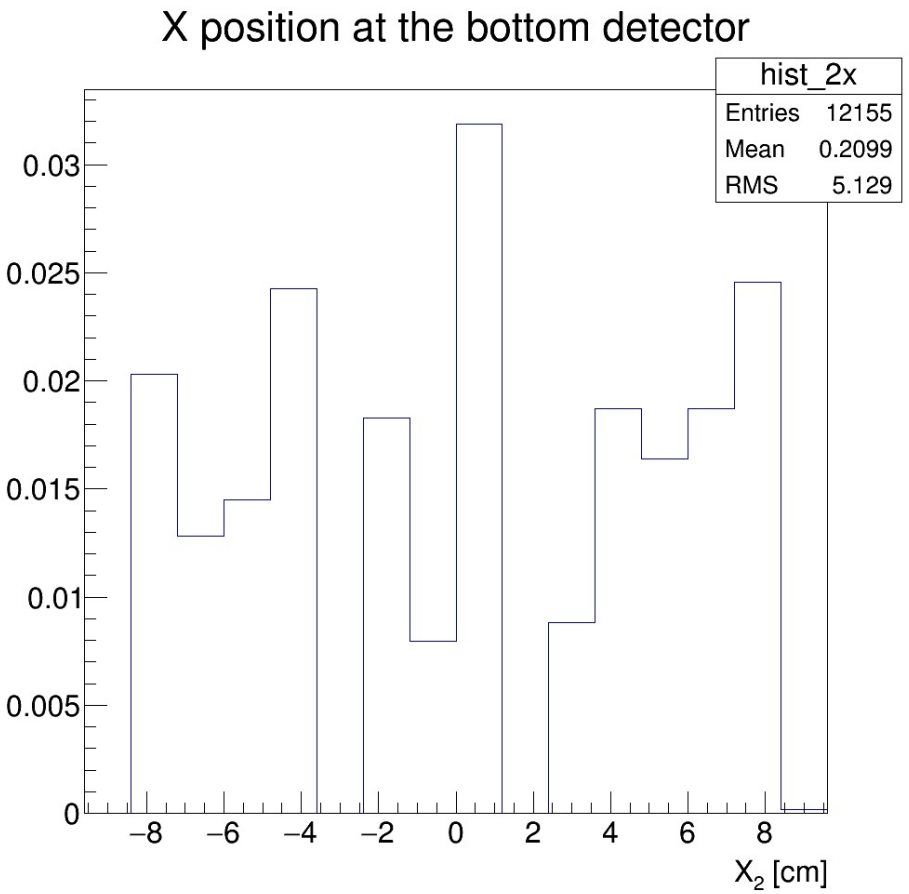


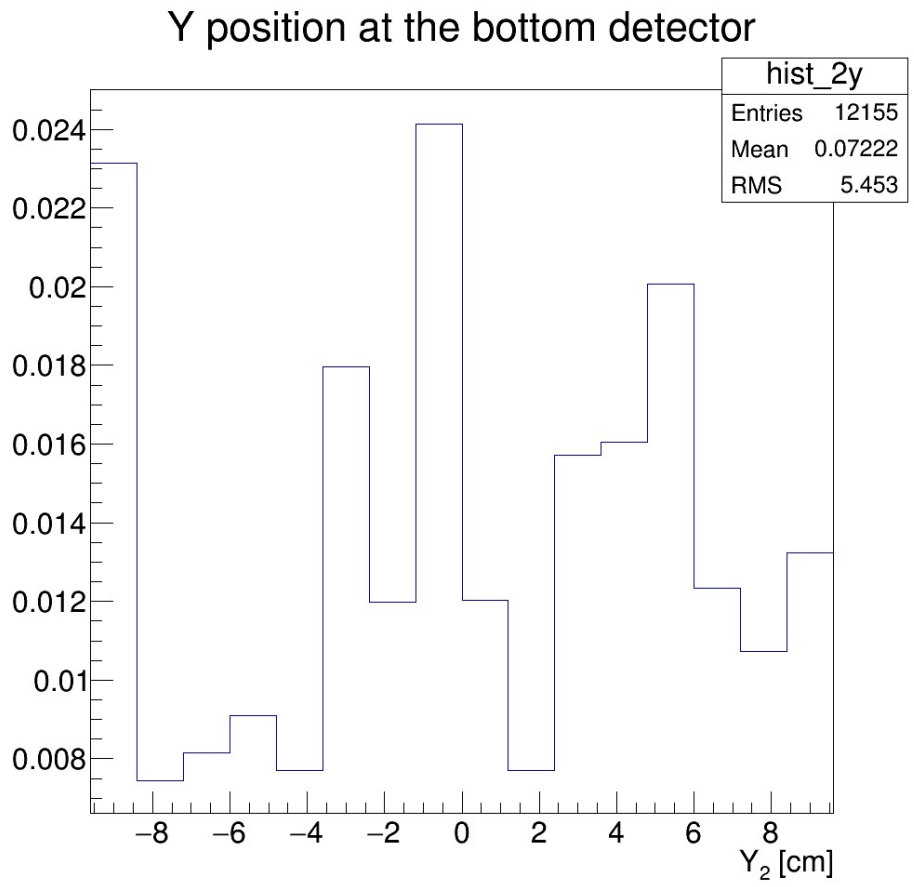
Hit position at the top detector without lead block



