Study of cosmic ray deflection on the Pb brick

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+ Experts/Students from Purple Mountain Observatory

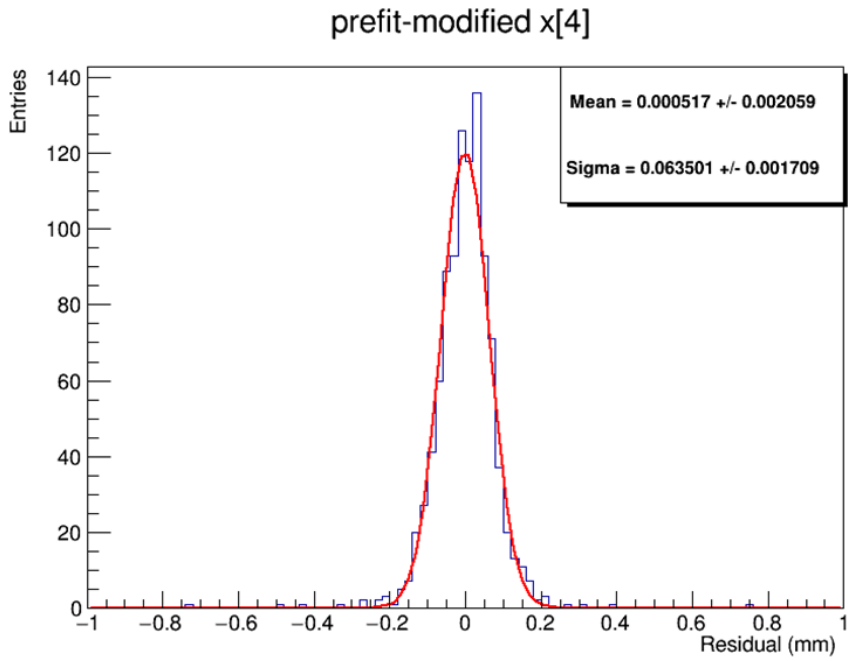
Data taking and Track alignment

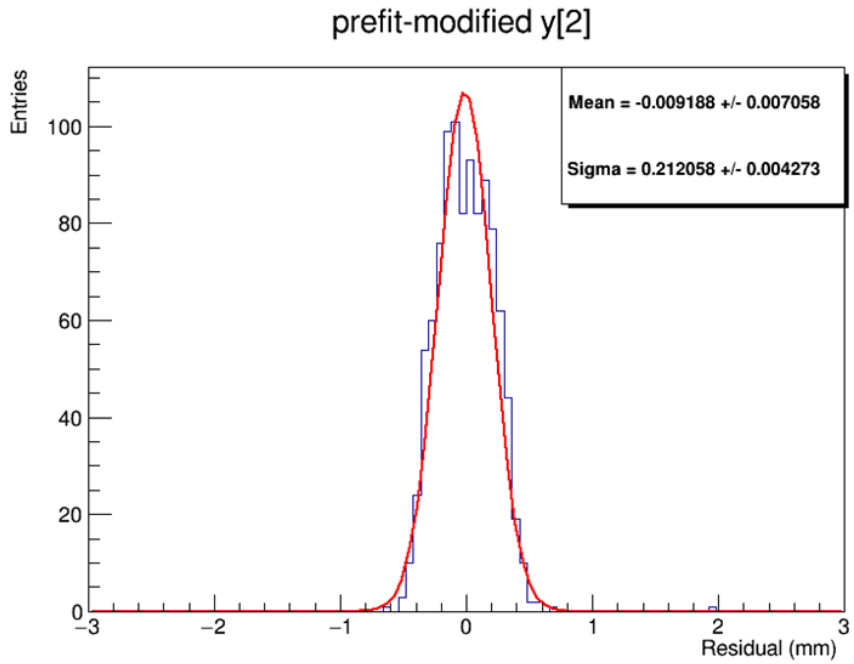
- Data taking without Pb brick for track alignment calibration: 2 weeks
- Data taking with 3cm Pb brick for scattering measurement: 3 weeks
- Now the detector is shut down and will be disassembled soon (next week).

Index	x (mm)	y (mm)	z (mm)	x°	y°	z°
0	-0.4287	0	1.255	3.39e-06	0.03748	-2.08e-06
1	0	0.1759	5.651	0.04047	-5.80e-07	-1.19e-06
2	-0.04316	0	99.76	-3.39e-06	0.0001083	-1.96e-06
3	0	0.6328	105.1	0.06500	-1.35e-06	-1.20e-06
4	1.008	0	198.9	-2.55e-06	0.004195	-1.98e-06
5	0	-1.288	204.1	0.06613	-2.06e-06	-1.16e-06
6	-0.3751	0	449.3	-3.93e-06	-0.004489	-1.94e-06
7	0	0.5503	455.1	0.06119	-1.05e-06	-1.21e-06
8	-0.6118	0	600.2	3.32e-06	0.03260	-1.98e-06
9	0	-0.01147	604.5	0.05863	-1.20e-06	-1.20e-06
10	0.4509	0	750.6	4.06e-06	0.04160	-2.10e-06
11	0	-0.05971	755.6	0.04537	-6.30e-07	-1.21e-06

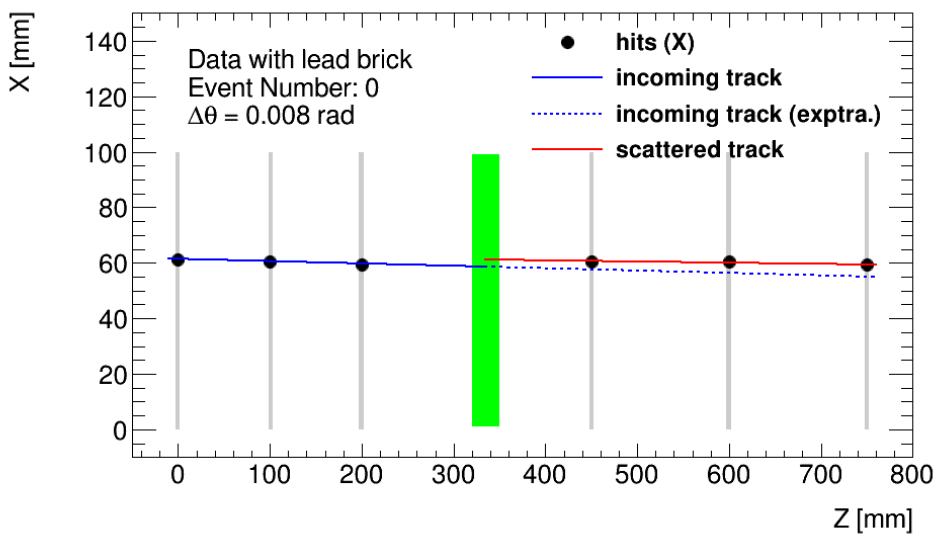
Residuals after track alignment

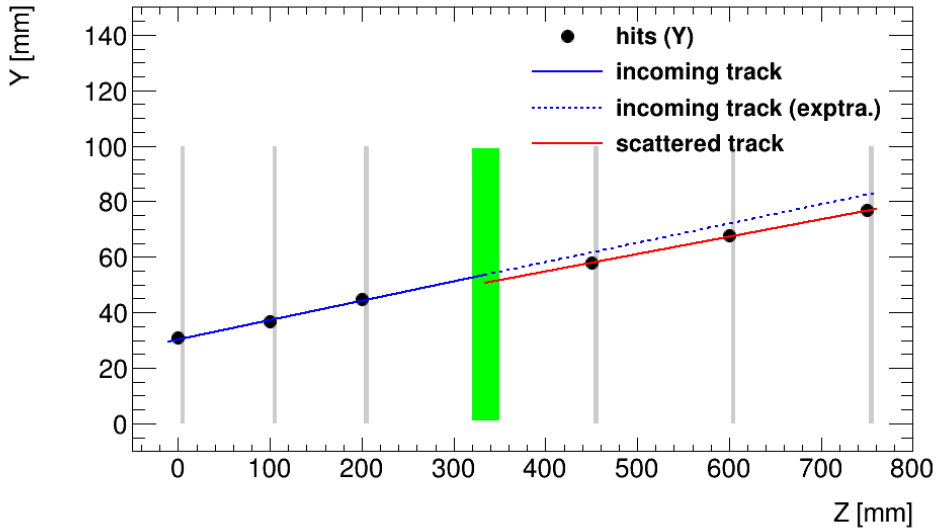
After track alignment, the detector resolution is 63.5um at best and 212um at worst.



