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# Exploring the Great Pyramid

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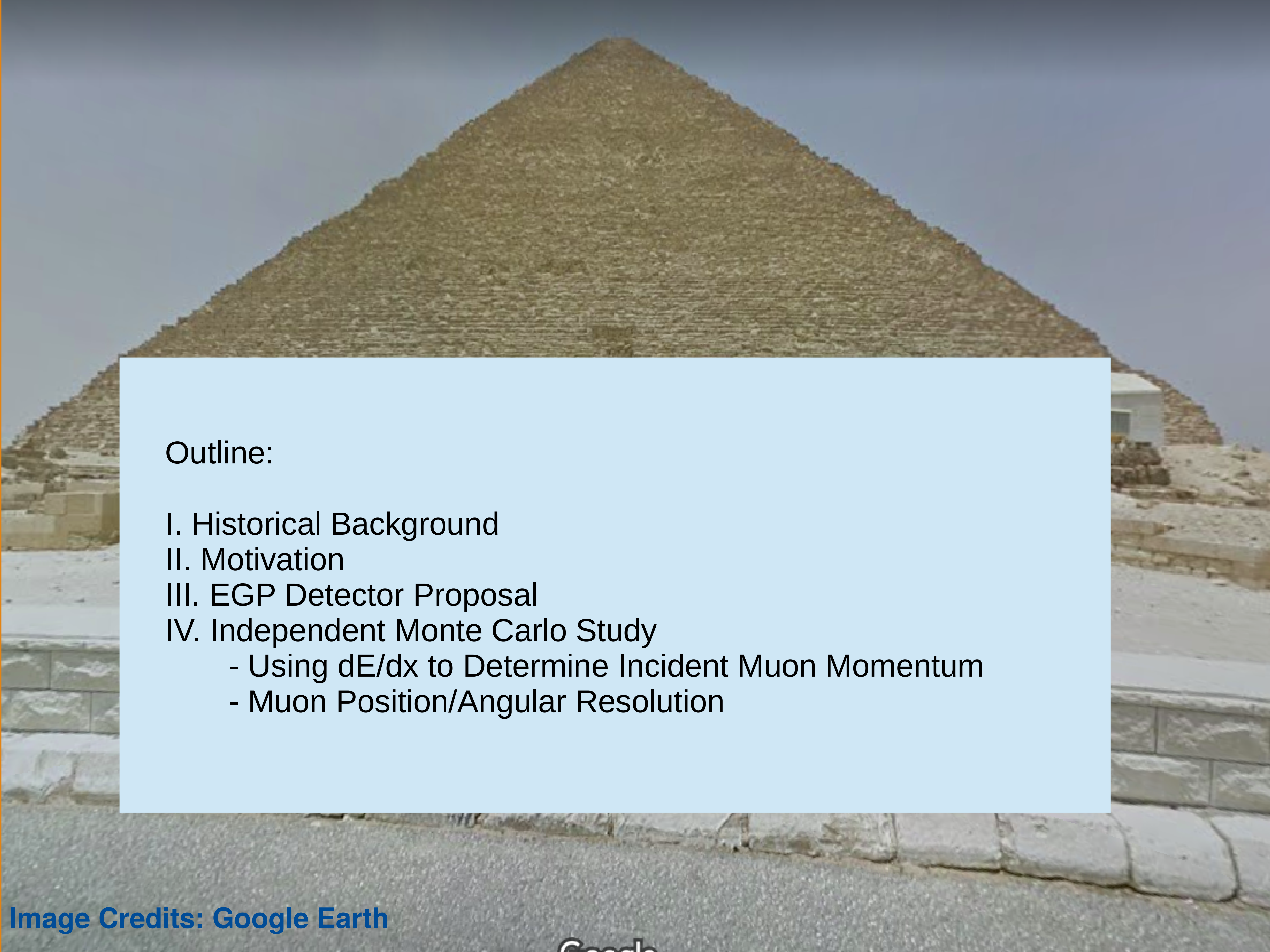


Outline:

I. Historical Background
II. Motivation
III. EGP Detector Proposal
IV. Independent Monte Carlo Study
- Using dE/dx to Determine Incident Muon Momentum
- Muon Position/Angular Resolution

Image Credits: Google Earth

# Historical Background: Cosmic-Ray Muon Radiography

## Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

The three pyramids of Giza are situated a few miles southwest of Cairo, Egypt. The two largest pyramids stand within a few hundred meters of each other. They were originally of almost exactly the same height (145 meters), but the Great Pyramid of Cheops has a slightly larger square base (230 meters on a side) than the Second Pyramid of Chephren (215.5 meters on a side). A photograph of the pyramids at Giza is shown as Fig. 1. Figure 2 shows the elevation cross sections of the two pyramids and indicates the contrast in architectural design. The simplicity of Chephren's pyramid, compared with the elaborate structure of his father's Great Pyramid, is explained by archeologists in terms of a "period of experimentation," ending with the construction of Cheops's pyramid (*1*). (The

mun in the 9th century A.D., almost 3400 years after its construction. Of our group only Ahmed Fakhry (author of *The Pyramids*, professor emeritus of archeology, University of Cairo, and member of the Supreme Council of Archeology, Cairo) was trained in archeology. As laymen, we thought it not unlikely that unknown chambers might still be present in the limestone above the "Belzoni Chamber," which is near the center of the base of Chephren's Second Pyramid, and that these chambers had survived undetected for 4500 years. [We learned later that such ideas had occurred to early 19th-century investigators (*2*), who blasted holes in the pyramids with gunpowder in attempts to locate new chambers.]