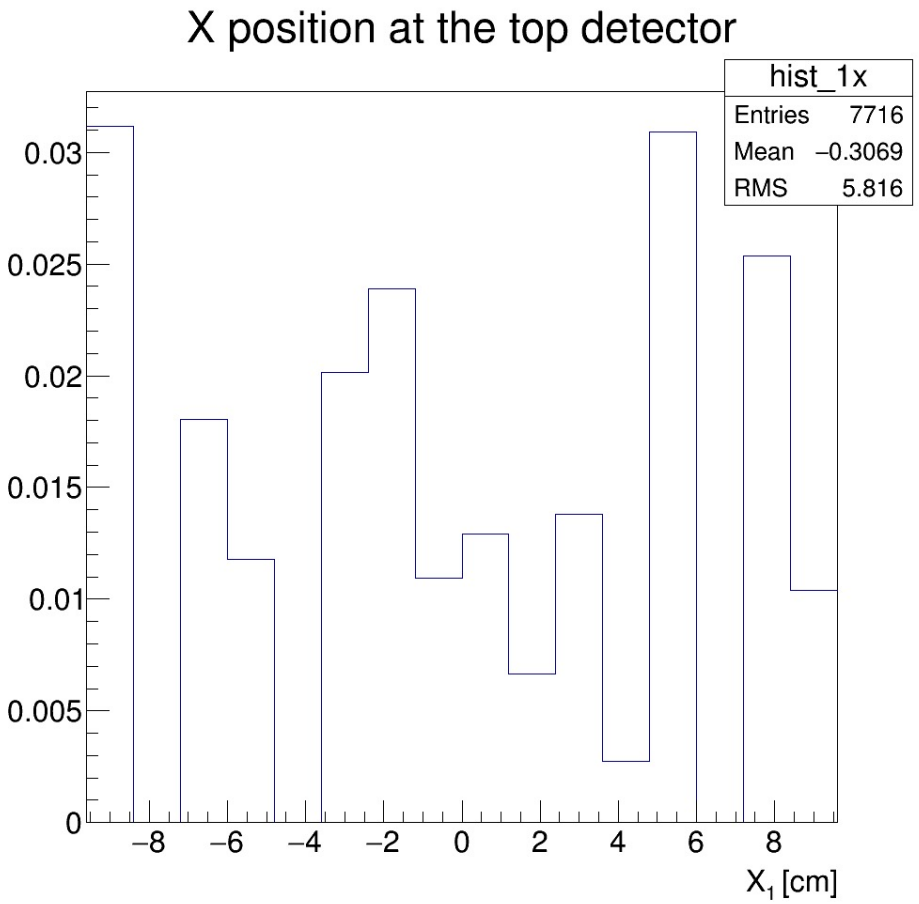


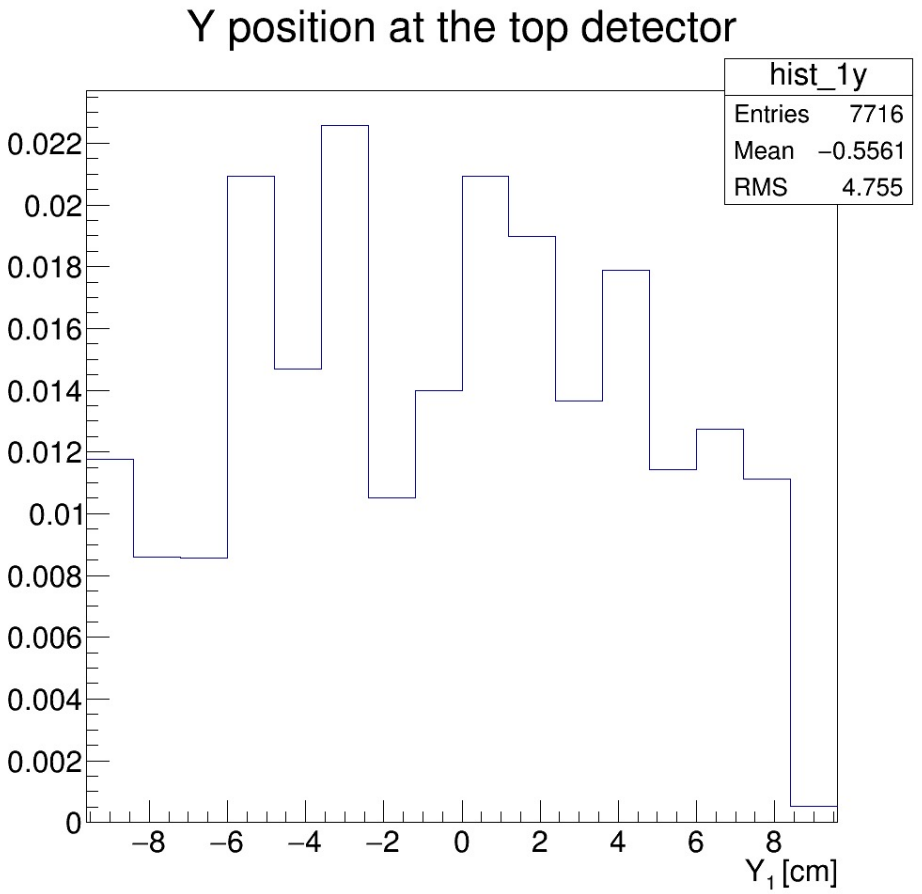
Hit position at the bottom detector without lead block