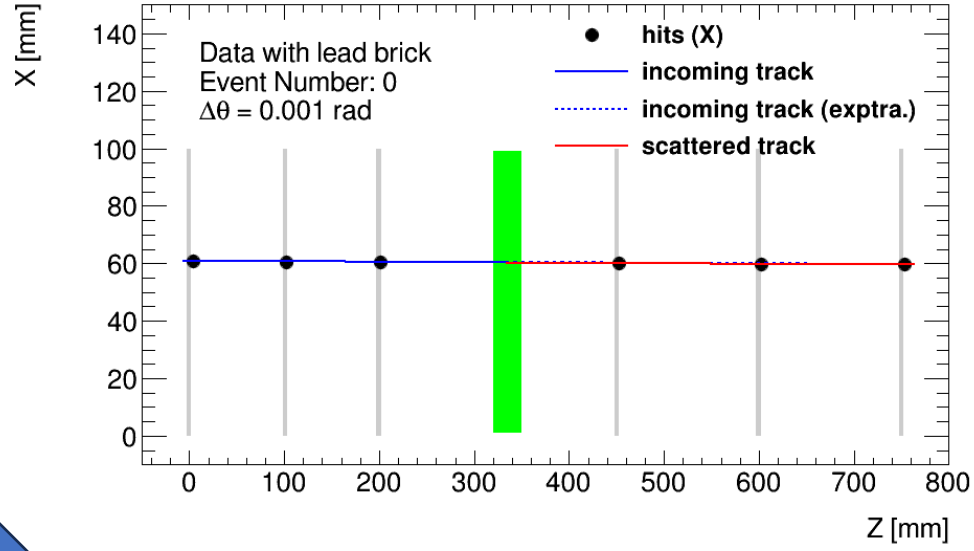


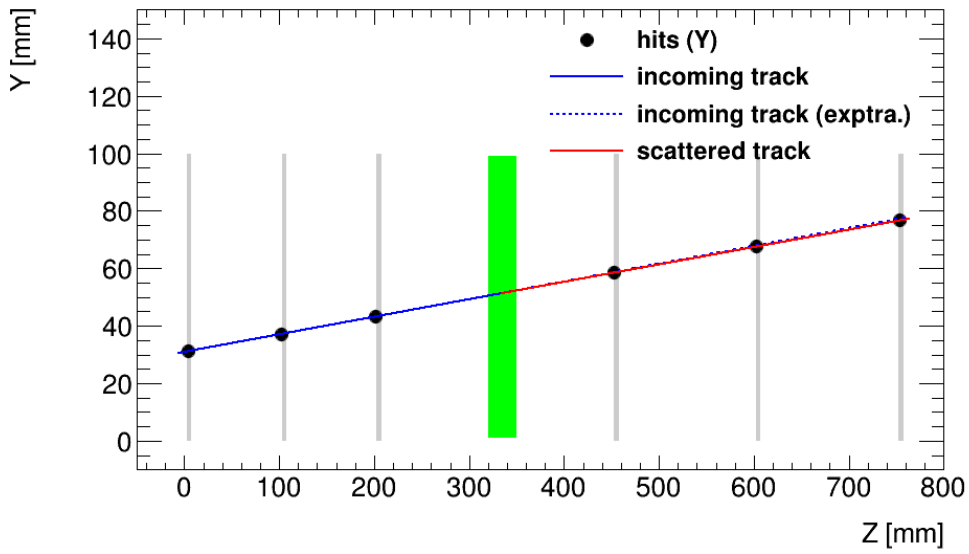
with or w/o alignment





alignment



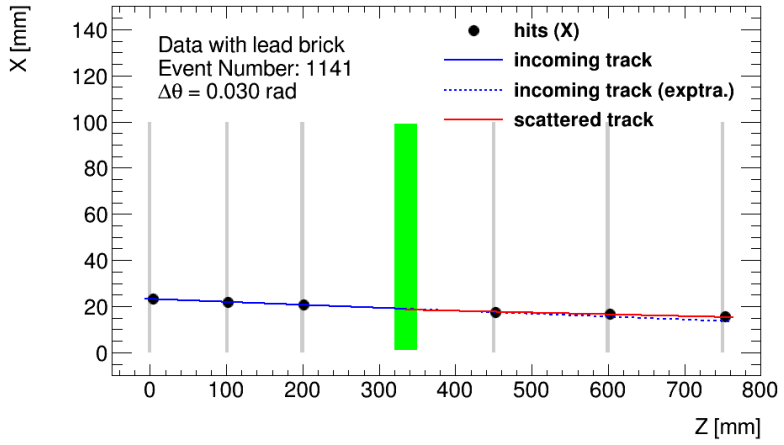


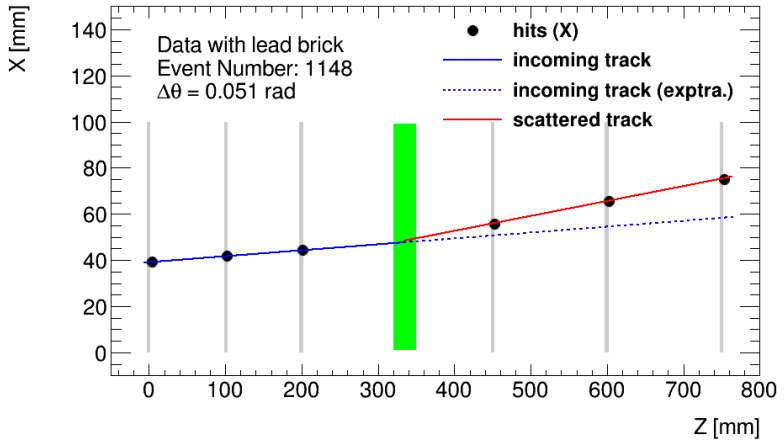
Deflection angle calculation

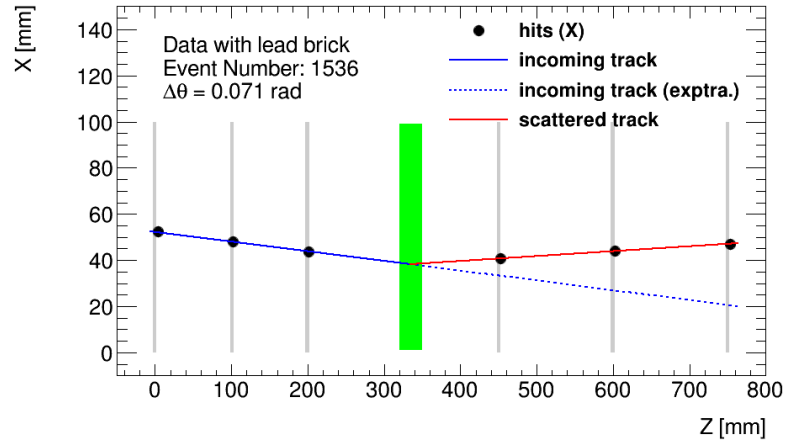
- incoming track: $(k_1 z + b_1, k_2 z + b_2, z) \propto (k_1 \Delta z, k_2 \Delta z, \Delta z)$
- scattered track: $(k_1' z + b_1', k_2' z + b_2', z) \propto (k_1' \Delta z, k_2' \Delta z, \Delta z)$
- deflection angle:

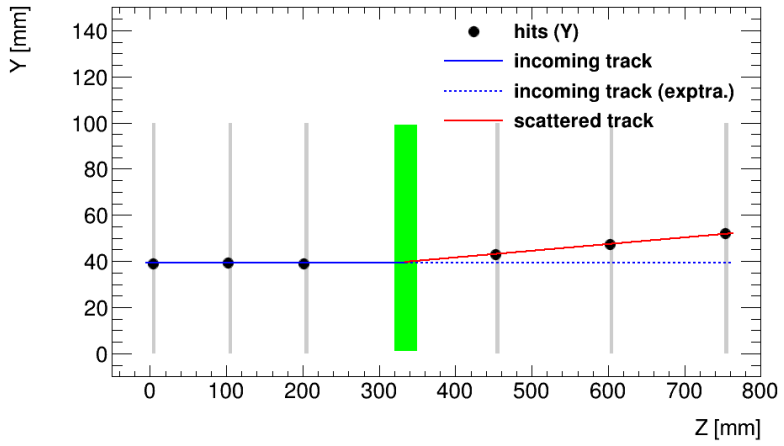
$$cos\theta = \frac{k_1 k_1' + k_2 k_2' + 1}{\sqrt{(k_1^2 + k_2^2 + 1)(k_1'^2 + k_2'^2 + 1)}}$$