In 1965 a proposal to probe the Second Pyramid with cosmic rays (*3*)

of the thickness of rock overlying an underground powerhouse in Australia's Snowy Mountains Scheme (*5*)].

The favorable response to the proposal led to the establishment by the United Arab Republic and the United States of America of the Joint U.A.R.–U.S.A. Pyramid Project on 14 June 1966. Cosmic-ray detectors were installed in the Belzoni Chamber of the Second Pyramid at Giza in the spring of 1967 by physicists from the Ein Shams University and the University of California, in cooperation with archeologists from the U.A.R. Department of Antiquities. Initial operation had been scheduled for the middle of June 1967, but for reasons beyond our control the schedule was delayed for several months. In early 1968 cosmic-ray data began to be recorded on magnetic tape in our laboratory building, a few hundred meters from the two largest pyramids. Since that time we have accumulated accurate angular measurements on more than a million cosmic-ray muons that have penetrated an average of about 100 meters of limestone on their way to the detectors in the Belzoni Chamber.

### Proof of the Method

Before any new technique is used in an exploratory mode, it is essential that the capabilities of the technique be demonstrated on a known system. We gave serious consideration to a proposal that the cosmic-ray detectors be tested first in the Queen's Chamber of the Great Pyramid, to demonstrate that the King's Chamber and the Grand Gallery could be detected. But this

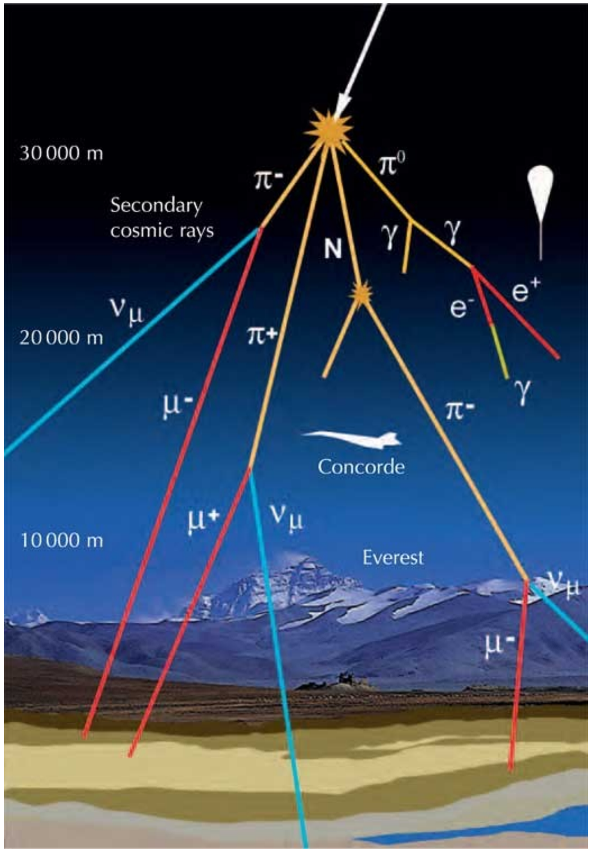
- **Feb. 1970**: Alvarez et al. publish study of Khafre's Pyramid using cosmic rays
- **Nov. 2017**: ScanPyramids Collaboration publishes *Nature* article announcing discovery of new void above Grand Gallery in the Great Pyramid of Khufu

# Motivation: Why do it again?

- Alvarez & ScanPyramids teams both focused on finding new voids
  - ScanPyramids succeeded
- Many other open questions!
  - Why did subsequent pyramids lack the complex internal structure that characterizes Khufu's tomb?
  - What can be learned about the details of this structure from high-resolution tomographic imaging?
    - Distinguish not only voids from solid stone, but also subtler variations in density
    - Gain insight regarding construction techniques – how was the Great Pyramid built?
    - Reveal unknown unknowns?

