Muon Tomography Applications Using Monte Carlo Simulation of Prototype Muon Telescope

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Background

Muon tomography is a technique that utilizes muon scattering and absorption to create images of large objects of interest such as volcanoes, buildings, or ancient archeological structures.

Muons are subatomic particles created in the Earth's upper atmosphere by cosmic rays colliding with atomic nuclei of molecules in the air, as show in figure A. These rays are forms of high energy radiation from outside our solar system consisting of mostly high energy protons, which most often decay into muons and muon neutrinos as the shower approaches sea level.

Muons lose energy mostly through inelastic collisions in materials per given path length causing substantial energy loss in dense materials. The energy loss is generally given by the Bethe-Bloch formula which describes the stopping power of a material. Muon tomography takes advantage of this density dependent energy loss thereby enabling image reconstruction. As shown in figure B.

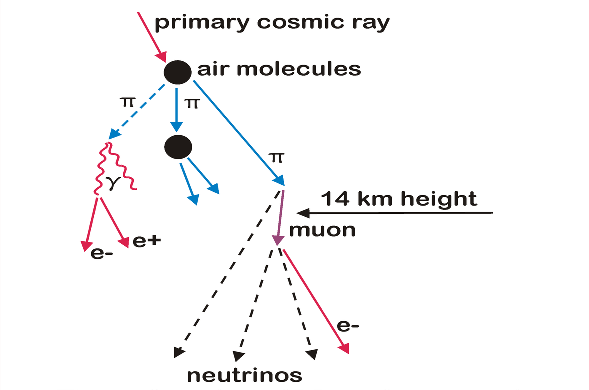

Fig A: Creation of Muon from cosmic ray shower.

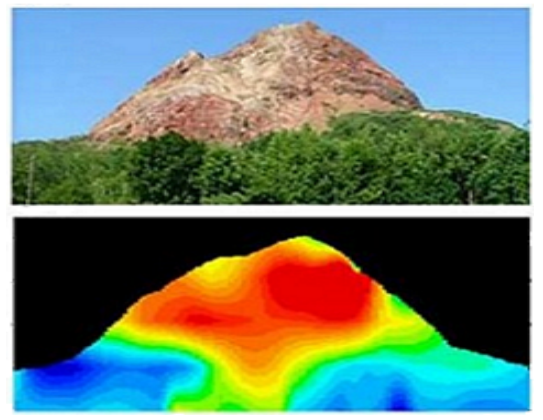

Fig B: Sample Muon Tomography Image.

Geant4 Environment Using QT

Intended for our group to test the experimental data, we created an ideal case of the water tower experiment. Geant4 is a very useful Monte Carlo simulation software that allows us to study the effects of muon particles interacting with the water tower.

Implementing the GUI known as QT, the environment of our simulation can be shown and edited with ease, as shown in Figure C. QT gives the user multiple options for a simulation that allows them to completely recreate the physical construct for use in other experiments. The simulation includes the material of each object, position, size, and the world for which our objects are placed. Figure D shows our MC simulated environment, while figure E shows the physical water tower and location of our telescope.

Setting up the environment allows us to see the interactions of the muon particles on their path from creation at the edge of the world. To track its path and momentum, we used geant4 to establish a magnetic field in the world.