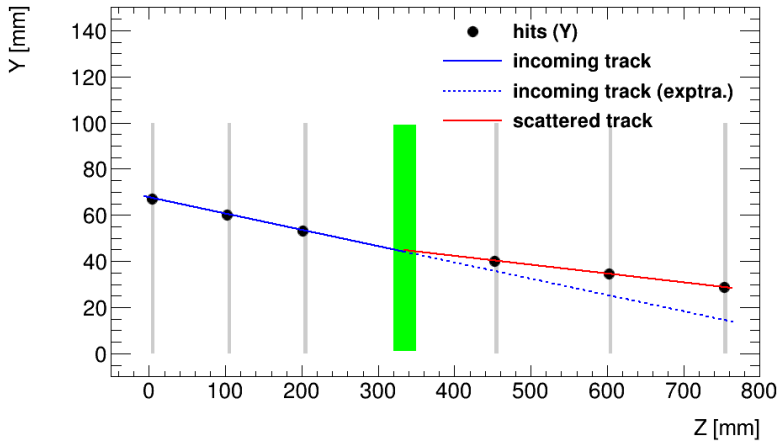
Examples for big deflections

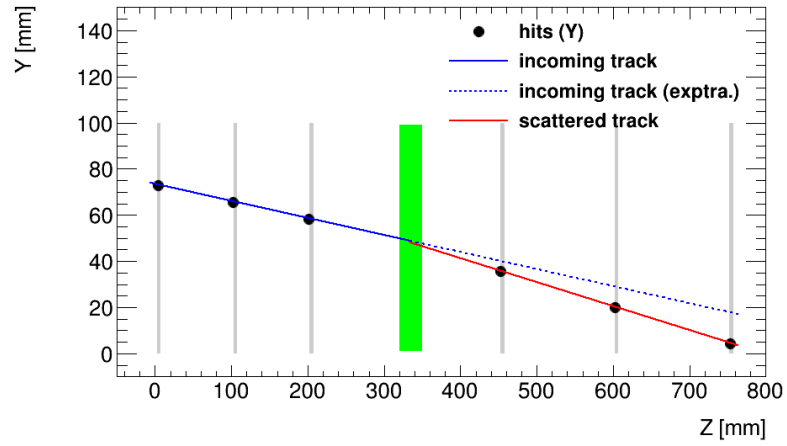






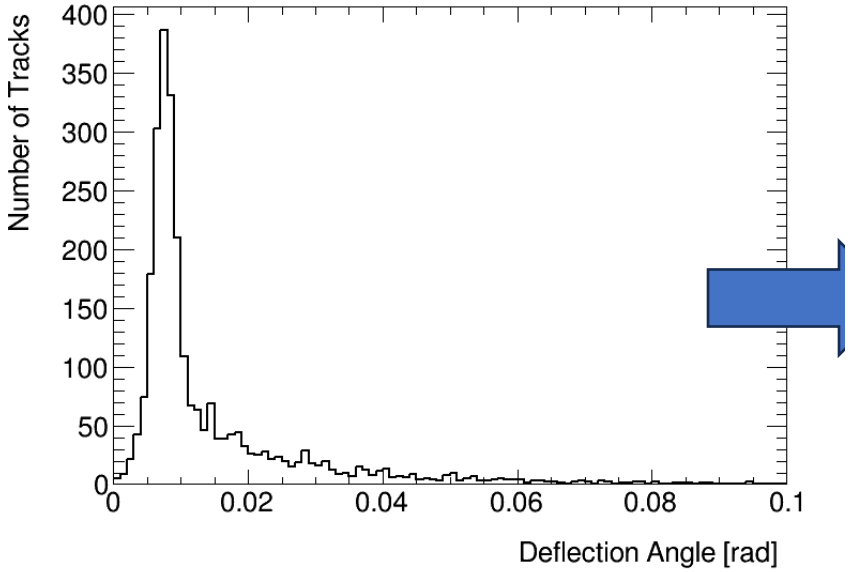




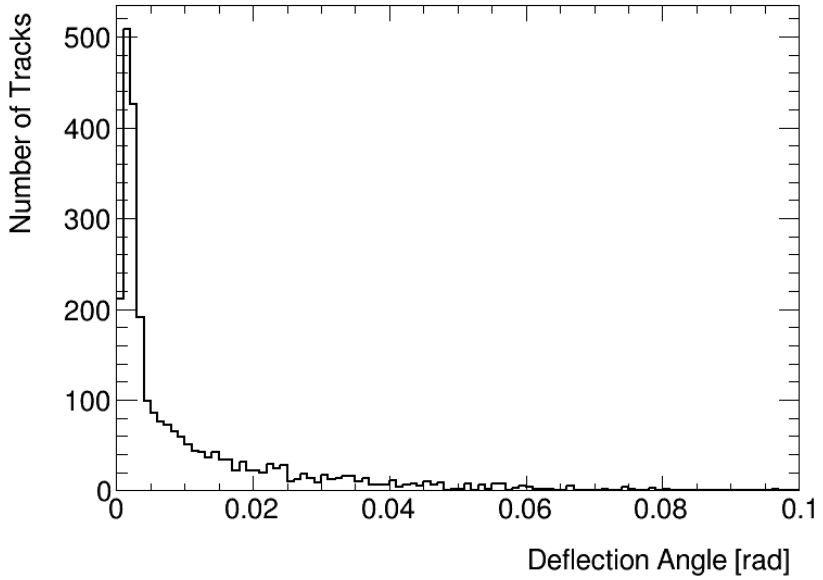


Deflection angle distributions

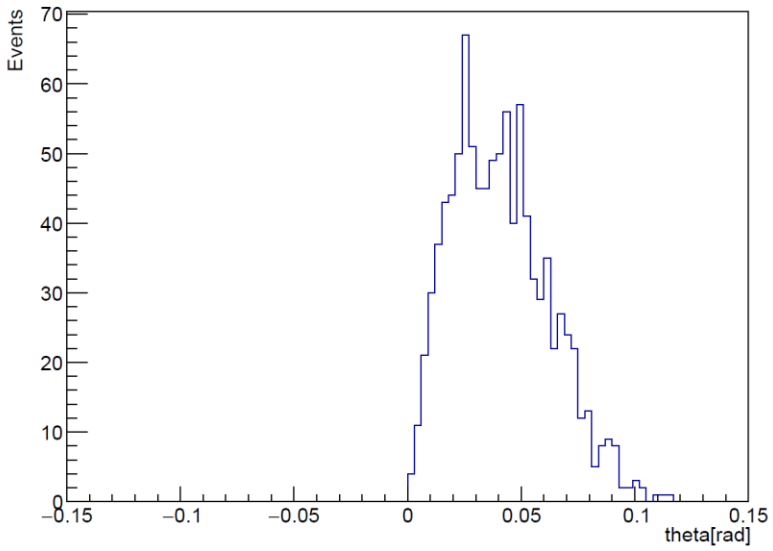
before alignment



after alignment

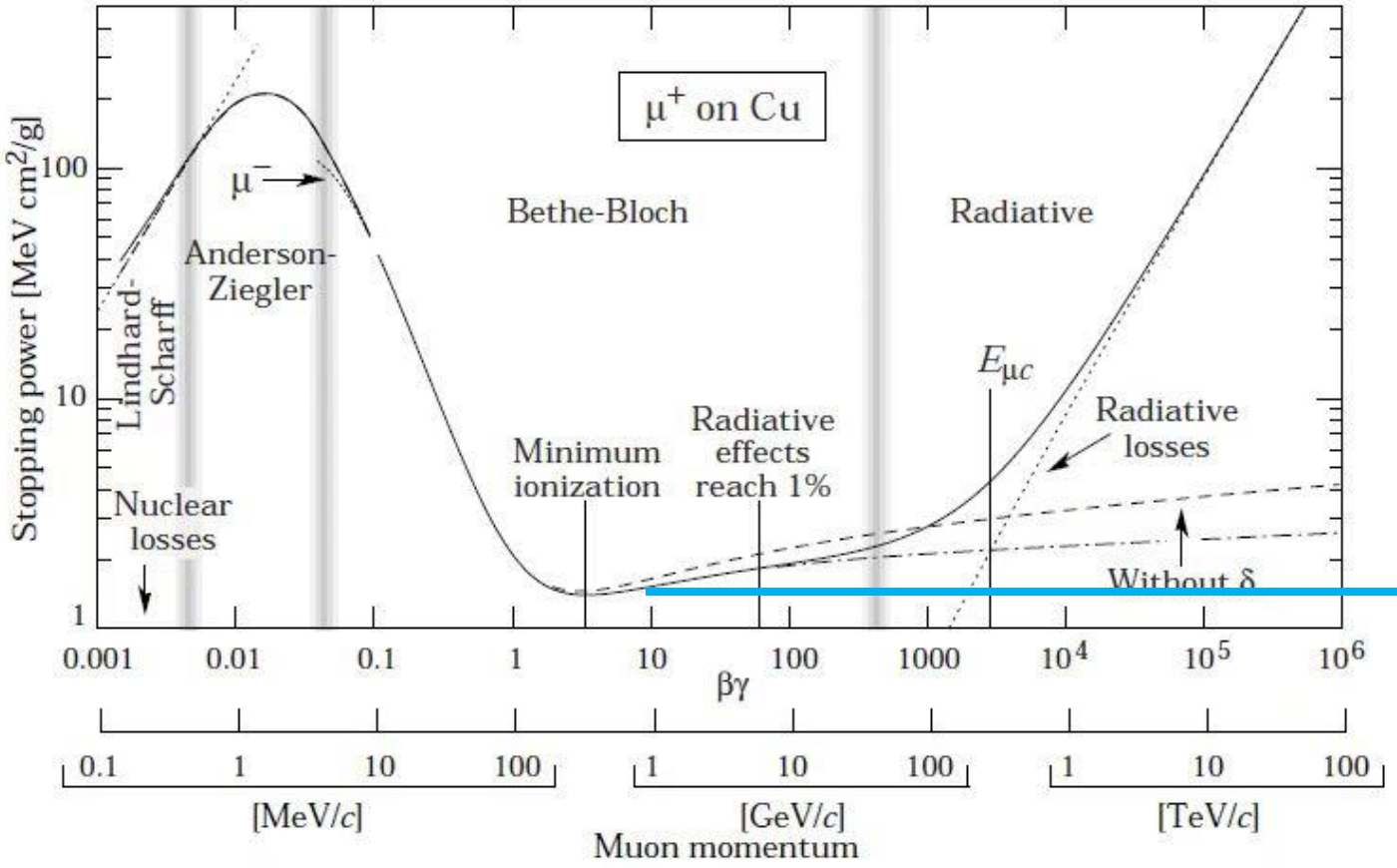


simulation



1GeV mu垂直入射30 mm铅块折射角度分布仿真图（孙行阳）

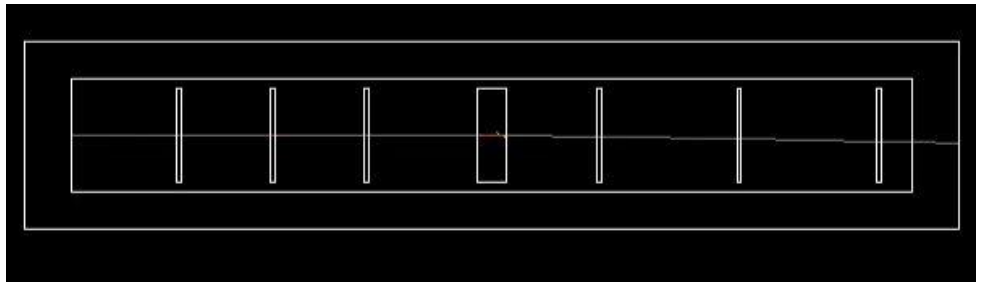
Energy filter

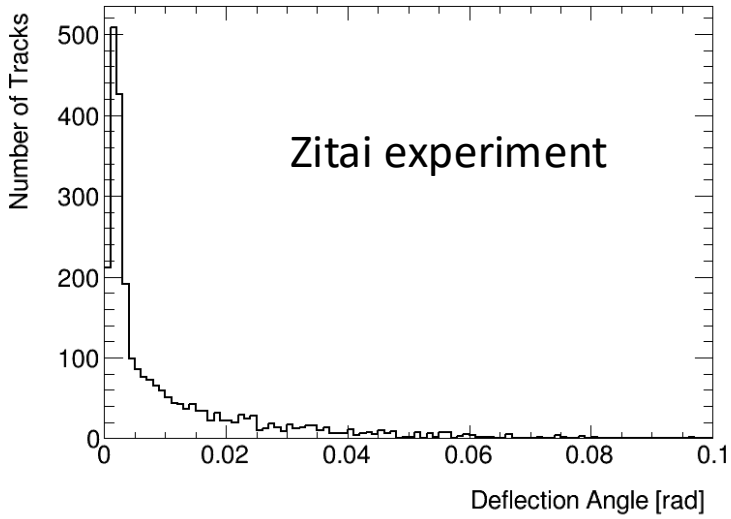


- For 1 GeV, the stopping power is about 1.5 MeV cm^2/g
- Lead density is 11.3 g/cm^3.
- Assume a thickness of 60 cm