# Muon Tomography

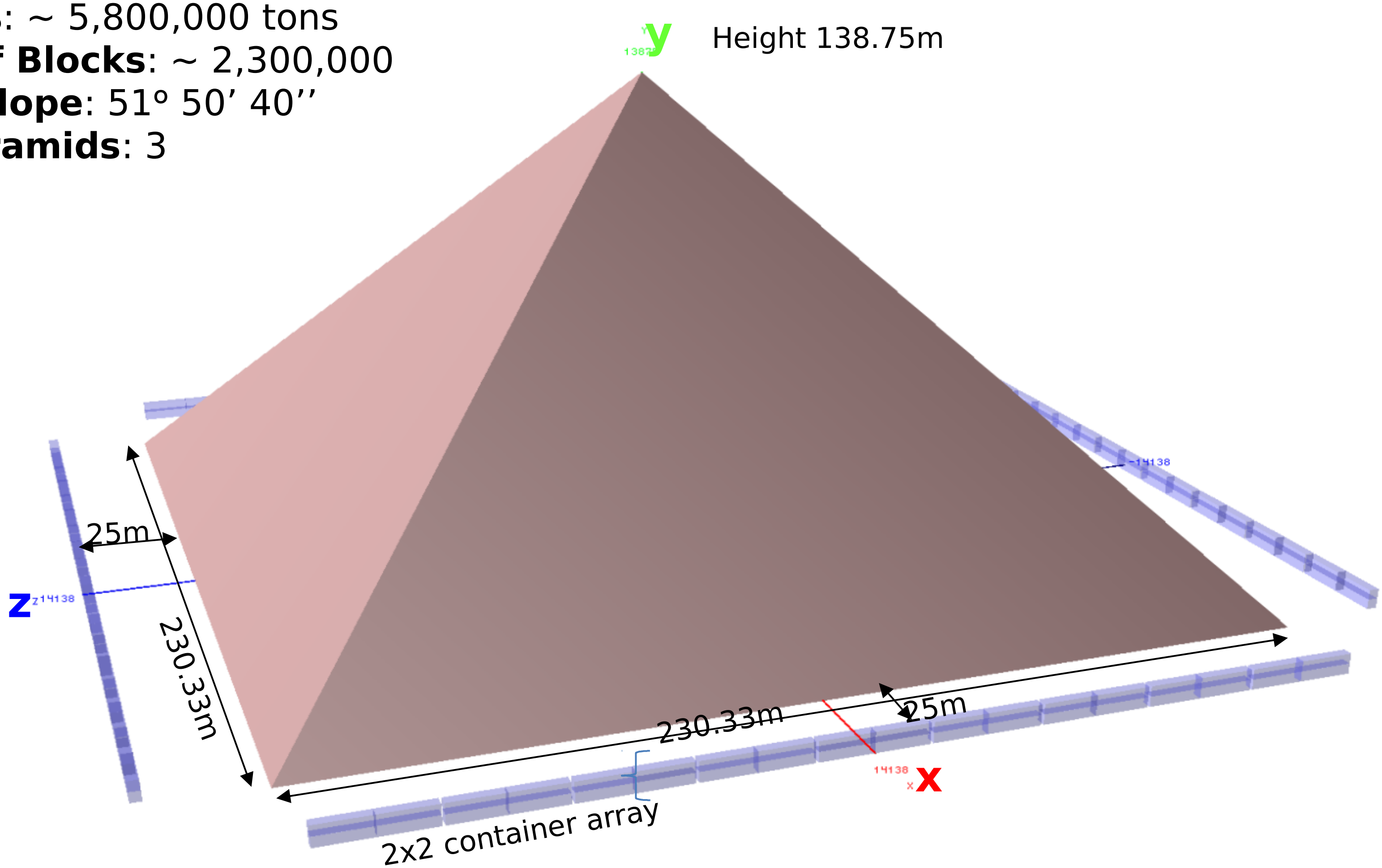
- Unlike previous projects, EGP will apply true tomographic imaging & reconstruction
  - Cosmic particles like protons interact w/ upper atmosphere → muons
  - When they reach Earth's surface, many muons still have enough energy to penetrate massive structures – like the Great Pyramid
  - Rate of muons that make it to the other side, measured as a function of angle, yields information about the structure
  - Repeating such measurements at many different locations around pyramid permits full 3D imaging of its interior!



# EGP Detector Proposal

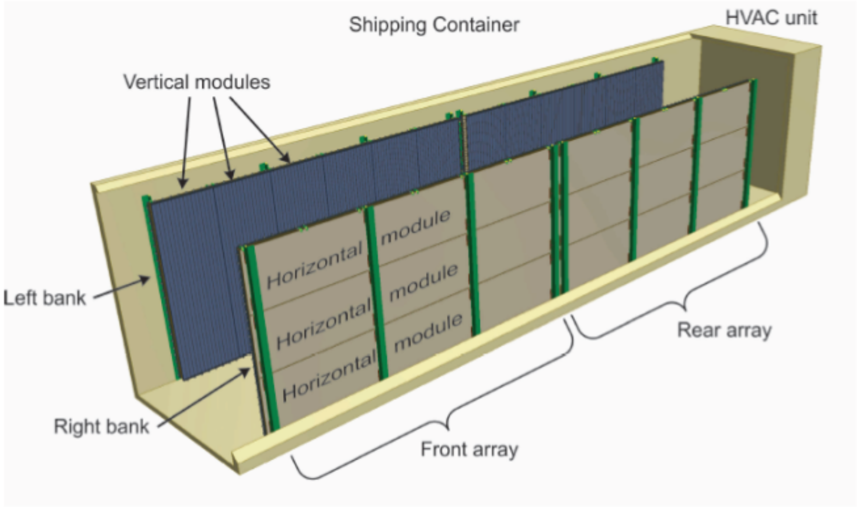
The Great Pyramid of Khufu by the numbers:

- **Total Mass**: ~ 5,800,000 tons
- **Number of Blocks**: ~ 2,300,000
- **Angle of Slope**: 51° 50’ 40’’
- **Queen Pyramids**: 3