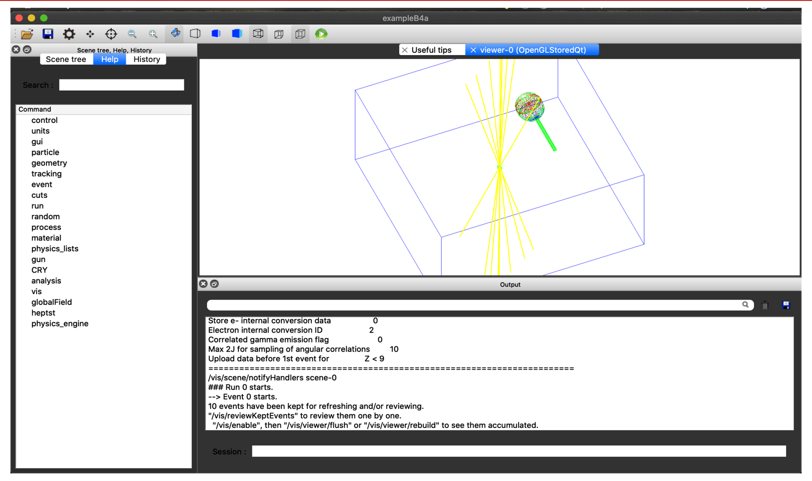

Fig C: QT GUI of Monte Carlo Simulation.

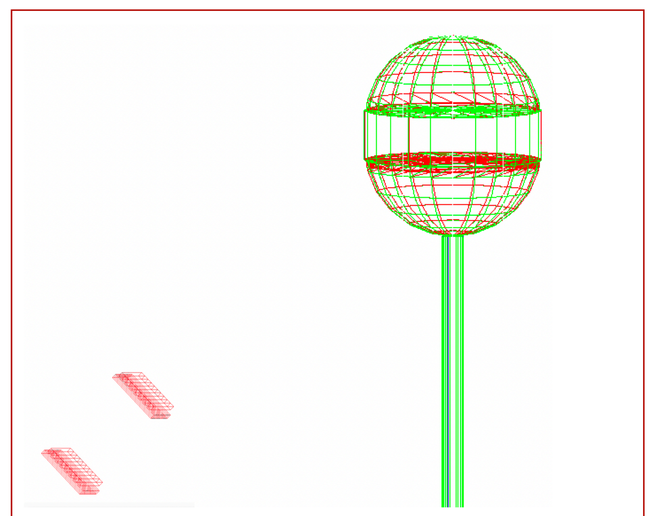

Fig D: The World Geometry in GEANT 4 simulation.

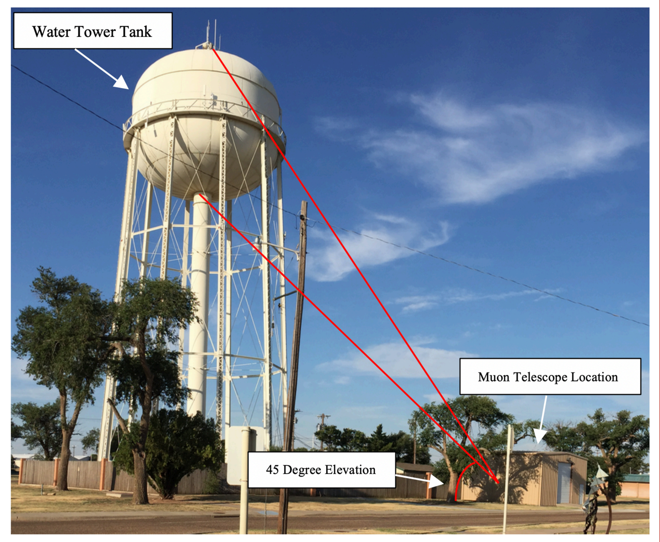

Fig E: The water tower.

Introduction

Our primary objective is to develop a portable muon telescope with excellent spatial resolution that will be able to image large structures in great detail. The present prototype allows us to study hardware components as well as software reconstruction techniques needed for advanced muon tomography.

Our current experiment involves the detection of a water tower and its contents using the Prototype-I telescope. A Monte Carlo (MC) Simulation was developed to improve our detector. The present MC Simulation utilizes Geant4 combined with Cosmic-ray Shower Library (CRY) and ROOT for data analysis. Using QT as a GUI speeds the development of our simulation through design and execution. The data collected is used to construct 2D muon images of the tower showing its contents. With the Prototype-I system, we can reconstruct 2-dimensional images of large objects with an angular resolution of 50 milliradians at an operating efficiency of 89%. In an effort to improve our prototype we are comparing the simulated results with our experimental results.