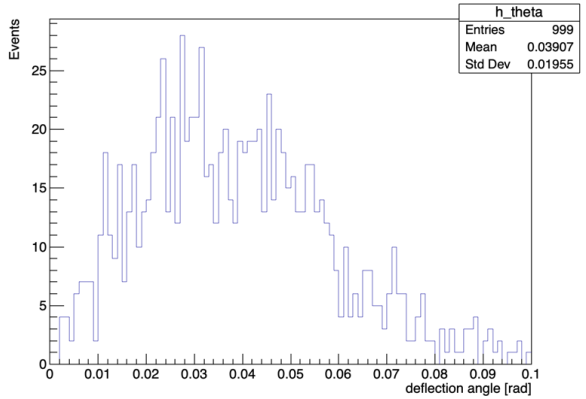
11.3*1.5*60=1017 MeV

Geant4 simulation

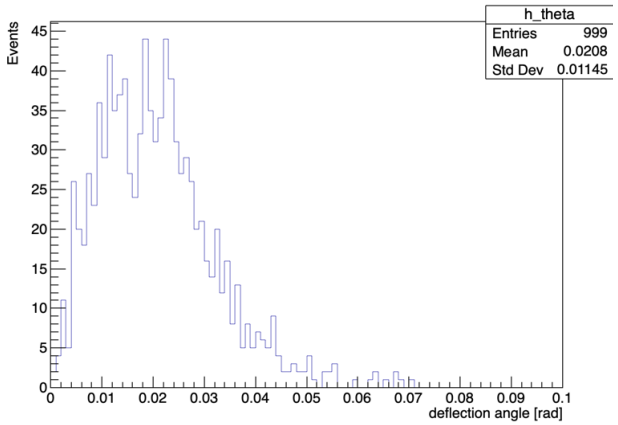




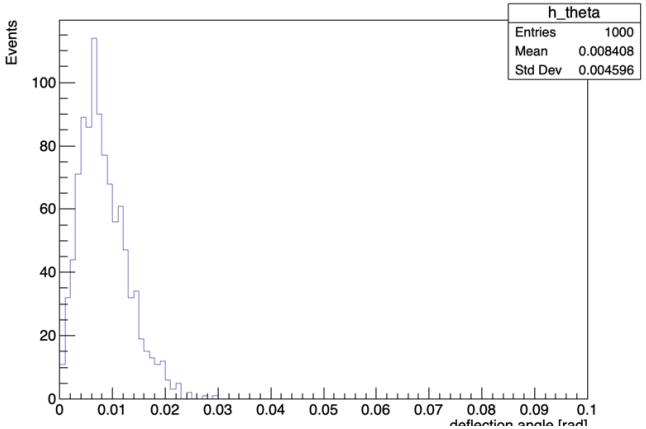
1GeV

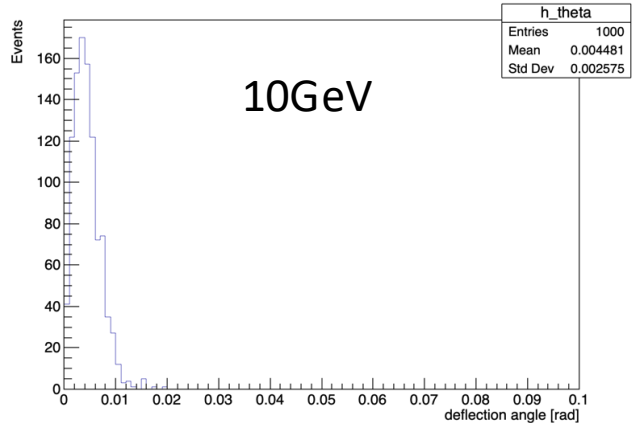


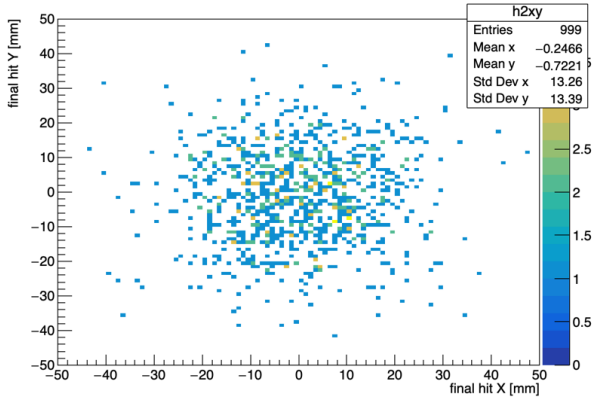
2GeV

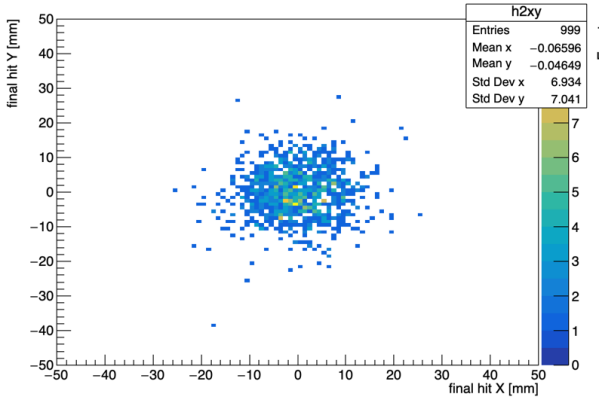


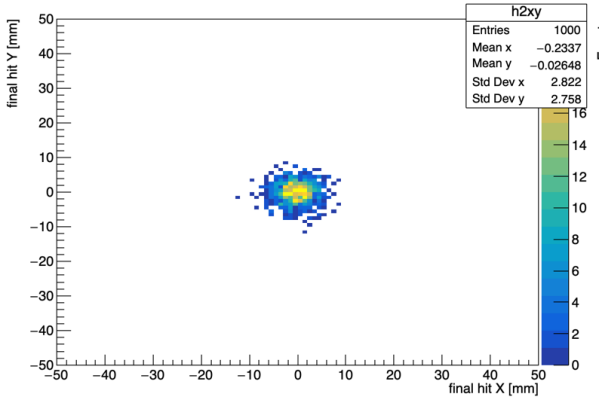
5GeV

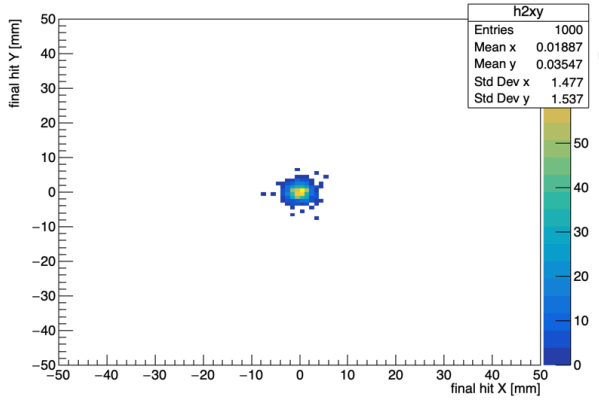




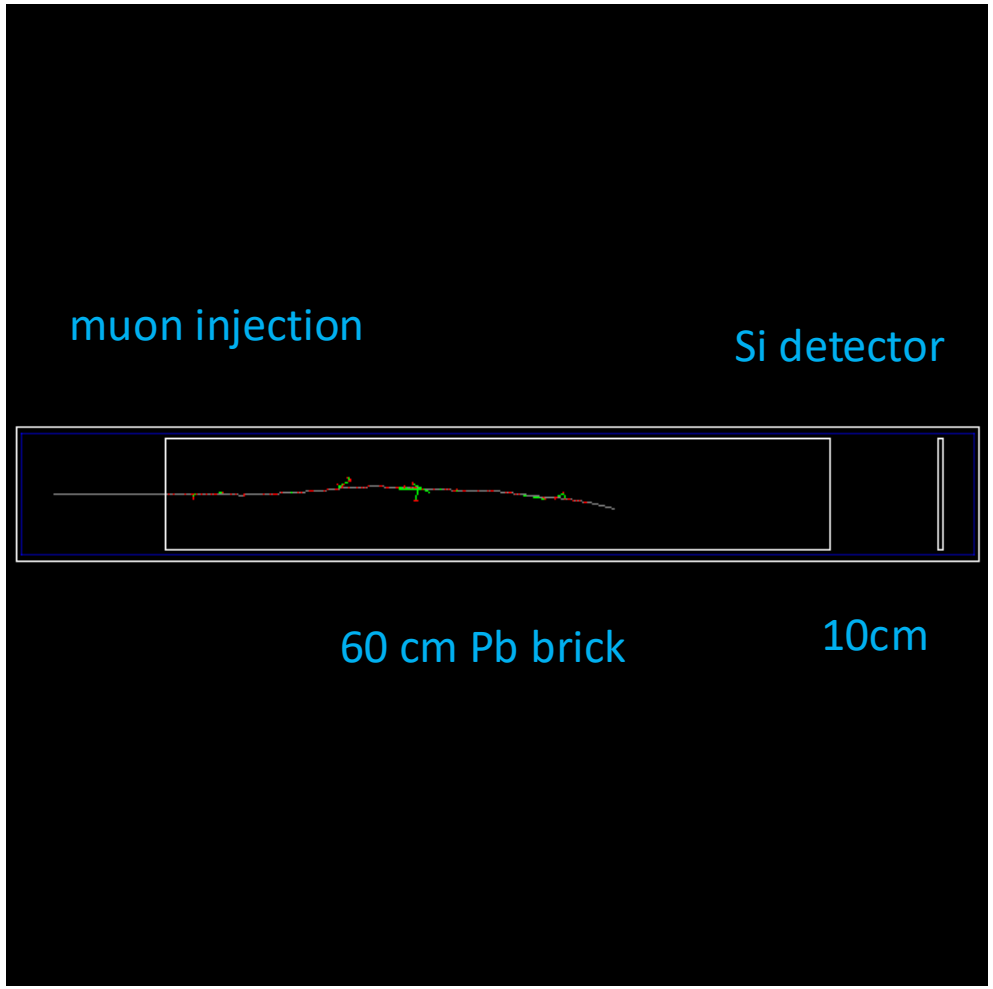








Geant4 simulation of muon energy filtering



setup:

- a 60-cm-thick Pb brick
- a silicon detector with 10cm from the Pb brick

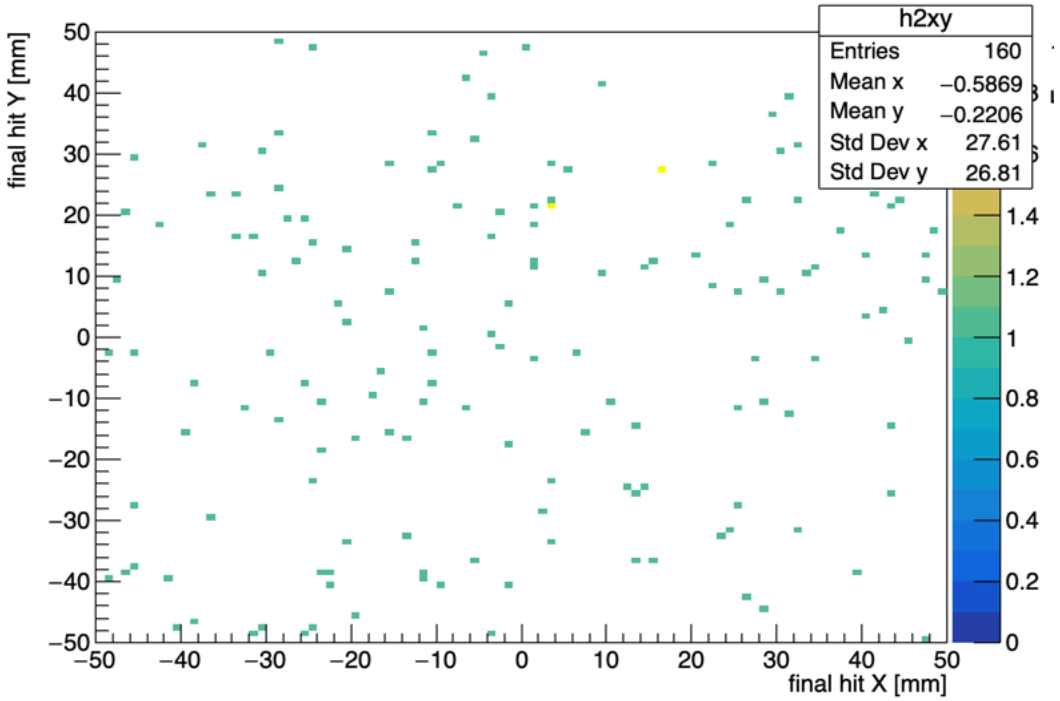
In reality, we have

- 48 cm Pb bricks at the bottom of the detector
- 4 layers of Reinforced Concrete (density is 2.5g/cm^3)
- each layer is 10cm-15cm thick.
- the total effective Pb thickness is 48+4*(10~15)*2.5/11.3=57~61 cm.

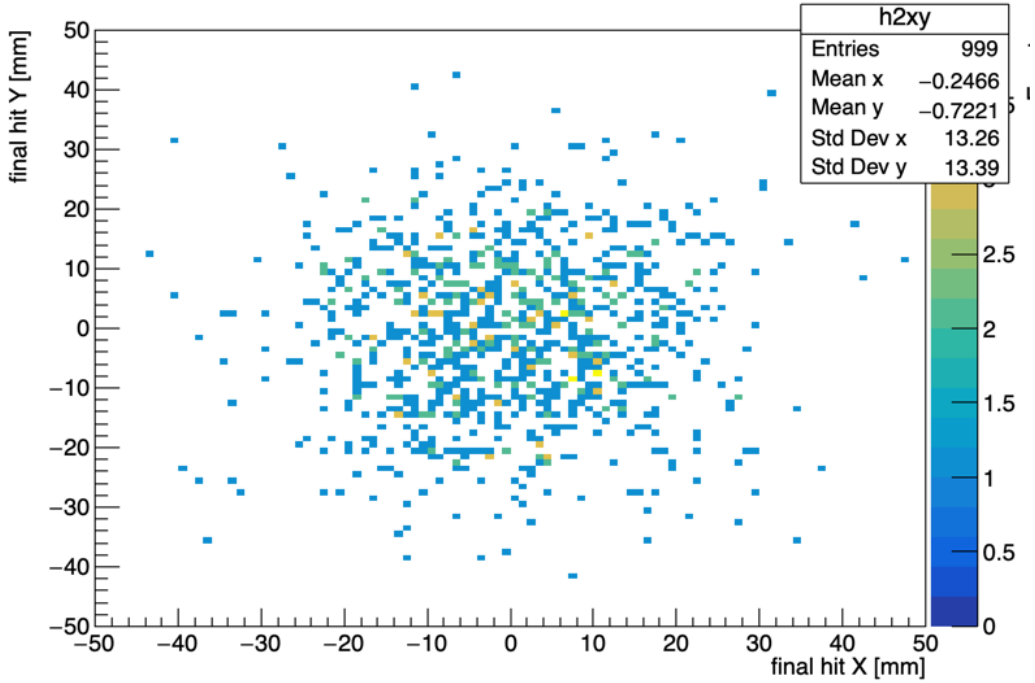
muon energy filter: 60 cm Pb brick

1000 muons with p=1GeV at production
pass rate=16% (10cm between Pb and detector)