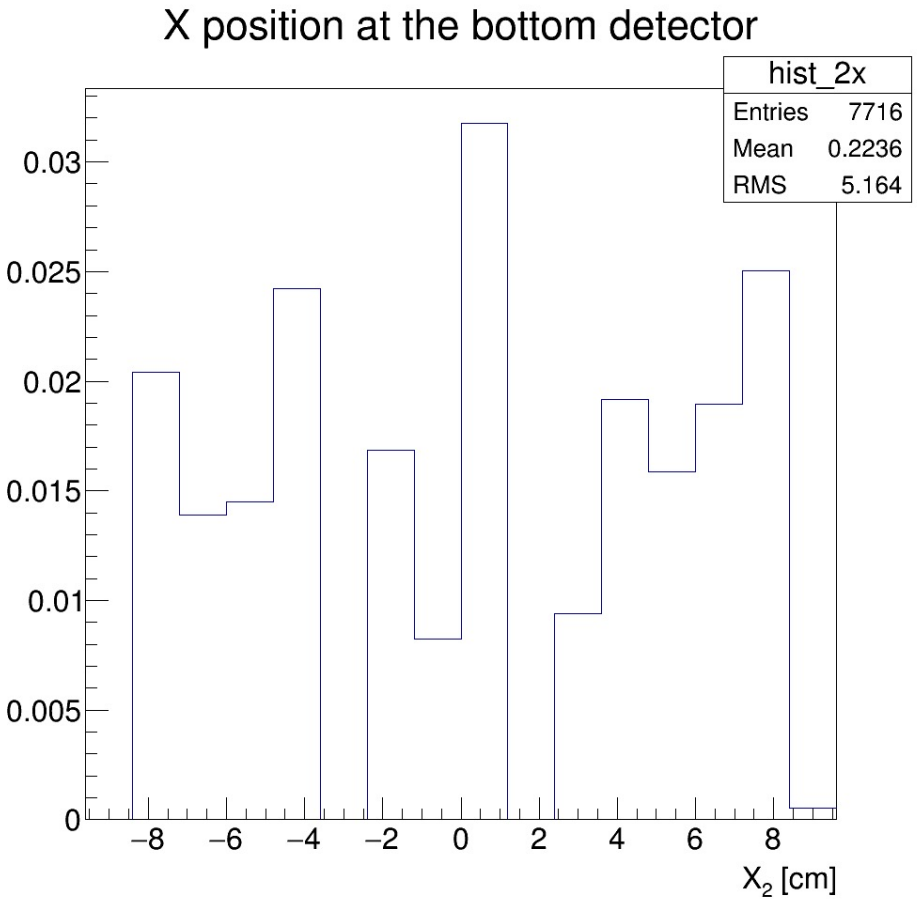


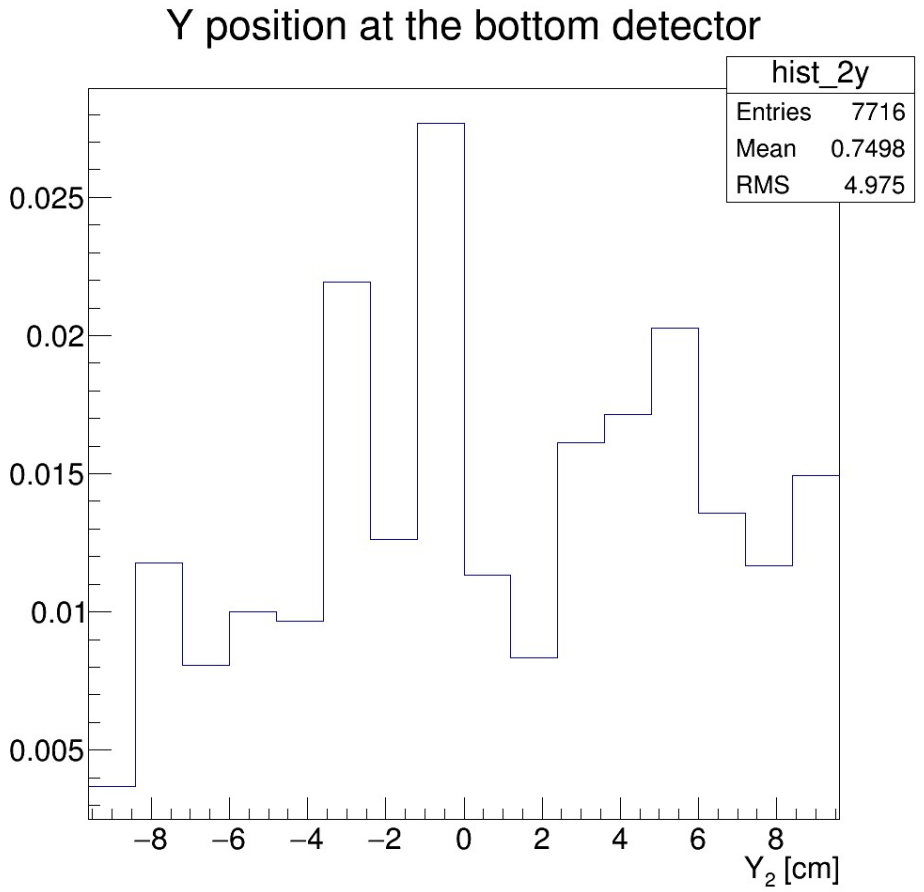
Hit position at the top detector with lead block





Hit position at the bottom detector with lead block



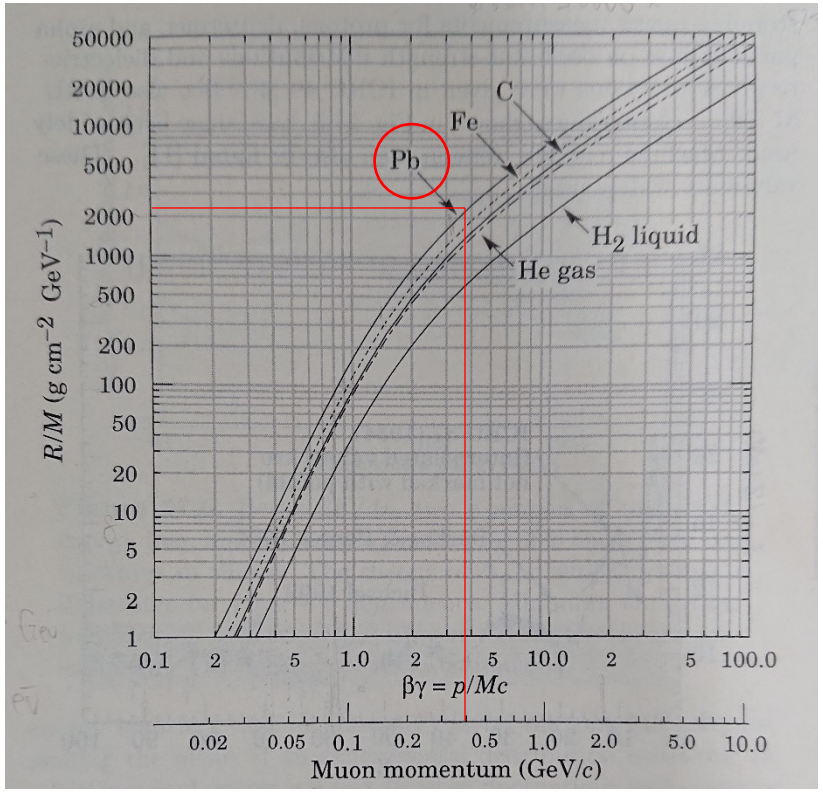


Range in Pb

- $R = 11.34[g/cm^3] \times 20\ [cm]$
  $= 226.8\ [g/cm^2]$… Pb surface density
- $M = 0.1056$ [GeV]…muon mass

- $R/M = 2148\ [g/cm^2/\text{GeV}]$
  ↓
- $p = 300 \sim 400$ [MeV]…muon momentum

*from Journal of Physics



Future plan

- Change the placement to measure attenuation along the depth direction of the target object

- Change the target object and its configuration to distinguish one from the other