Cosmic-ray Shower Library (CRY)

Once the environment is set, we start running the simulation using a set number of events. This duration of events is controlled by CRY. CRY creates a pre-set number of muon particles of our choosing, thus allowing us to control how many muon particles we want to analyze. The randomly generated muon particles represent the muon flux created in the earth's atmosphere, which is then detected by our Prototype-I telescope. Recreating this flux using CRY allows us to fully understand how muons interact in our simulated world by tracking the properties using Geant4.

An image of the muons path through our telescope's scintillator bars is represented by the dashed yellow lines, as shown in Figure E.

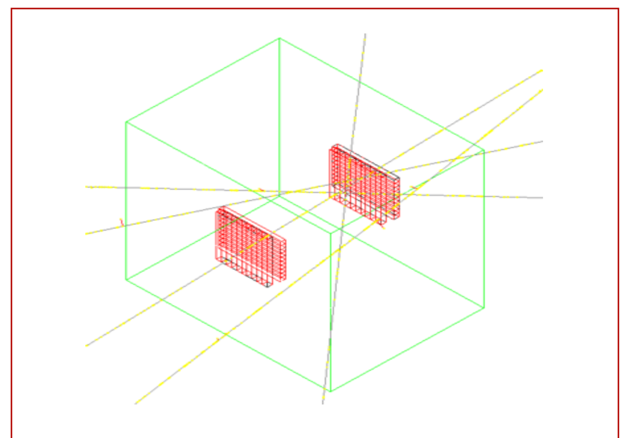

Fig E: muon particles paths through detector.

ROOT Data Analysis

The data collected is analyzed using ROOT to create comparable histograms with our experimental data. Throughout the simulation, we track important attributes of the muon particles interaction with the materials and geometry. Using the attributes we can find the particle id, energy deposit in each scintillator bar, and the momentum of a particle when it is detected by our Prototype-I telescope in a specific axis. Creating these histograms allow us to compare them to the data from the experiment. Figures 1.0 and 1.2 show the MC data that is being compared to our experimental data in figures 1.1 and 1.3. The energy deposited in a scintillator bar is proportional to the ADC count detected by our hardware components as shown in the figures below. The muon angular distribution provides information for us to create a projection of the muons path, that can be used for creating an image of the water tower.

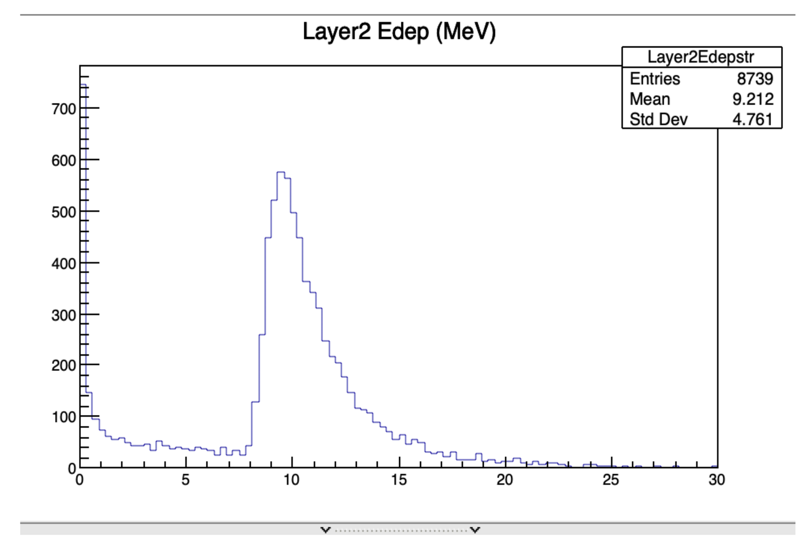

Fig 1.0 : Energy deposit in layer 2 in MC.