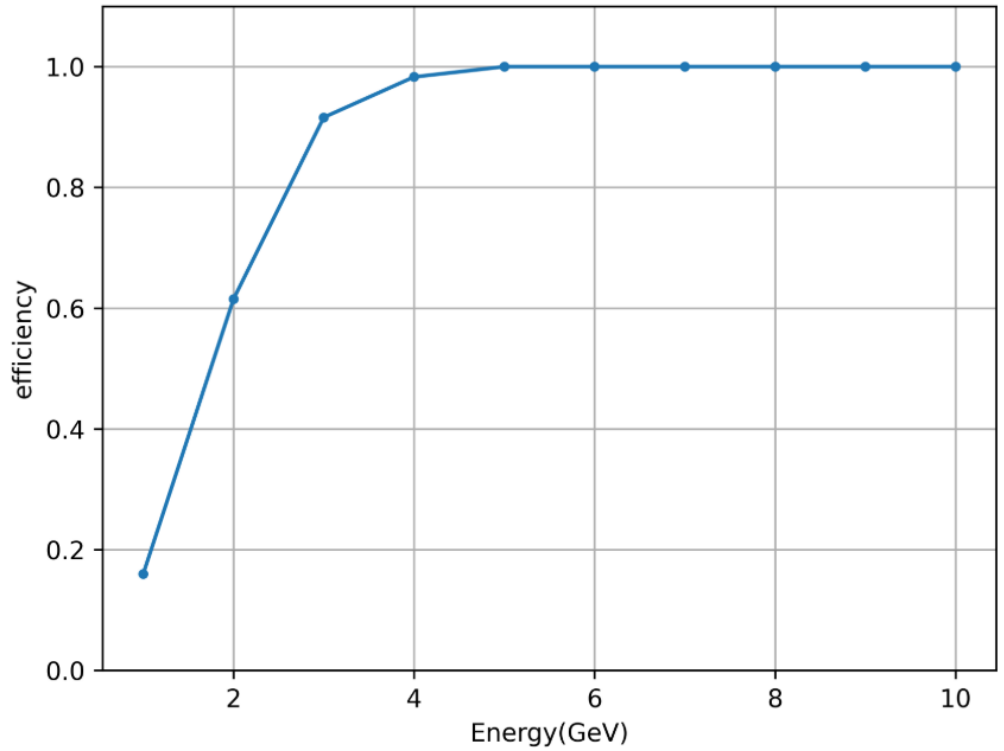
60cm Pb



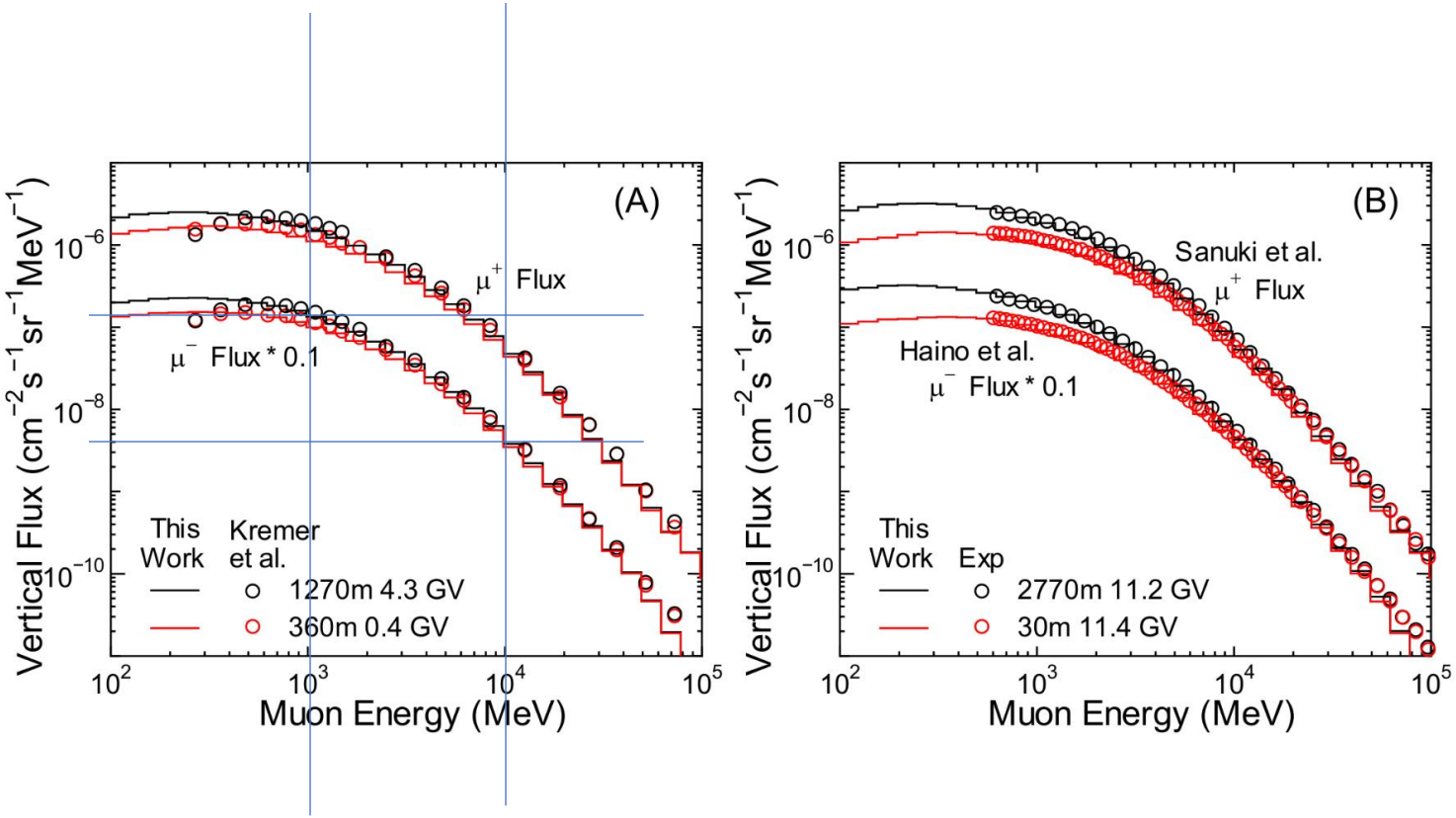
3cm Pb



Energy filtering efficiency for a 60cm-thick lead brick



Cosmic muon energy spectrum approximation



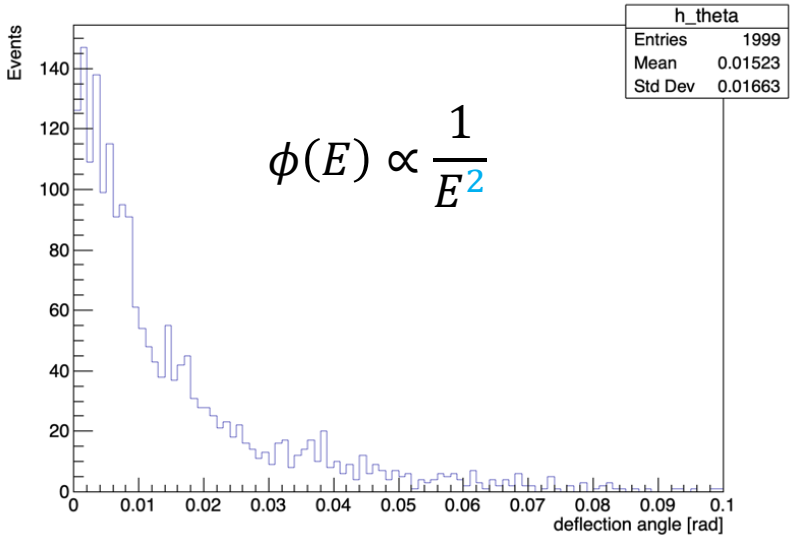
$$\phi(E) \propto \frac{1}{E^{1\sim2}}$$

$$\epsilon(E) = \begin{cases} 0.1 + \dfrac{1-0.1}{5-1}(E-1), E < 5GeV \\ 1, E \geq 5GeV \end{cases}$$

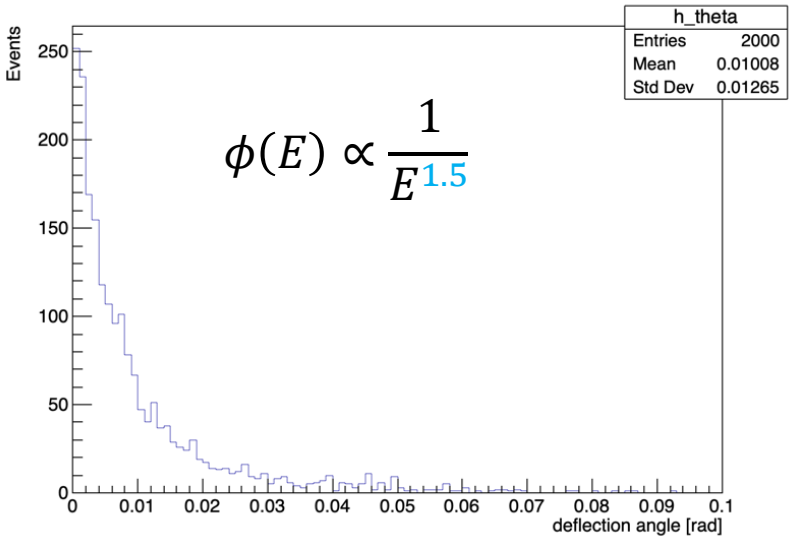
$$\phi^{obs}(E) = \phi(E) \times \epsilon(E)$$

Paper: https://journals.plos.org/plosone/article/file?id=10.1371/journal.pone.0144679