# EGP Detector Proposal

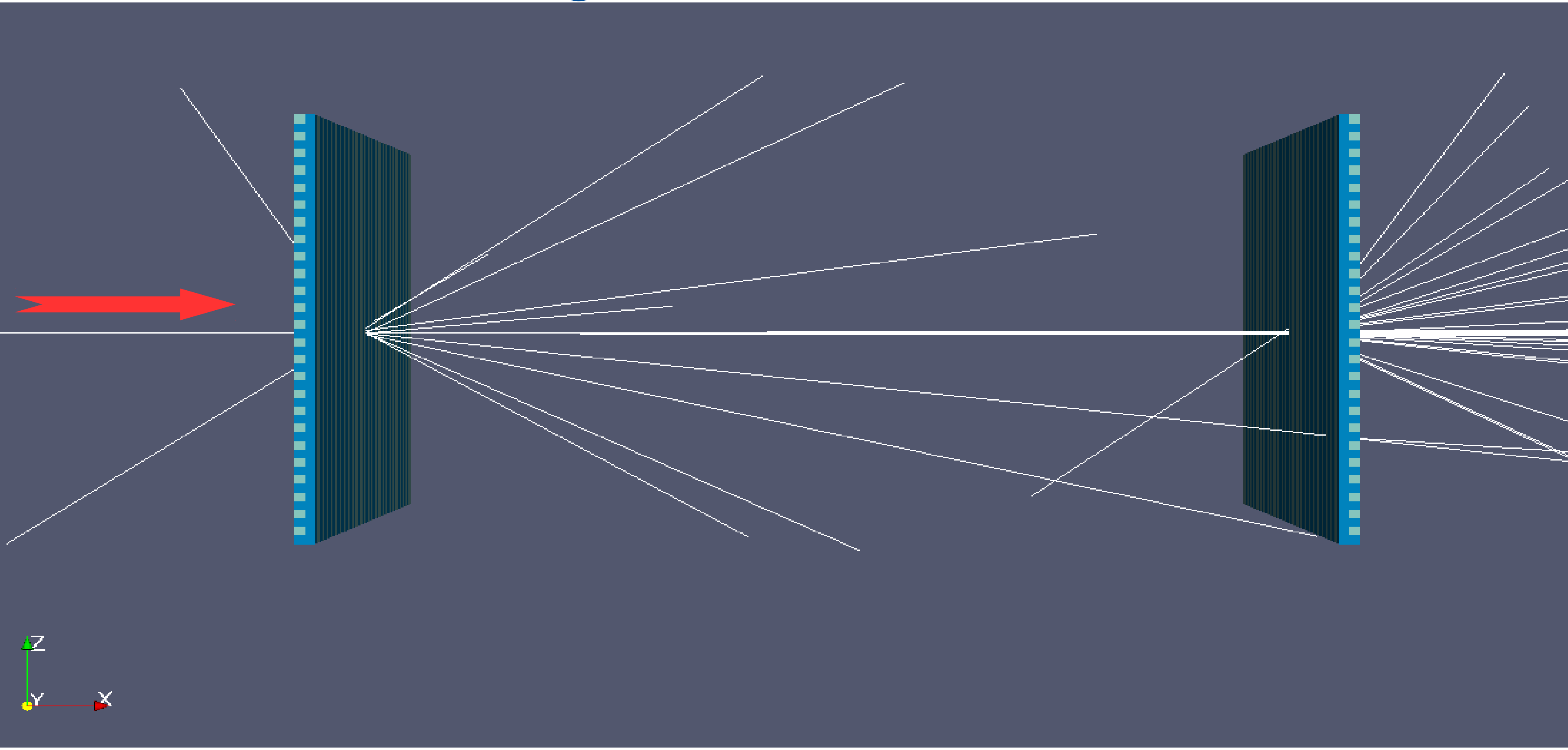
- Detectors housed in 40-ft. steel shipping containers
- Field 8 such containers in 2 x 2 arrays
  - Move around pyramid perimeter for tomographic image reconstruction
- On each container wall, 2 arrays of extruded scintillator strips
  - In each array, 6 vertical modules (40 strips each) & 3 horizontal modules (40 strips each) for a total of ~1400 strips
  - Vertical strips ~ 2.4 m. in length, horizontal strips ~4.8 m.; walls separated by 2 m.
- Scintillator strips:
  - Emit light when exposed to ionizing radiation (here, muons)
  - Embedded w/ wavelength-shifting fibers to collect a fraction of this light & transmit it to SiPMs