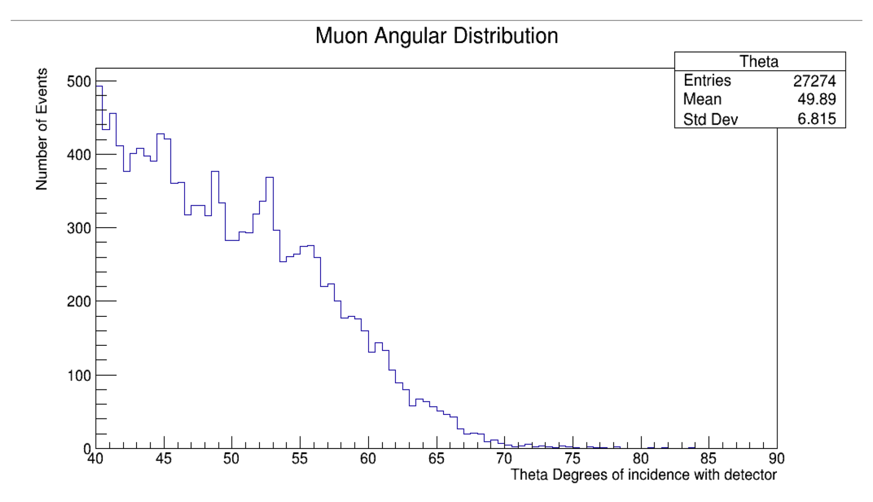

Fig 1.2 : Muon Angular Distribution for MC.

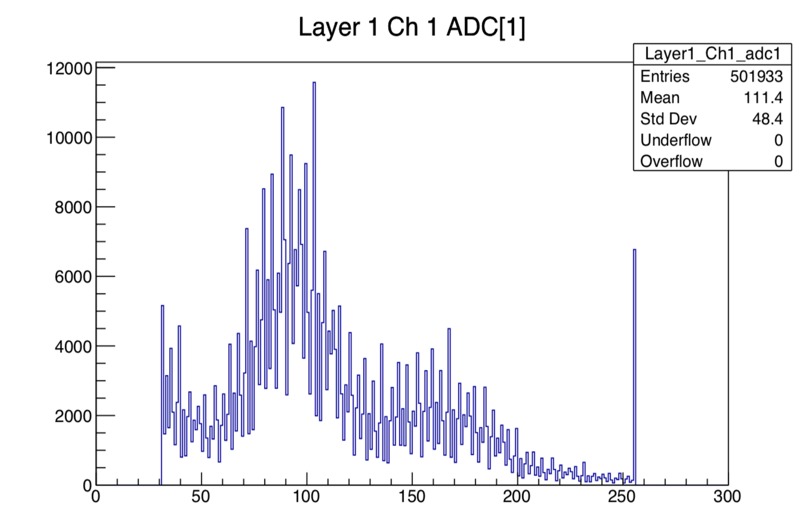

Fig 1.1 : ADC count detected for layer 1.