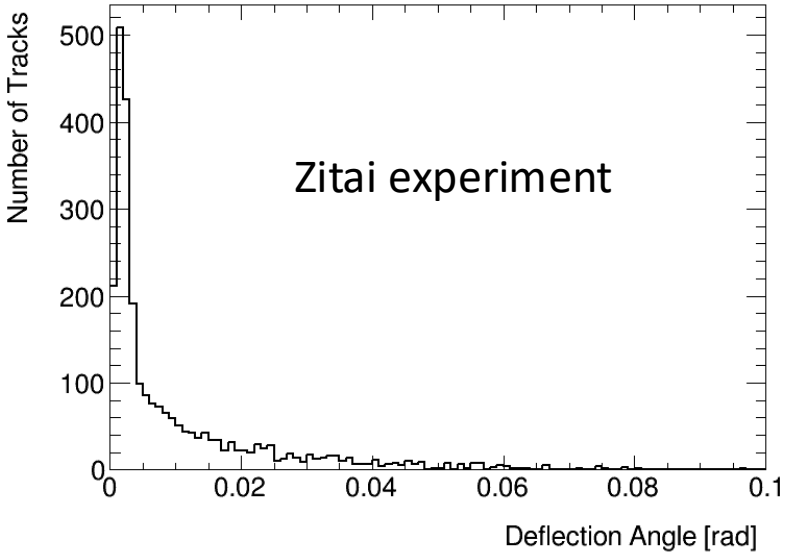
Geant4 simulation for cosmic muons

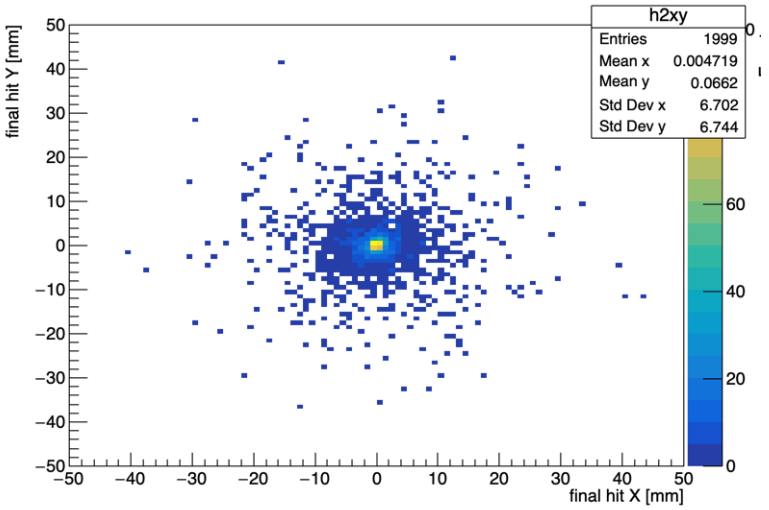


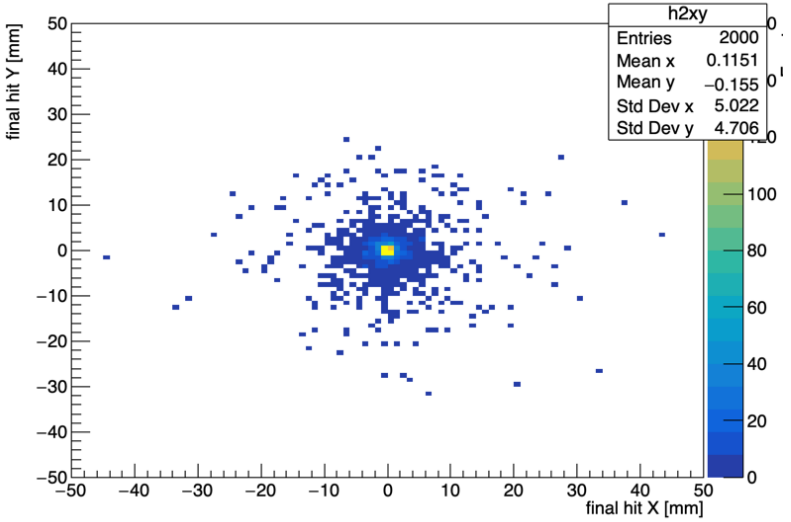
$$\phi(E) \propto \frac{1}{E^2}$$



$$\phi(E) \propto \frac{1}{E^{1.5}}$$

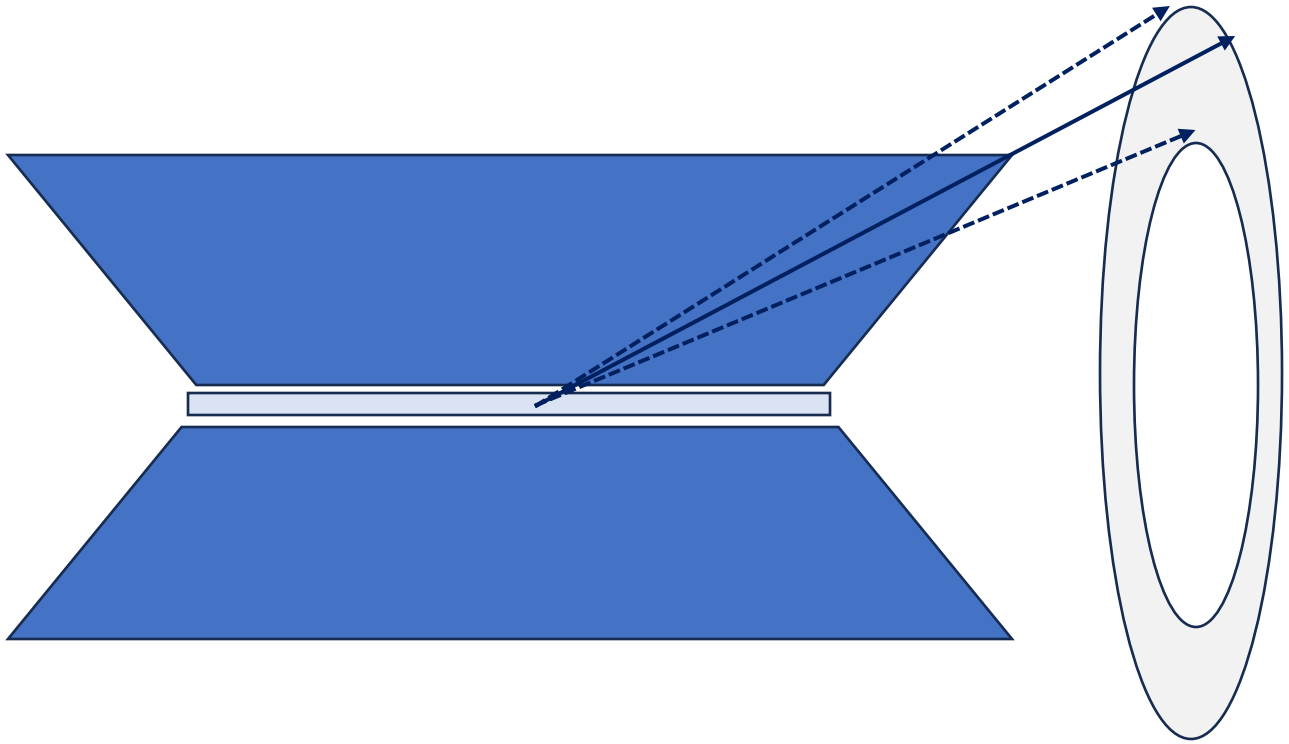


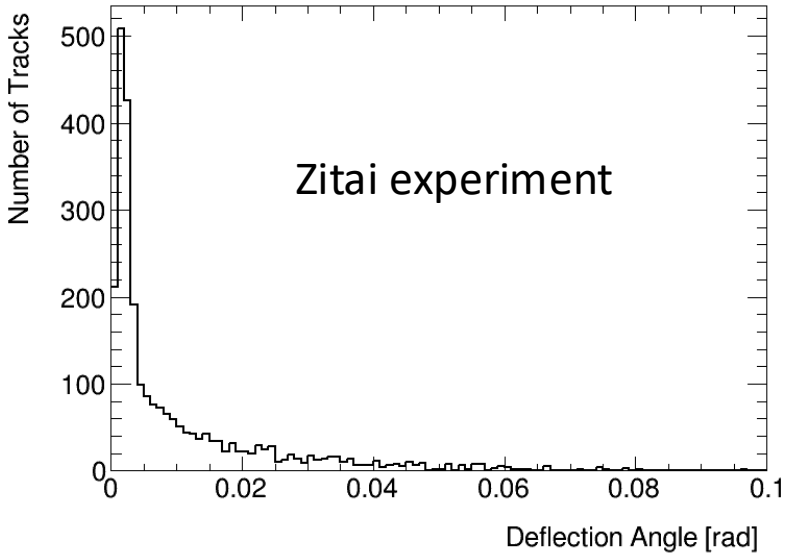


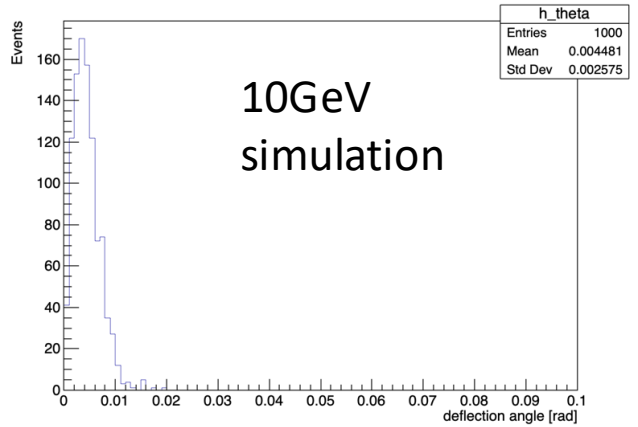


Luminosity measurement (Bhabha events)

- Bhabha cross section explodes at ~0 degree.
- E(e+/e-) > 100 GeV (CEPC)
- In this scattering experiment, we cannot measure muon energy. The data indicates that the deflection angle is < 0.005 for muons > 10 GeV.
- Based on this, how much uncertainty?







Summary

- Preliminary analysis of the lead scattering data
- The scattering angle distribution is consistent with geant4 simulation (based on rough muon energy spectrum and efficiency)

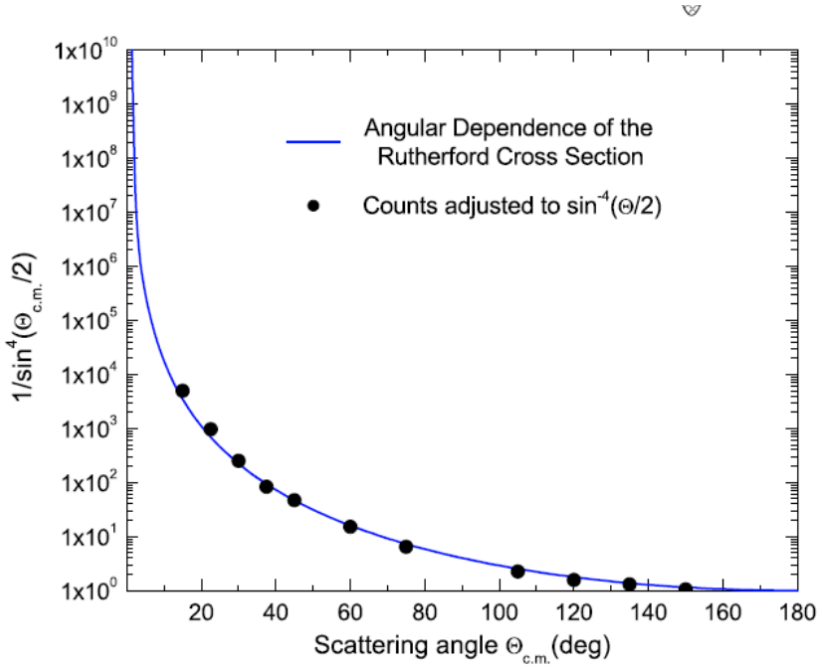
- Work to do:
  - Precise muon energy spectrum and energy filtering efficiency
  - Consider different muon directions at injection
  - Estimate the impact on the luminosity measurement using bhabha due to Be pipe

- BACK UP

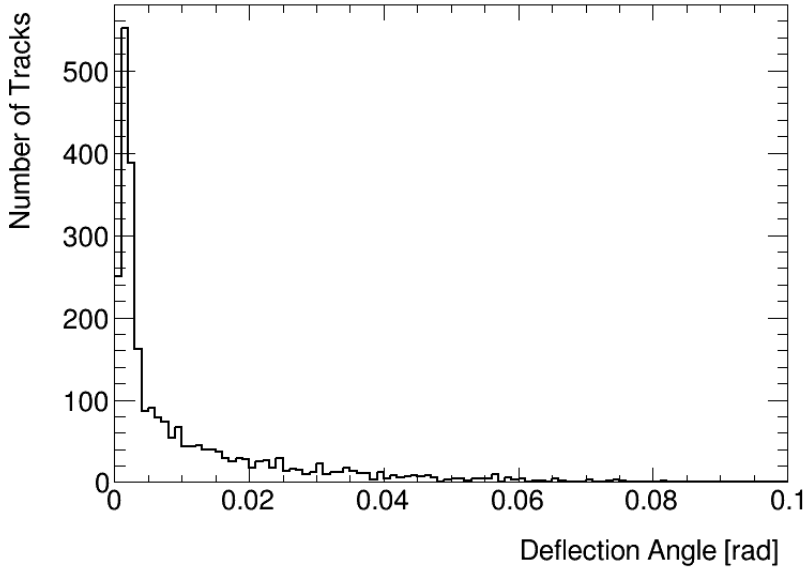
Deflection angle distributions

Coulomb scattering cross section:

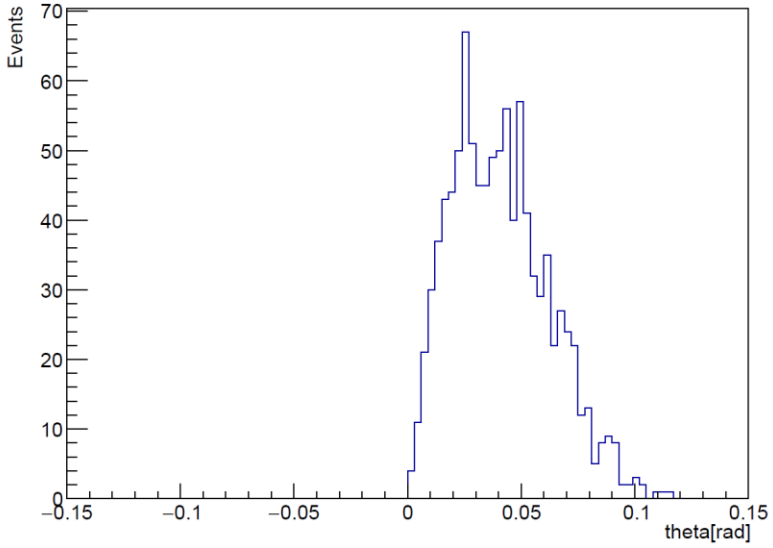
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2|\mathbf{p}|^2\beta^2\sin^4(\theta/2)}\left(1-\beta^2\sin^2\frac{\theta}{2}\right)$$



after alignment



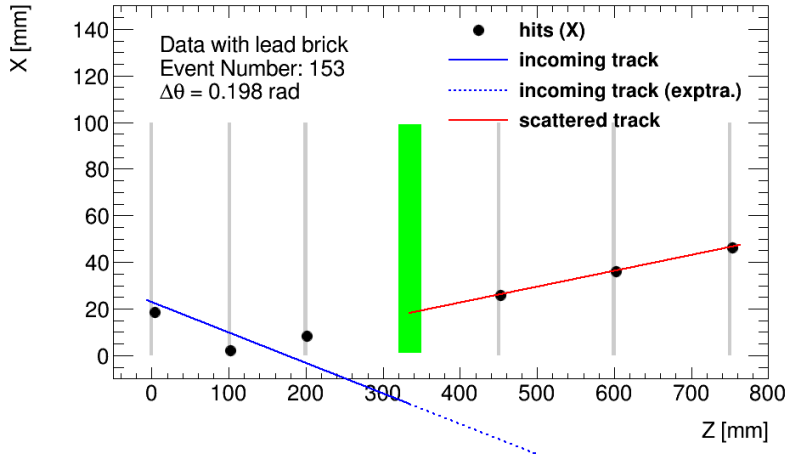
simulation

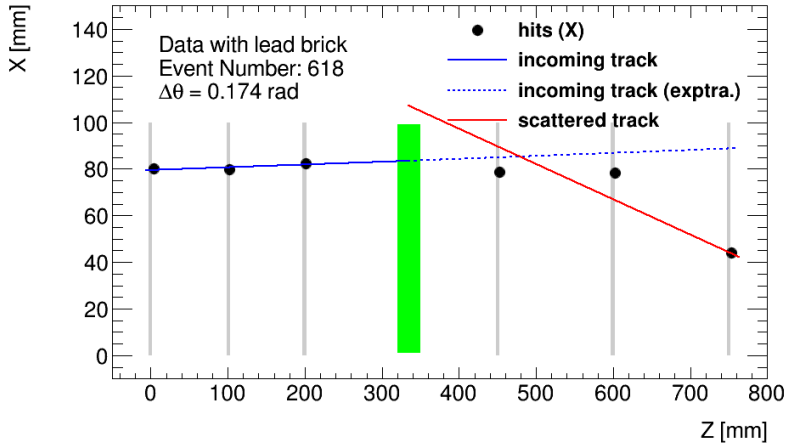


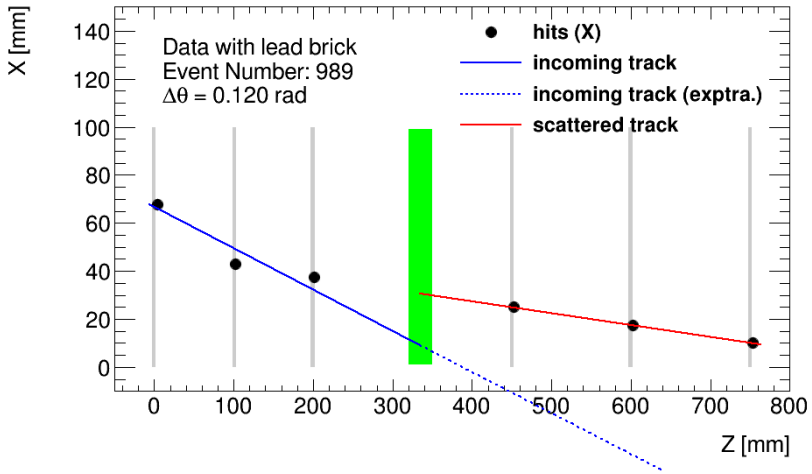
1GeV mu垂直入射30 mm铅块折射角度分布仿真图（孙行阳）

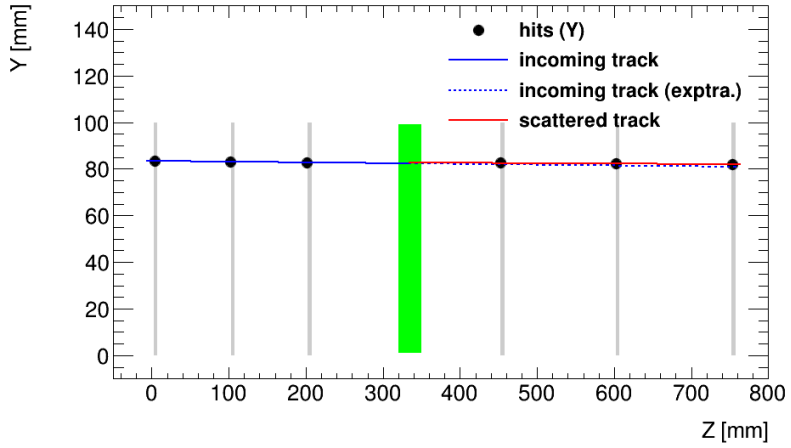
Is it wrong or due to multiple scattering?