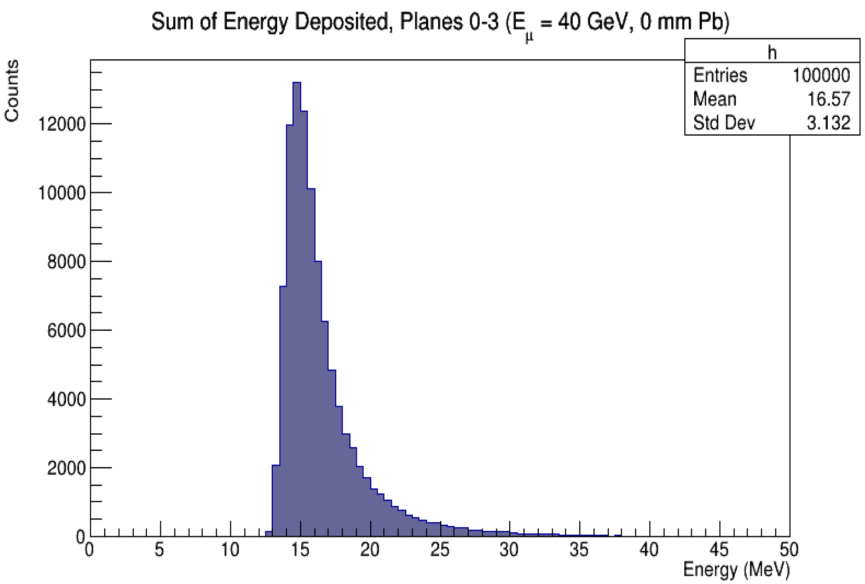
# Independent Monte Carlo Study

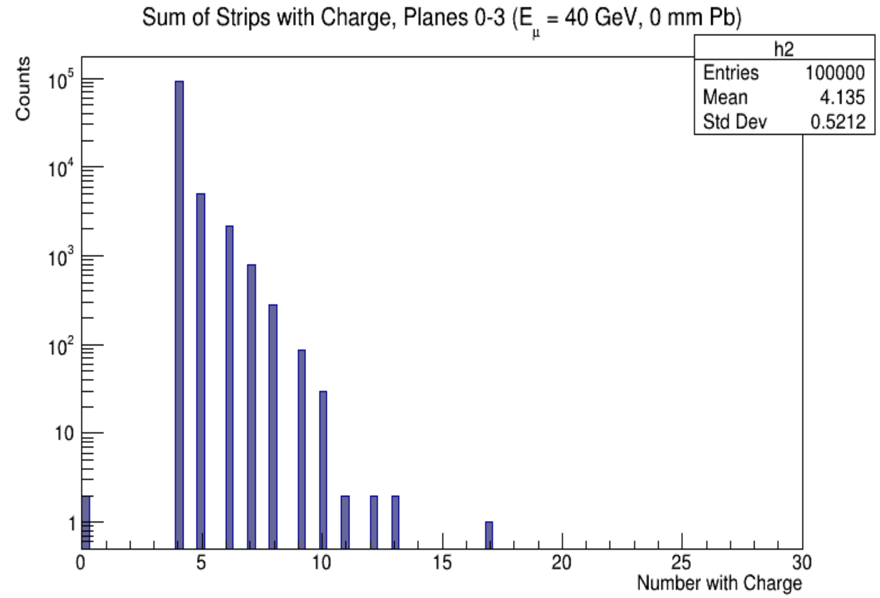
- Goal: isolate problem of detector design in a stand-alone GEANT4 simulation
- Two primary questions:
  - What is the necessary detector resolution?
    - Limited by multiple scattering effects
  - Is it feasible to differentiate incident muon momenta based on energy deposited in scintillator?
    - Could permit the use of only muons that fall in a "sweet spot" of energies for reconstruction
- Supporting data analysis and visualizations in Root and Paraview

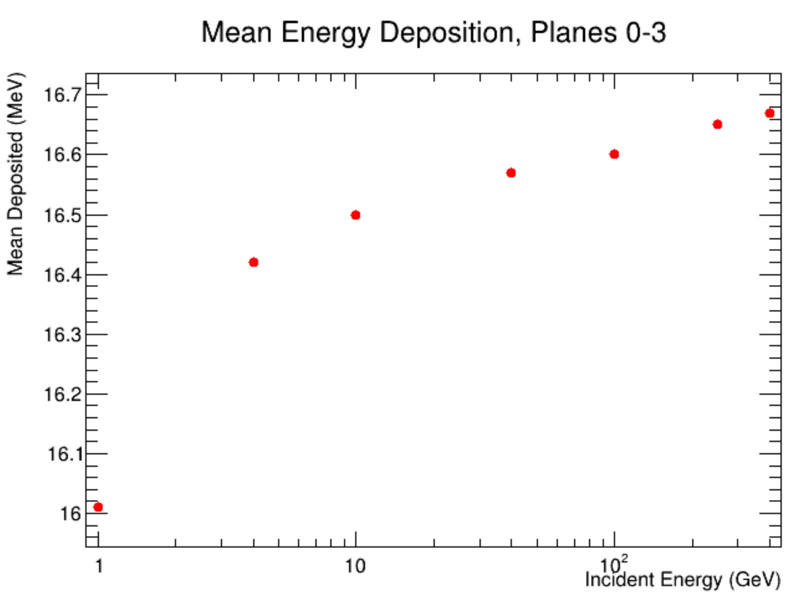
# MC: Detector Design & Particle Gun

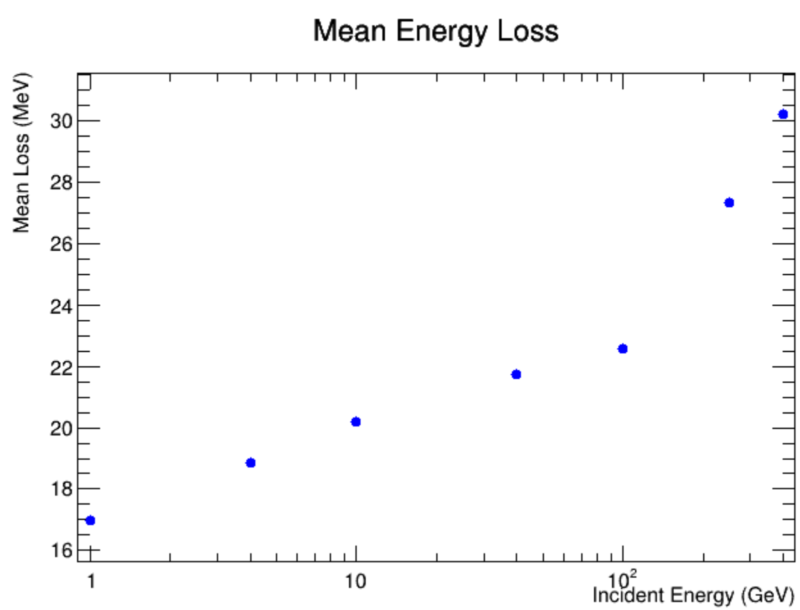



**Simulation contains two detectors, each consisting of two 1 m x 1 m scintillator planes and each plane composed of 50 2 cm x 2 cm x 1 m strips; there is a 2 m gap between the first and second detectors. G4ParticleGun produces 1 muon at a time, with the same initial momentum and position each time.**