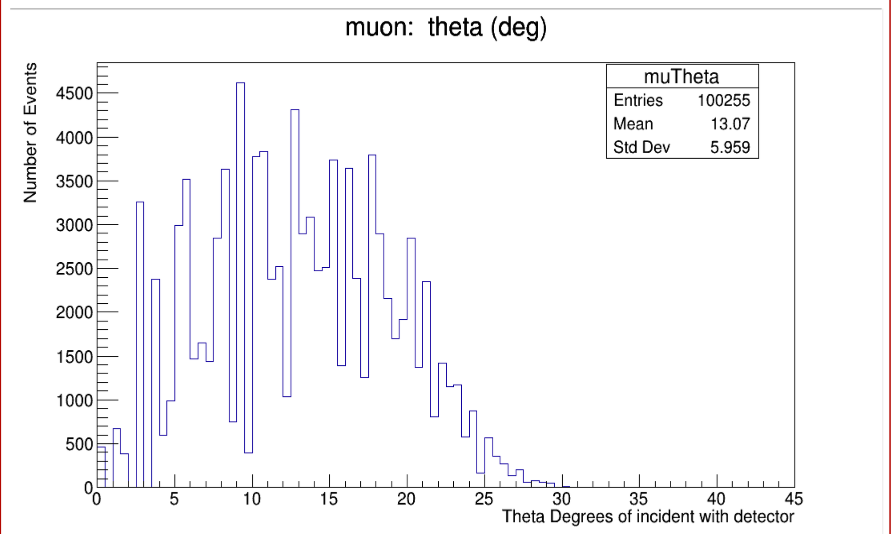

Fig 1.3 : Muon Angular Distribution for MC.

Results

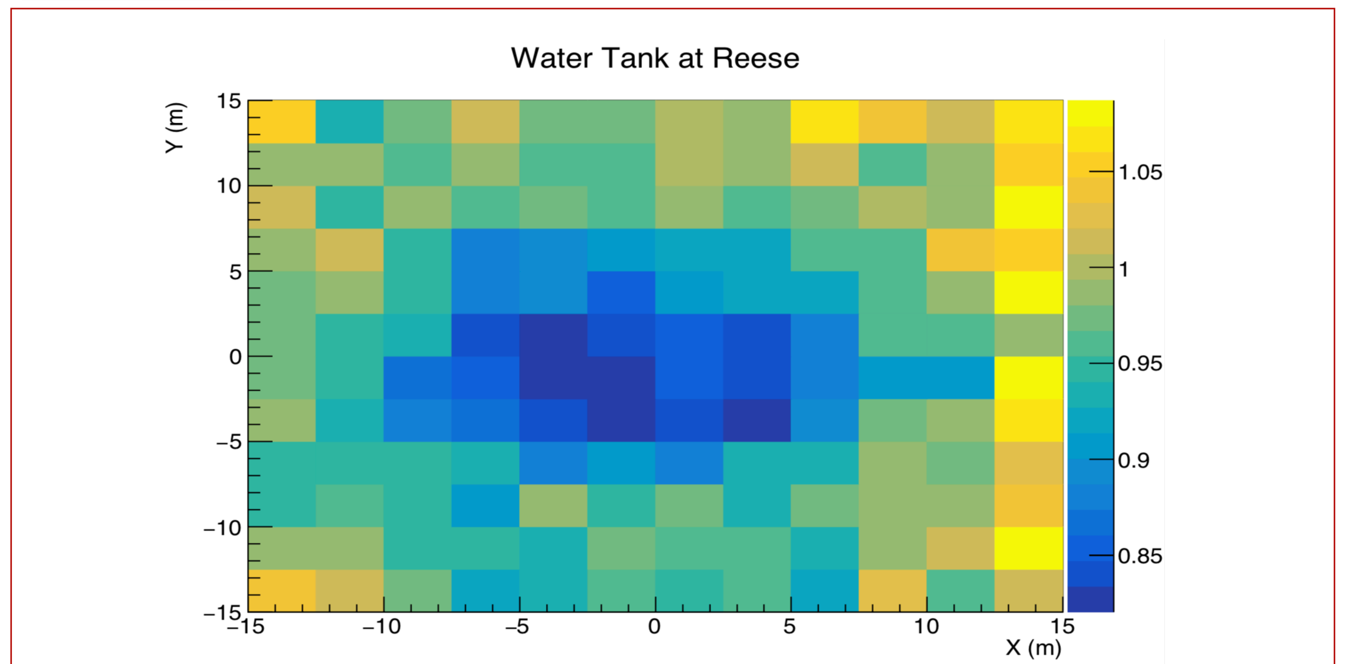

Fig F : 2D image of muon deficit in experiment.