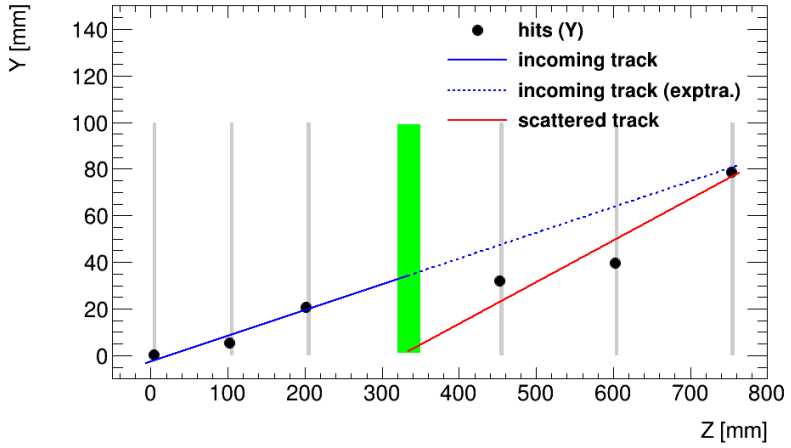
Examples for bad tracks

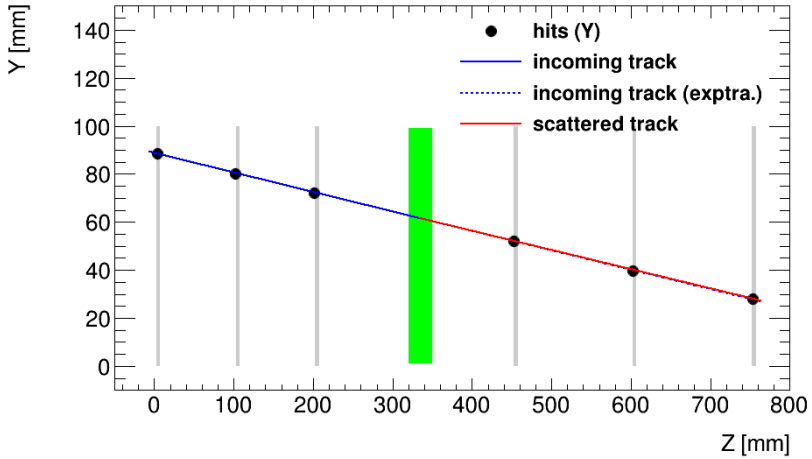




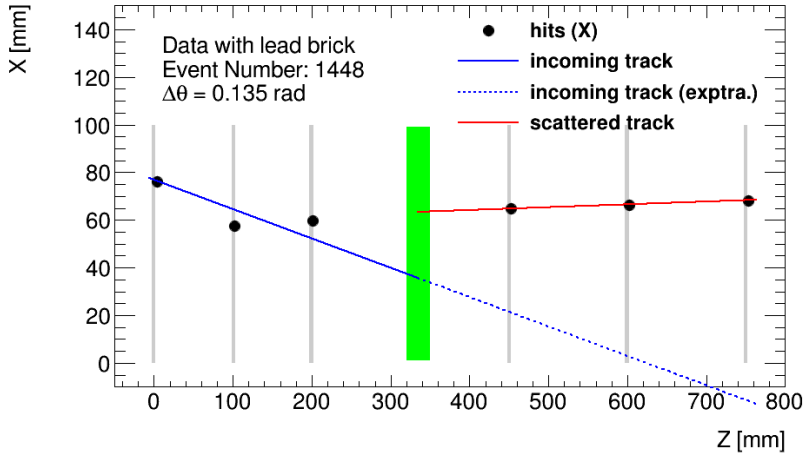


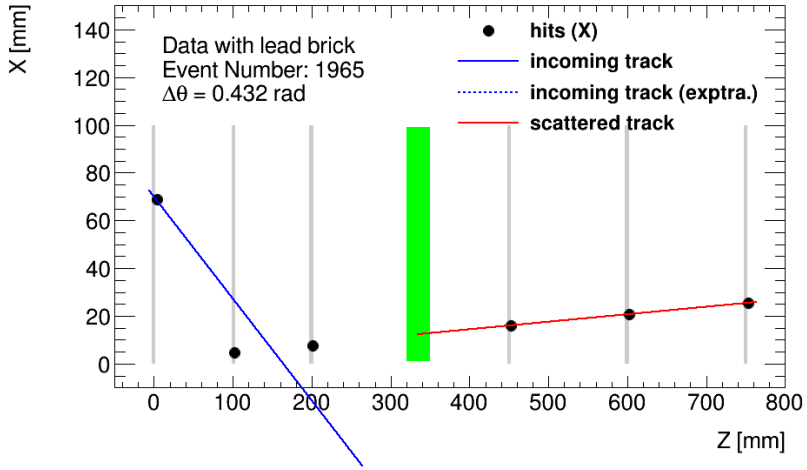


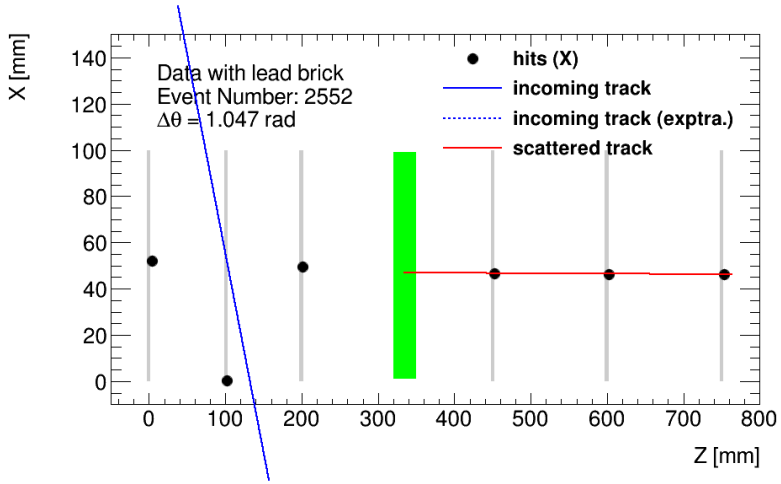


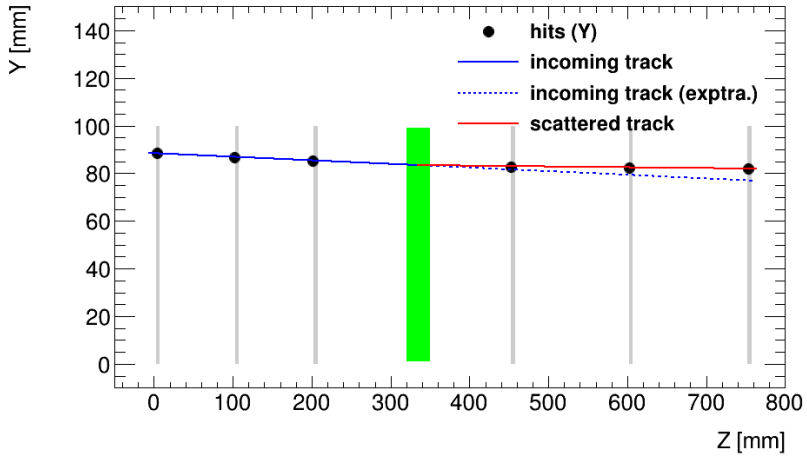


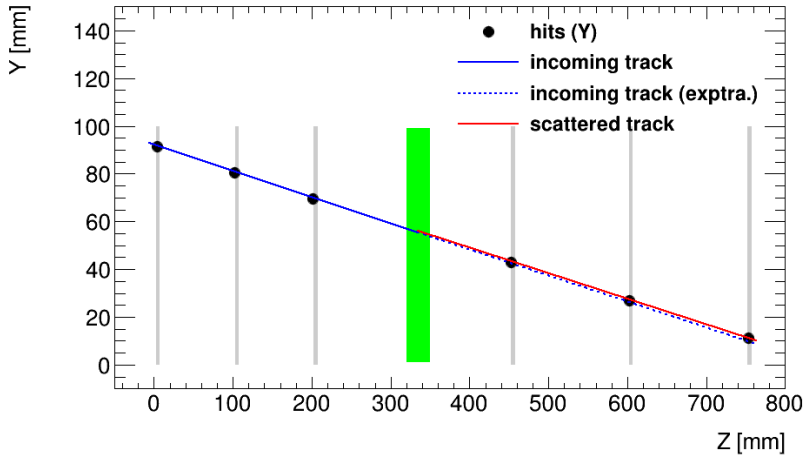
more bad tracks

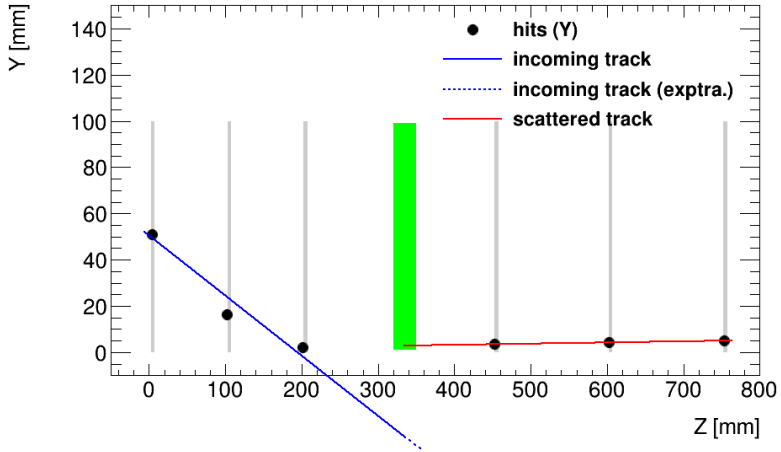








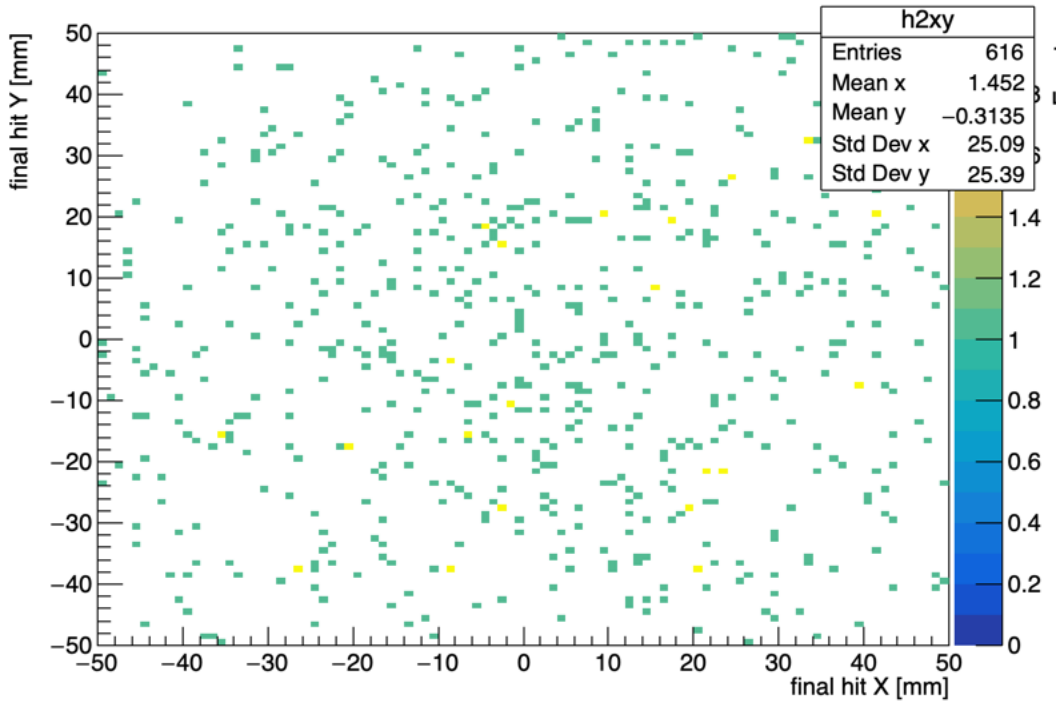




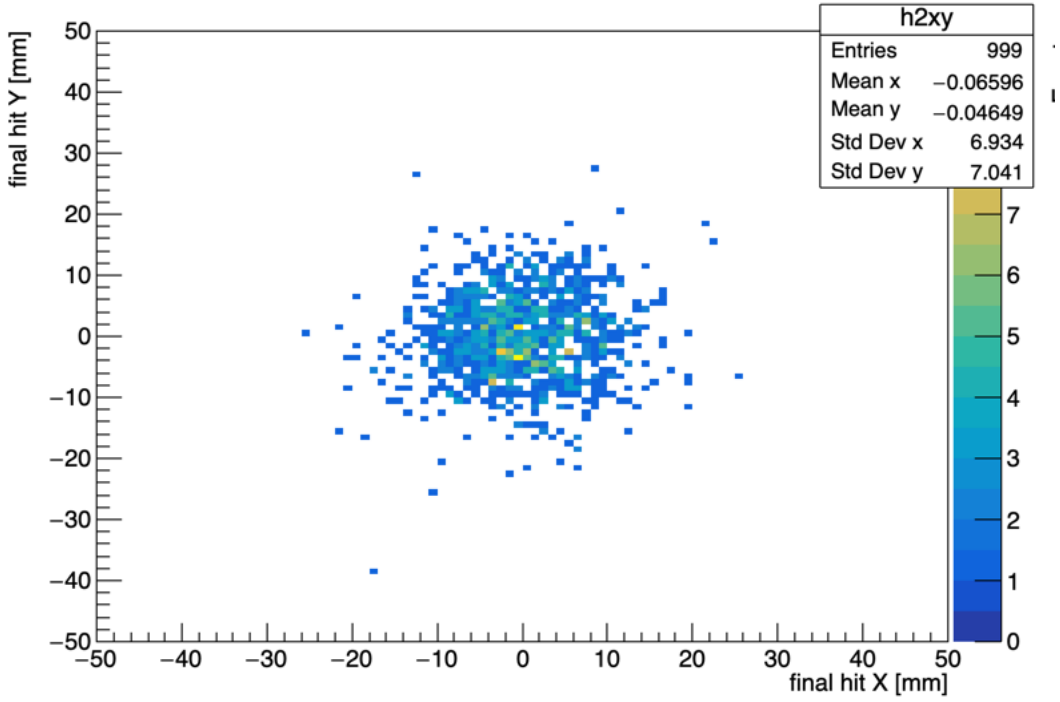
muon energy filter: 60 cm Pb brick

1000 muons with p=2GeV at production
pass rate=61.6% (5cm between Pb and detector)

60cm Pb



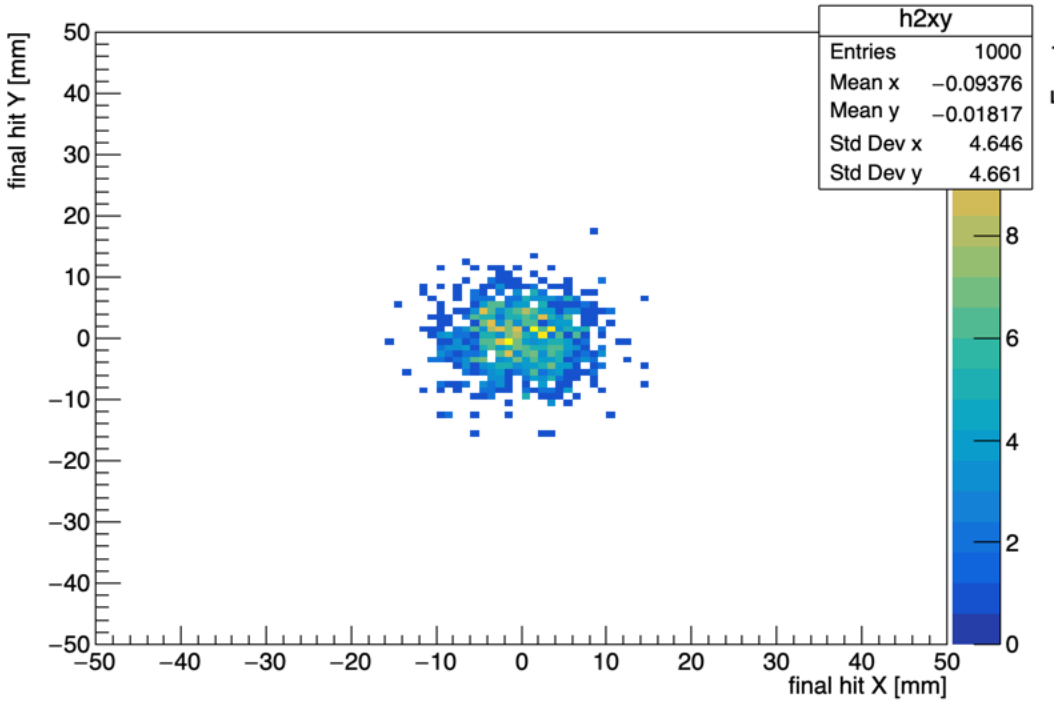
3cm Pb



muon energy filter: 60 cm Pb brick

1000 muons with p=15GeV at production
pass rate=100% (5cm between Pb and detector)

60cm Pb



3cm Pb