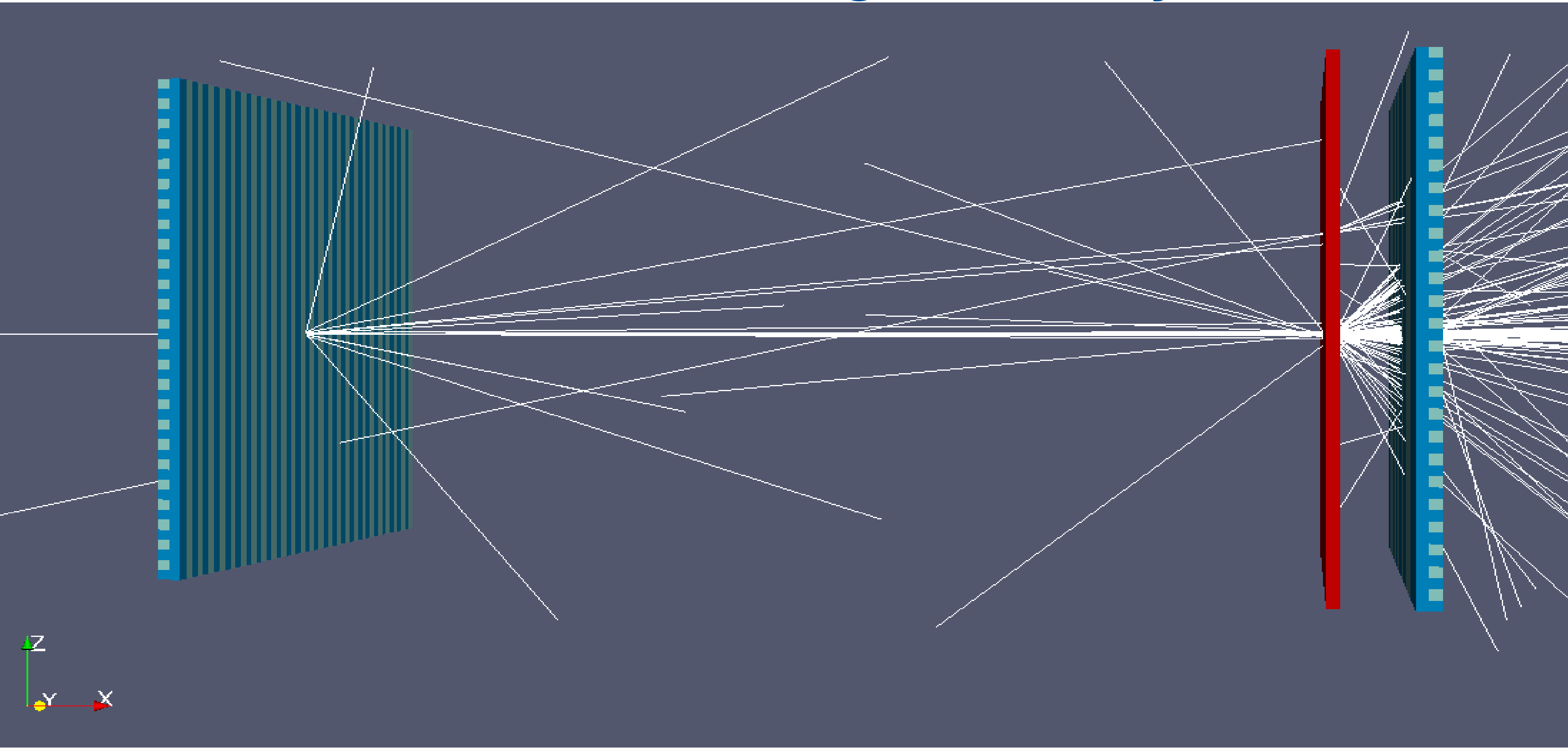

Sum of Energy Deposited, Planes 0-3 ($E_\mu$ = 40 GeV, 0 mm Pb)
h
Entries 100000
Mean 16.57
Std Dev 3.132
Counts
Energy (MeV)


Sum of Strips with Charge, Planes 0-3 ($E_\mu$ = 40 GeV, 0 mm Pb)
h2
Entries 100000
Mean 4.135
Std Dev 0.5212
Counts
Number with Charge


Mean Energy Deposition, Planes 0-3
Mean Deposited (MeV)
Incident Energy (GeV)

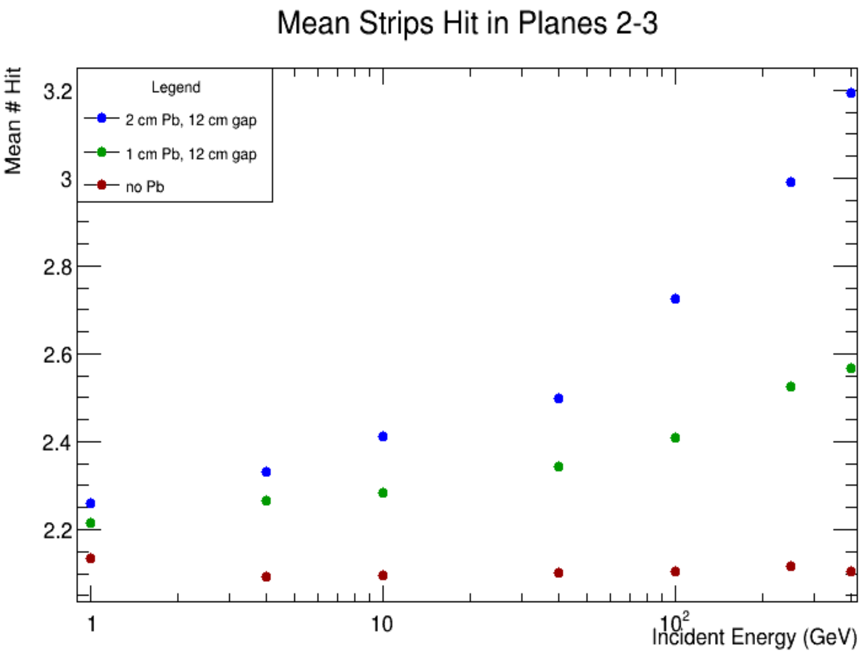

Mean Energy Loss
Mean Loss (MeV)
Incident Energy (GeV)