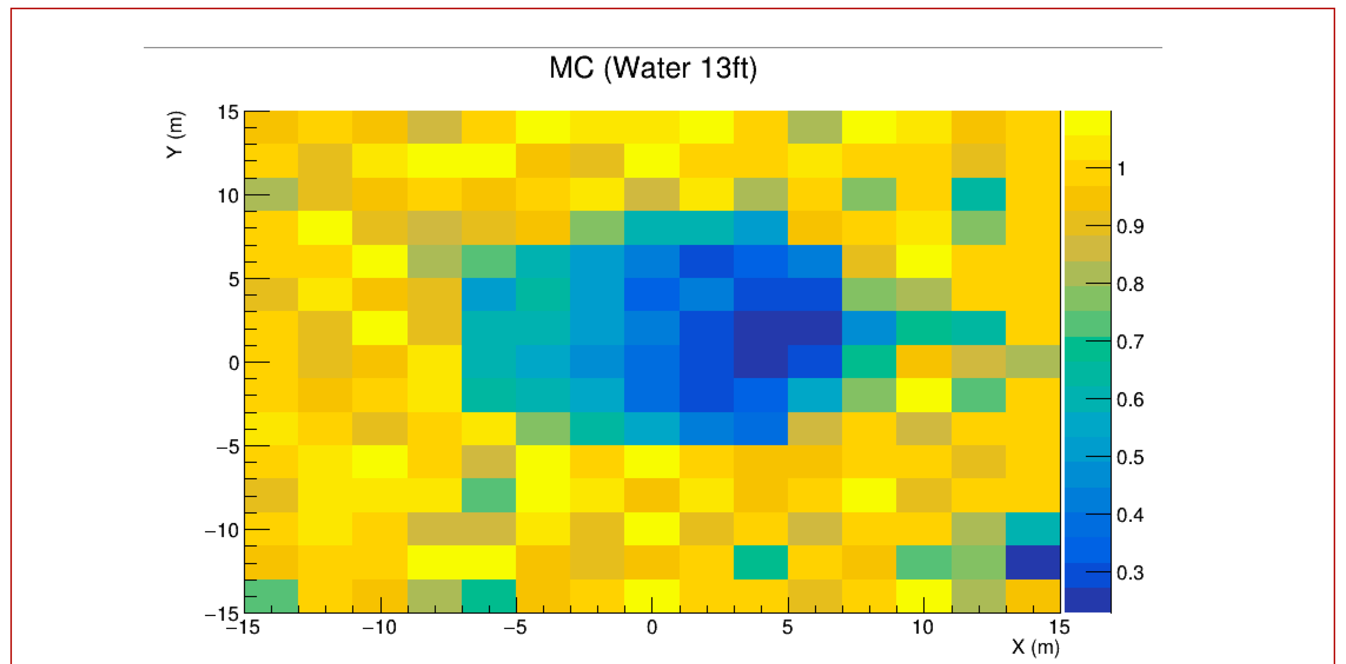

Fig G : 2D image of muon deficit in MC.

During the experiment, we collected roughly 3 million events in a single day with only 5.2% of it giving us a usable single muon track that could be used towards imaging. Figure F shows a 2D image of the water tower. The color scale is obtained by taking the ratio between the data sets with and without the water tower for the same number of reconstructed muons. In both cases the greater frequency of muons is represented by the brighter pixel luminance value, thus showing a low density of muons in the center. This low density is what shows the presence of the water tower tank. The data indicates that there is ~15% loss of muons due to the presence of the filled water tower. We similarly produced the same 2D image using simulated events, as shown in figure G. The simulation suggests about 70% effect. The disagreement between the two is currently being studied.

Conclusion

Using Monte Carlo methods, we are successfully able to recreate our experiment and results that allow us to observe the shadow of the water tank using muons and the Prototype-I telescope. The questions of low efficiency and disagreement between data and the simulation are now being investigated. Further analysis using the current simulation is ongoing with new parameters being implemented. We are currently developing the simulation for our next prototype using wave shifting fibers as a potential replacement of scintillator bars for much finer segmentation. Further improvements in the simulation are being investigated to guide our aim to achieve a resolution of 0.5 milliradians with the next prototype (Prototype-II).

Acknowledgment

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