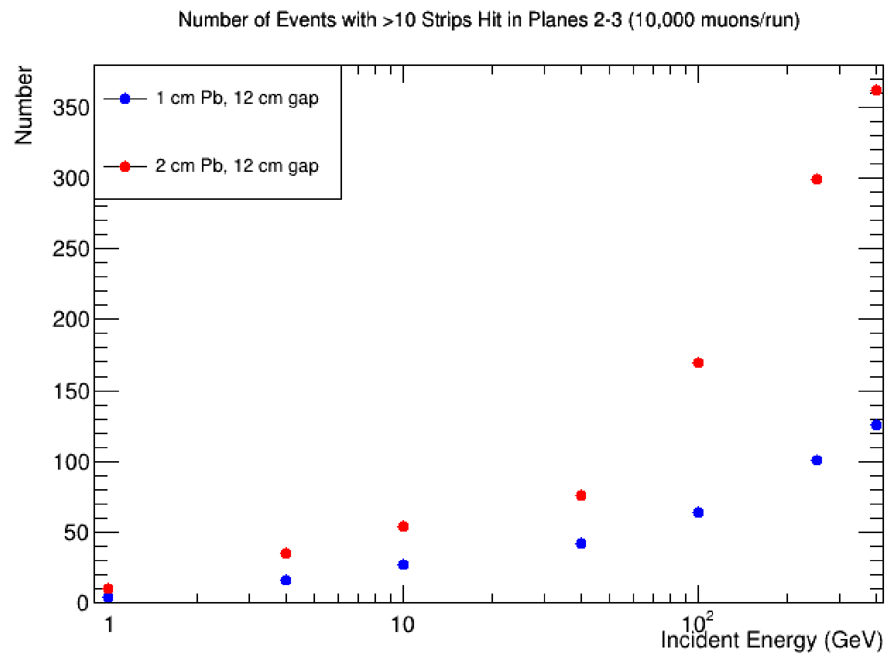
# MC: Alternate Detector Design – Pb Layer




**The modified detector design includes a lead sheet of varying thickness between the two detector planes, and the placement of this sheet ranged from 12 cm – 20 cm upstream of detector 2. The goal of this addition was to increase the number of secondaries striking detector 2 without degrading position resolution, as this would help differentiate low- and high-energy muons.**

# MC: Pb Layer – Energy Results



# MC: Muon Hit Position & Angular Resolution

- The strips hit in each detector provide a point in space which lies on the muon's trajectory
- Can combine hits from both detectors to reconstruct muon's path → backproject to predict where muon came from at any desired distance
  - RMS error from cell of width A = A /√12
- What size scintillator strip is needed, given the effects of multiple scattering in the pyramid?

$$\theta_0 = \frac{13.6\ \mathrm{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big]$$



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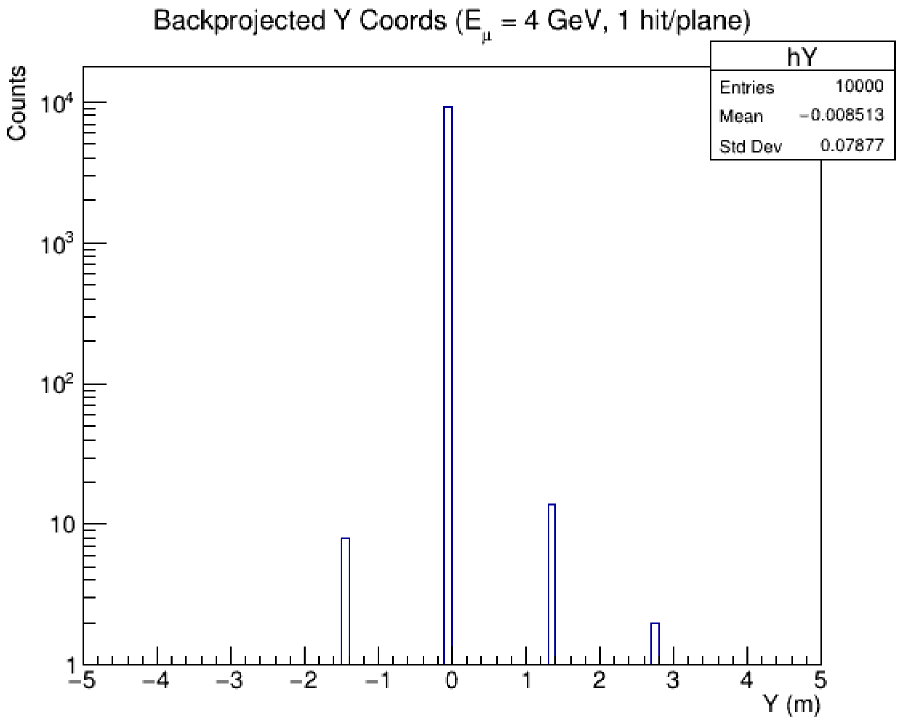
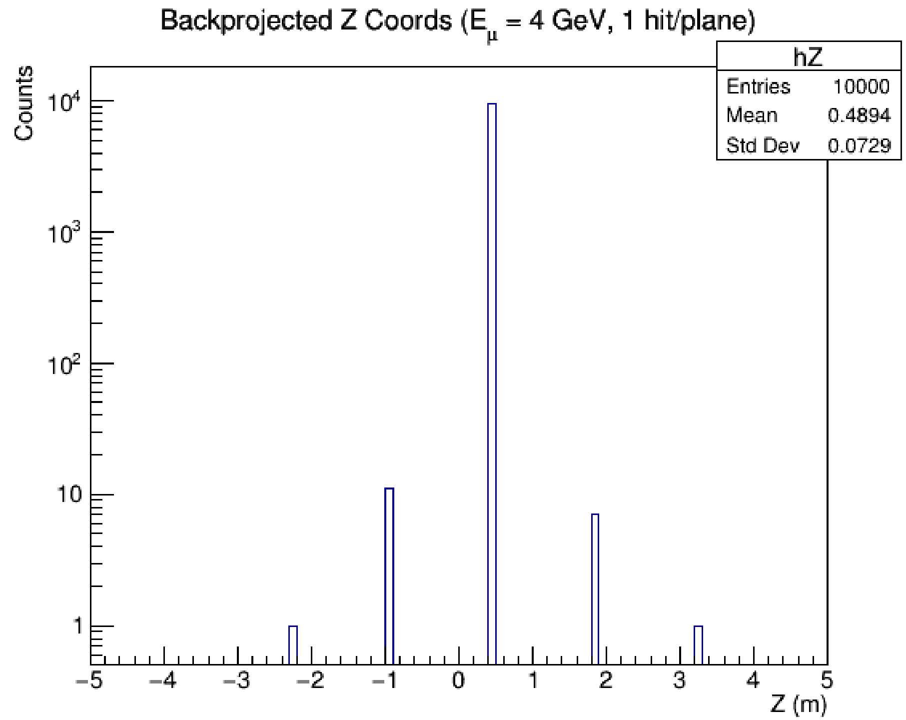
# MC: Position Resolution




**Preliminary results from position resolution algorithm (beam at normal incidence, backprojected a distance of 140 m). Non-central bins stem from events in which the muon scattered to a different strip in the detector.**

# MC: Future Work

- Likely not feasible to use number of hits to tag muon energy
  - Small increase in mean # hit over the energy range of interest
  - Small fraction of total muons results in this increase
- Continue development of hit position clustering algorithms
- Vary angle of muon beam and repeat angular resolution studies
- Add concrete block as pyramid dummy
  - Study effects of multiple scattering on angular resolution
  - Optimize scintillator strip size and shape

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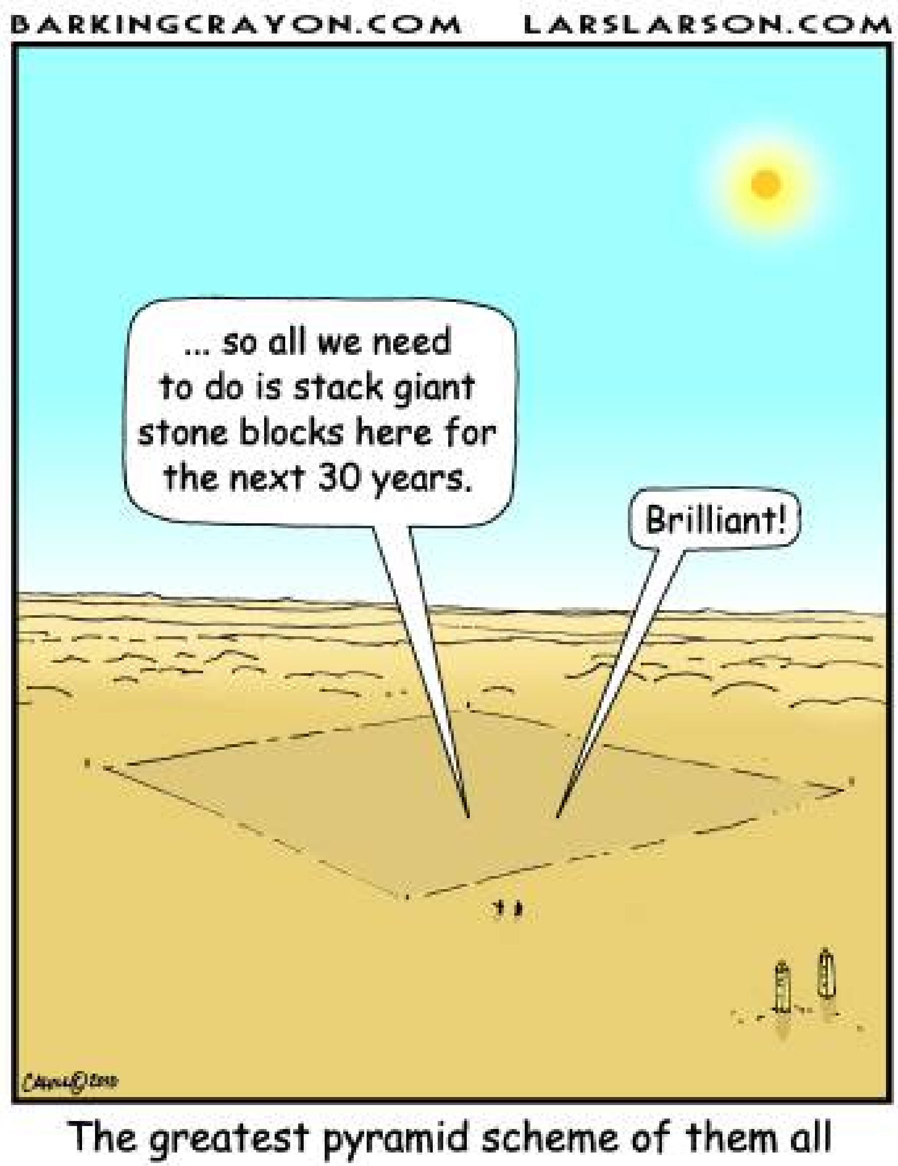
# Thank You!

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